Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

Eddy Current Flow Measurements in the FFTF

December 2016

DL Nielsen   RP Omberg
DL Polzin   BJ Makenas

TerraPower™

U.S. DEPARTMENT OF
ENERGY

This document was printed on recycled paper.
(9/2003)

Eddy Current Flow Measurements in the FFTF

DL Nielsen   RP Omberg
DL Polzin   BJ Makenas

December 2016

Executive Summary

The Fast Flux Test Facility (FFTF) is the most recent liquid metal reactor (LMR) to be designed, constructed, and operated by the U.S. Department of Energy (DOE). The 400-MWt sodium-cooled, fast-neutron flux reactor plant was designed for irradiation testing of nuclear reactor fuels and materials for liquid metal fast breeder reactors. Following shut down of the Clinch River Breeder Reactor Plant (CRBRP) project in 1983, FFTF continued to play a key role in providing a test bed for demonstrating performance of advanced fuel designs and demonstrating operation, maintenance, and safety of advanced liquid metal reactors. The FFTF Program provides valuable information for potential follow-on reactor projects in the areas of plant system and component design, component fabrication, fuel design and performance, prototype testing, site construction, and reactor control and operations. This report provides HEDL-TC-1344, "ECFM Flow Measurements in the FFTF Using Phase-Sensitive Detectors", March 1979.

Acronyms

ARD	Advanced Reactor Division
CRBRP	Clinch River Breeder Reactor Plant
DOE	U.S. Department of Energy
ECFM	Eddy-Current Flowmeter
FFTF	Fast Flux Test Facility
FTR	Fast Test Reactor
LMFBR	Liquid Metal Fast Breeder Reactor
LMR	Liquid Metal Reactor

Contents

1.0   Eddy Current Flow Measurements in the FFTF

The Fast Flux Test Facility (FFTF) is the most recent liquid metal reactor (LMR) to operate in the United States, from 1982 to 1992.The 400-MWt sodium-cooled, low-pressure, high-temperature, fast-neutron flux, nuclear fission test reactor was designed specifically to irradiate Liquid Metal Fast Breeder Reactor (LMFBR) fuel and components in prototypical temperature and flux conditions. FFTF played a key role in LMFBR development and testing activities. The reactor provided extensive capability for in-core irradiation testing, including eight core positions that could be used with independent instrumentation for the test specimens. In addition to irradiation testing capabilities, FFTF provided long-term testing and evaluation of plant components and systems for LMFBRs.

This report provides HEDL-TC-1344, "ECFM Flow Measurements in the FFTF Using Phase-Sensitive Detectors", W.T. Nutt and J.L. Stringer, Hanford Engineering Development Laboratory, March 1979. The Eddy-Current Flowmeter (ECFM) is an accurate electromagnetic device for measuring the velocity of a conductor along the longitudinal axis of the flowmeter. Misconceptions about the inherent accuracy of the flow signal resulted in the belief that the ECFM had little flow sensitivity at low flow velocities (see References 1, 2 and 3 of TC-1344). The report dispelled that notion and describes the equipment and procedures for accurately measuring very low flows in the FFTF using an Eddy Current Flowmeter. Calibration results from the Transient Test Loop were analyzed and are presented in the report. Analysis of the hardware operation in extracting a flow reading from the flowmeter signal was used to show the efficacy of the phase-sensitive detection procedure

HEDL-TC-1344

ECFM Flow Measurements in the FFTF Using Phase Sensitive Detectors

TC-1344

ECFM FLOW MEASUREMENTS IN THE FFTF USING PHASE-SENSITIVE DETECTORS

Hanford Engineering Development Laboratory

W. T. Nutt

J. L. Stringer

March 1979

ECFM FLOW MEASUREMENTS IN THE
FFTF USING PHASE-SENSITIVE DECTECORS

W. T. Nutt

J. L. Stringer

ABSTRACT

The equipment and procedures for accurately measuring very low flows in the Fast Flux Test Facility using an Eddy Current Flowmeter are described. Calibration results from the Transient Test Loop are analyzed and presented. Analysis of the hardware operation in extracting a flow reading from the flowmeter signal is used to show the efficacy of the phase-sensitive detection procedure.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to
W. L. Thorne for his invaluable assistance and cooperation
during the testing phase of this work.

CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

The Eddy-Current Flowmeter (ECFM) is an accurate electromagnetic device for measuring the velocity of a conductor along the longitudinal axis of the flowmeter. While such devices have been in use for several years, misconceptions about the inherent accuracy of the flow signal have produced the notion that the ECFM has little flow sensitivity at low flow velocities (see References 1, 2 and 3). It was not until recently (see Reference 4) that the reason for the apparent loss of sensitivity at low flows was recognized. The existence of "non-flow" components in the ECFM signal was the real culprit. In this report the calibration of ECFMs using Phase-Sensitive Detection (PSD) techniques is discussed and the results of the calibration program at the Transient Test Loop (TTL) Facility at HEDL are presented.

1.1 Overview

The remainder of the introductory section describes the measurement goals and ECFM configurations of the Fast Flux Test Facility (FFTF). Section 2 gives a brief overview of the ECFM from a hardware point-of-view and also describes the electronic processing which produces the flow signal using either Amplitude Detection (AD) or PSD. An analysis of the general theory behind ECFMs and of AD and PSD along with a discussion of error sources and calibration results constitute Section 3. Finally, in Sections 4 and 5, procedures for the implementation of PSD in the field are discussed.

1.2 FFTF Goals

In the FFTF Natural Circulation Testing, the flow velocities in the fueled subassemblies will be less than 10% of full flow. In order to obtain a reasonable flow map in the core at these low flows and to be able to describe the FOTA flows, greater accuracy is required than is available with the AD System. These low flow measurements are required for code verification and model tuning from both a safety and an engineering standpoint.

There are twelve ECFMs in the instrument tree which measure the flow through the reactor, all but ten are over fueled assemblies, the last two being in the reflectors in Row 7. These reflectors carry about 7% of the flow for

1

a fueled subassembly. They have a low-flow measurement requirement even at maximum flow. Figure 1-1 shows the distribution of the PSD equipped ECFMs in the initial core load of FFTF.

This arrangement represents an effort to make use of the accurate low-flow data to characterize fuel elements in each orificing zone, power category and FOTA neighborhood.

ECFMs are present in two different configurations: The Open Test Assemblies (OTA), which have long instrument stalks extending above the core, have their ECFMs inside the instrument stalk and provide very accurate flow measurements, (see Figure 1-2) Fuel Driver Assemblies and reflectors do not extend beyond the top of the core, rather they terminate with a handling socket. The ECFMs in this case are in an instrument tree which is placed above the core. Figure 1-3 shows the two types of configuration in the FFTF.

FTR CORE MAP
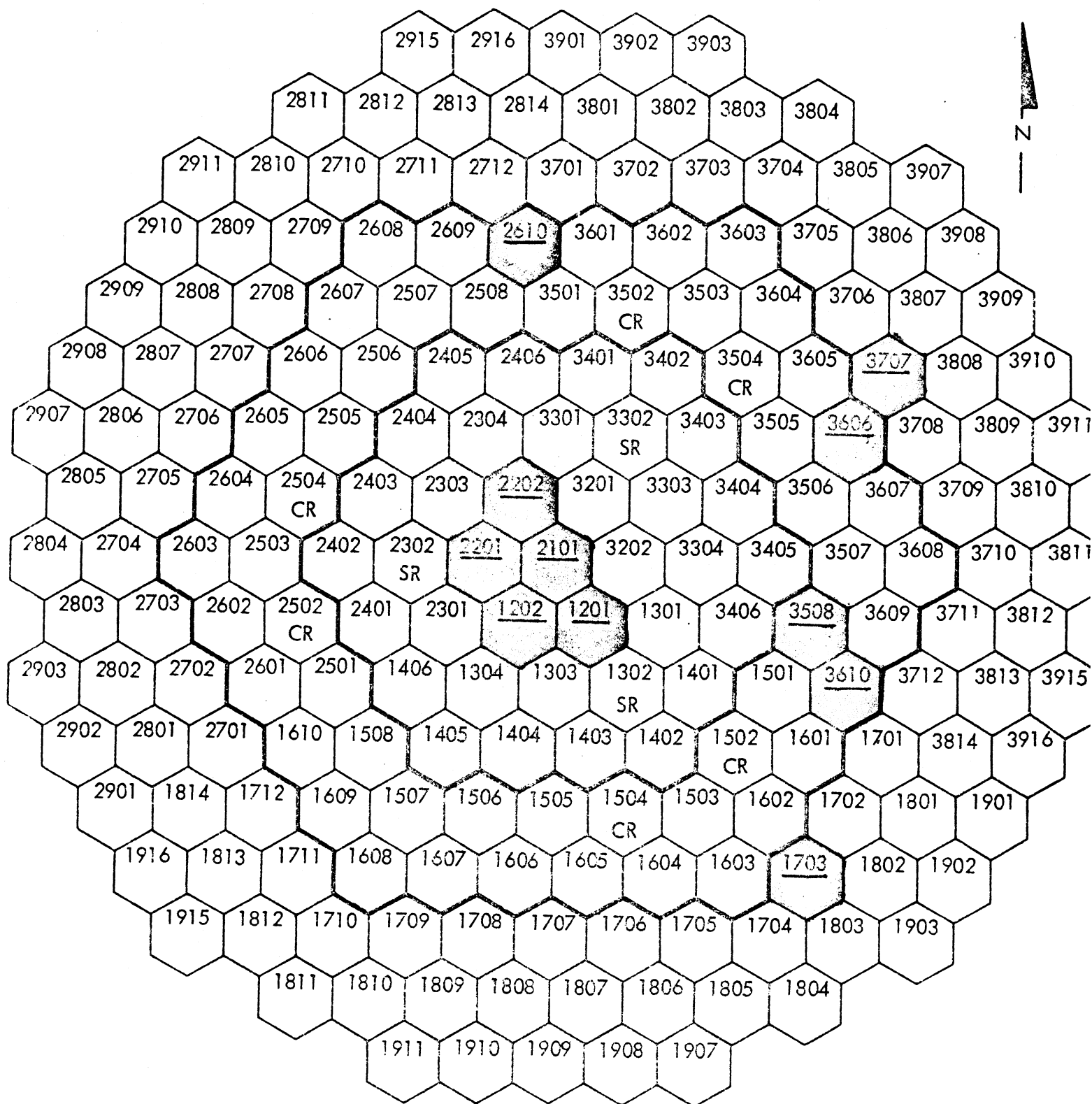
Figure 1-1   Placement of ECFMs with Phase-Sensitive Detection Electronics for FFTF Acceptance Testing.

SPOOLSPIECE

COOLANT
EXIT PORTS

PROCESS
INSTRU
FLOWMETER
AND T/C (3)

CONTACT
INSTRUMENTATION

≈40 FT

FOTA SHEAR
PLANE

CONTACT
INSTRUMENT
LEADS

12 FT

MATERIALS
EXPERIMENTS

FOTA   PIOTA   MOTA
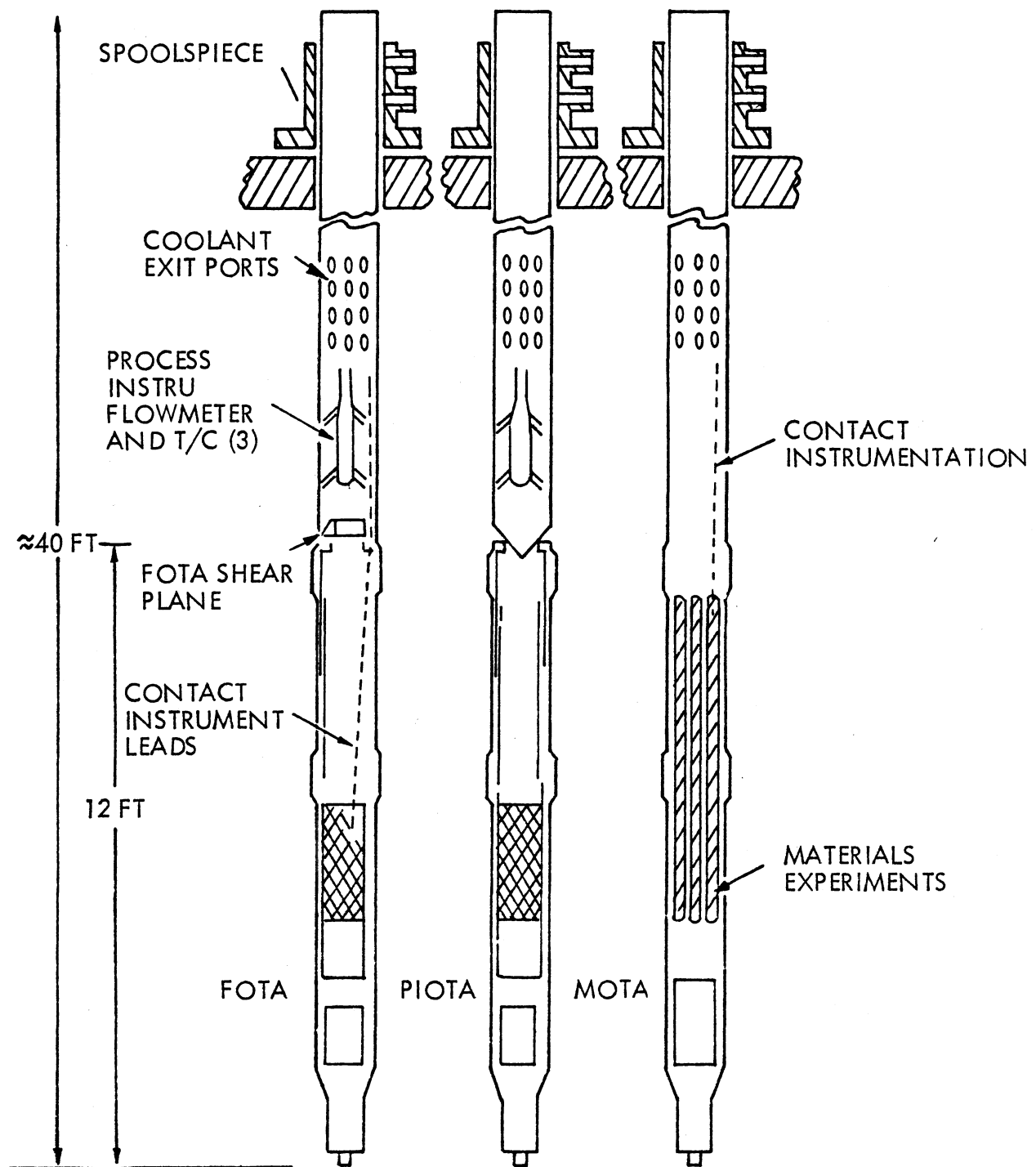
HEDL 7902-043.1

FIGURE 1-2a Open Test Assembly Types.

4

FUELS OPEN TEST ASSEMBLY (FOTA)

SPOOLPIECE

HEAD

FOTA STALK ASS'Y

INSTRUMENTED
FUEL ASS'Y

RETAINING PLATE

HOLDDOWN RING

ELECTRICAL
CONNECTOR

PRESSURE TUBES

HCDA RETAINING
TUBE ASS'Y

SPOOL PIECE

CLOSURE HOLD -
DOWN MECHANISM

INSTRUMENTATION
LEADS

TOP CUTTER HEAD

ELASTOMER O-RINGS

REMOVABLE
INSTRUMENT ASS'Y

BULKHEAD

LOCK TUBE

CUTTER GUIDE TUBE

SHIELDING WAFERS

SPOOL PIECE
NOZZLES

BULKHEAD

MECHANICAL SEAL

LOCK TUBE

ELECTRICAL LEADS

HEAD BOLTS

SPOOL PIECE TO HEAD
MECHANICAL SEAL

REACTOR HEAD

BULKHEAD

LOCK TUBE

FIGURE 1-2b Fuels OPEN TEST ASSEMBLY (FOTA)

FUELS OPEN TEST ASSEMBLY (FOTA) CONTINUED

SPOOLPIECE

HEAD

FOTA STALK ASS'Y

INSTRUMENTED FUEL ASS'Y

SHIELD WAFERS

BULKHEAD

BULKHEAD

CUTTER GUIDE TUBE

LOCK TUBE

COOLANT OUTLET PORTS
(TYPICAL 4 ROWS)

TAPERED FLOW PLUG

THERMOCOUPLES

FLOWMETER

FLOWMETER
WELL

LOCK TUBE

HANDLING
SOCKET
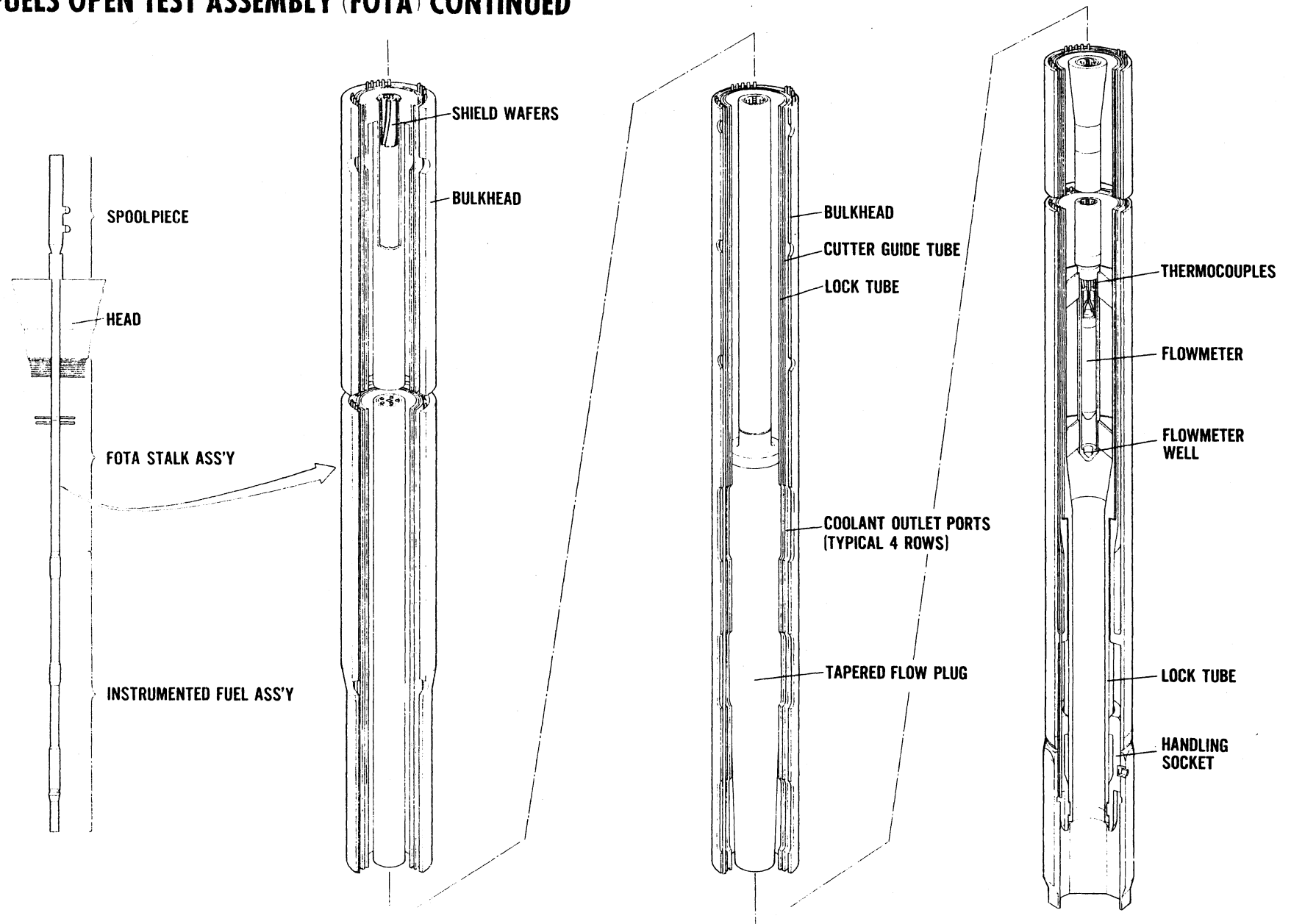
HEDL 7409-59.2

FIGURE 1-2b   (Continued)

9
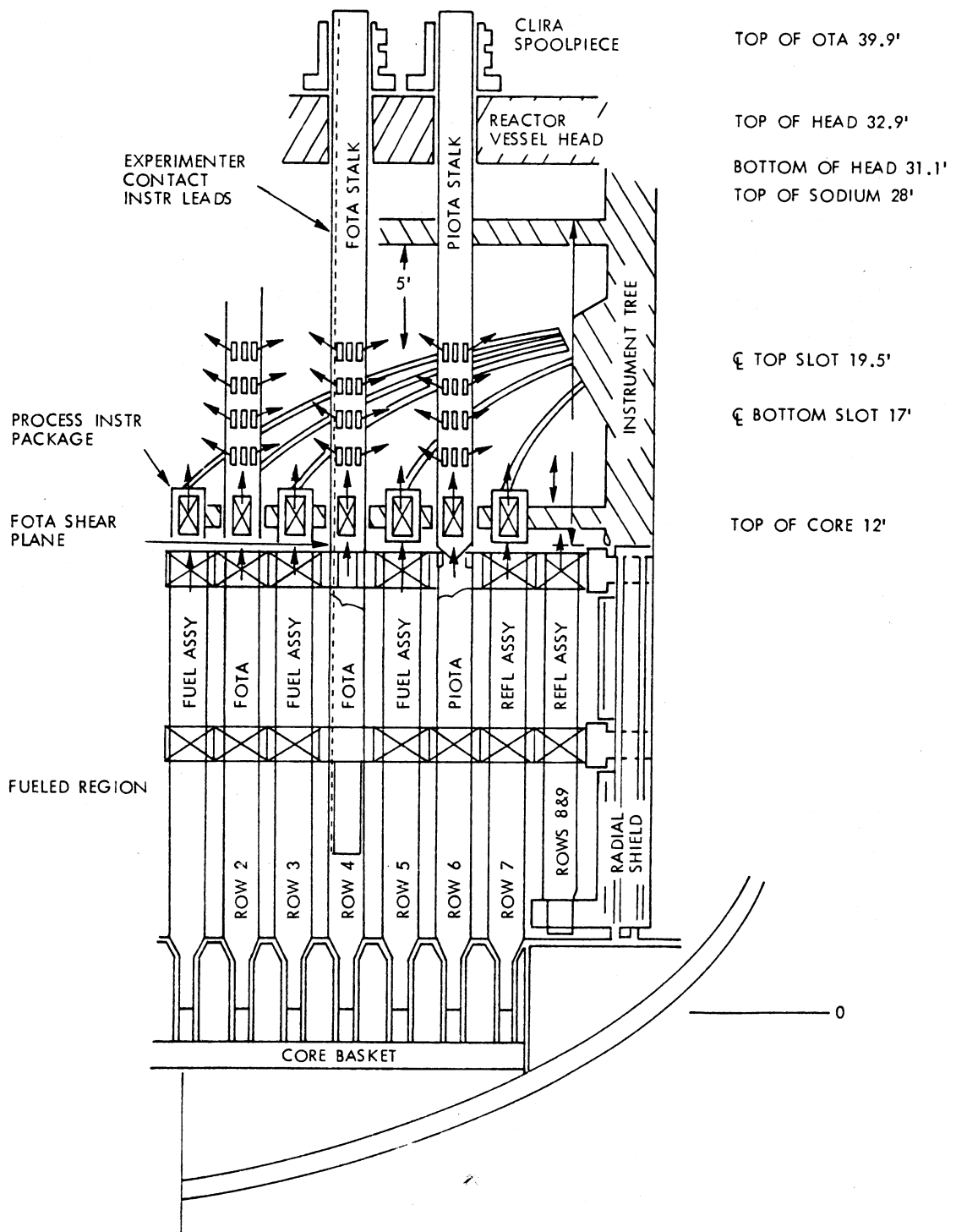
FIGURE 1-3 Schematic of Typical OTA Core Arrangement.

HEDL 7902-043.12

7

2.0 HARDWARE DESCRIPTION

This section presents a physical description of the ECFM and the associated electronics, both AD and PSD. In operation the ECFM is placed in a stainless steel thimble which isolates it from the sodium. The thimble is oriented with respect to the flow such that the flow is along its axis.

2.1 ECFM

The ECFM consist of three coils placed on a single axis inside a steel container (see Figure 2-1). The middle coil in this configuration is the primary coil and the other two are secondary coils. The secondary coils are connected to provide an output which is the difference of the two induced EMFs. The physical properties of the ECFM probe were specified in Standard RDT & C-4-7, Reference 5.

2.2 Amplitude Detection Electronics

The AD electronics consist of two basic modules. One module contains the system power supply and a master 1 KHz oscillator. The second module contains a signal conditioning (SC) circuit and a current regulating (CR) circuit which provides a nominal 0.5 ampere a.c. drive current to the primary coil of the ECFM. The power supply and oscillator provide power and signal to operate six SC/CR modules housed in a standard 19″ NIM Bin and are themselves housed in a standard 19" NIM Bin along with two more power supply/oscillator packages.

The power supplies are standard items manufactured by Lambda Electronics Corporation of Melville, New York. Details of the specifications for these modules are included in Operations Maintenance Manual, OMM-092-00-002, Volume 1 and Standard RDT & C-10-5, Reference 6.

The SC/CR (see Figure 2-2) provides a "constant current" a.c. sine wave of 0.5 amperes rms amplitude at 1 KHz frequency to the primary coil of the ECFM. The CR (essentially a non-inverting feedback amplifier) is excited by the output of the oscillator in the power supply/oscillator module. The SC section of the module has three basic circuits: 1) the differential

FIUGRE 2-1   Photograph of a longitudinal cross section of an Eddy
             Current Flowmeter. The instrument lead enters at the
             top of the figure, where three thermocouples are located.
             Paired primary and secondary coils are wound around the
             hollow central shaft which occupies most of the picture.
             The truncated leads to the primary (the middle two wire
             pairs) and secondary (the outer pairs) coils are seen
             in this hollow central shaft. At the bottom of the picture
             is the stainless steel ogive which caps the stainless
             steel jacket surrounding the thermocouples and the
             flowmeter coils.

FIGURE 2.1

9
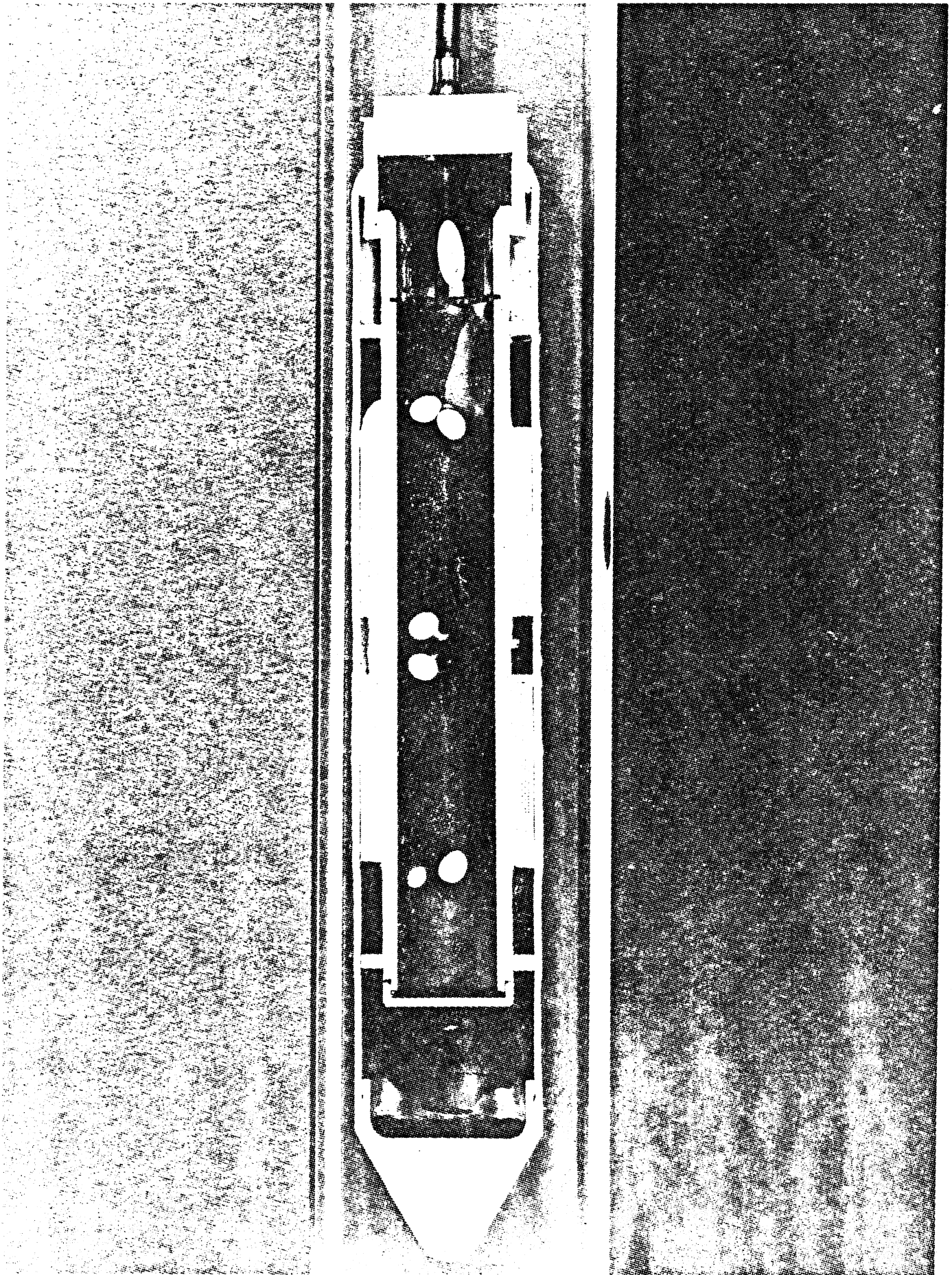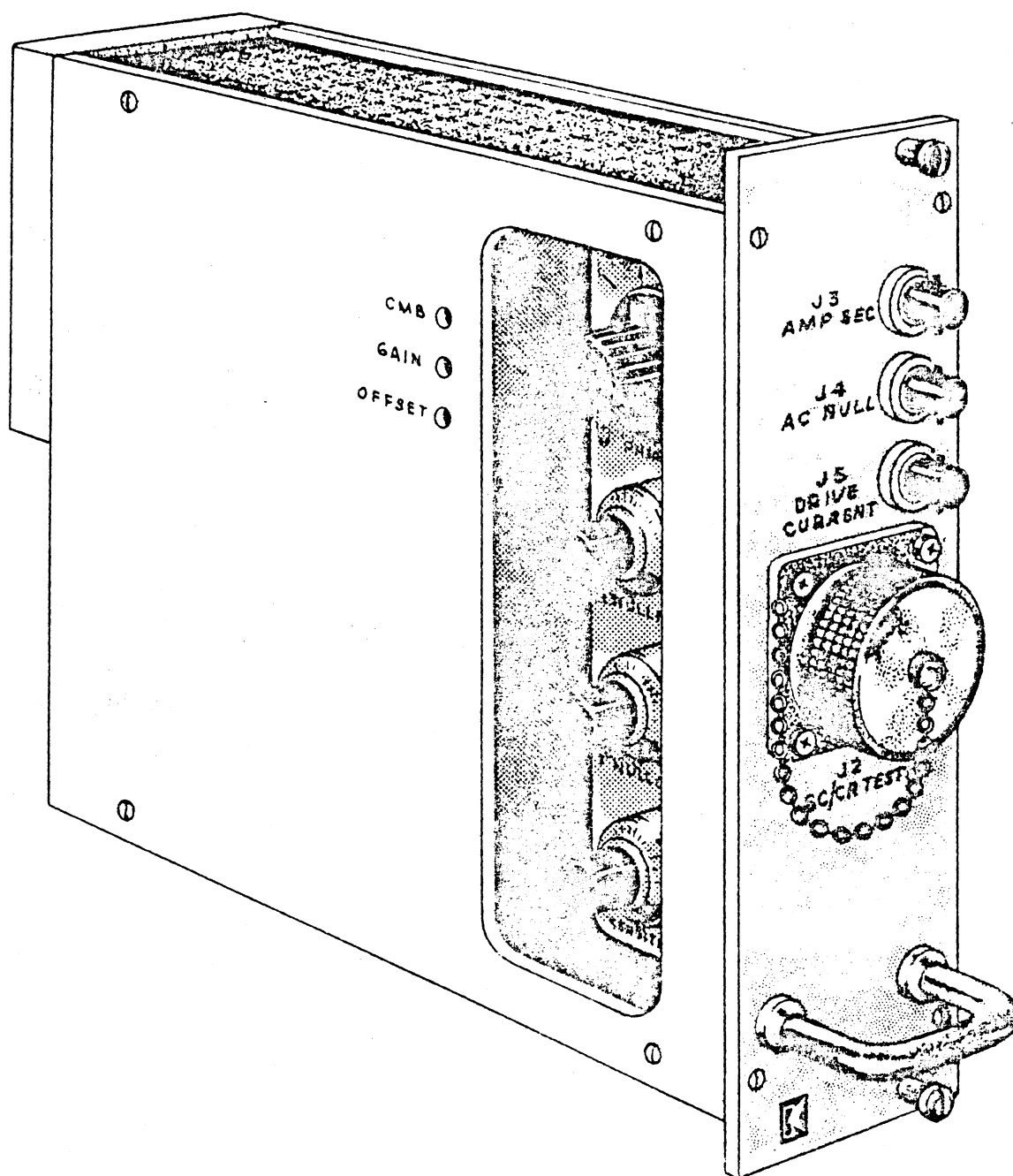
FIGURE 2-2 Signal Conditioner/Current Regulator Module

10

amplifier/bandpass filter, 2) the a.c. nulling circuit and 3) the detector circuit. Emf imbalances from the ECFM secondary coils are amplified, filtered and the internally generated signal from the a.c. nulling circuit is used in the summing amplifier to remove any residual biases. Figure 2-3 provides a schematic summary of the action of the SC/CR in providing the d.c. output from the coil imbalances.

The test calibration station (see Figure 2-4) incorporates the capability for testing every function of the system. It contains a built-in Fluke digital voltmeter which makes all measurements and it is designed to operate in conjunction with or independently of the flowmeter system as the station incorporates its own power supplies. The station also incorporates internal circuitry and a test switch which provides the station with a self-test capability. In operation, the station is capable of checking the ECFM by either taking d.c. resistance measurements or actual flow readings. The station further incorporates an ECFM simulator circuit which allows for simulation of the zero flow condition for an ECFM.

The zero flow signal is utilized in calibration, checkout, or adjustment of a SC module at full load by connecting the SC module to the test station. Any SC module can be adjusted to a specific ECFM via the procedure of simulating zero flow independent of the actual state of the system.

The test station also has the capability for checking the output of any power supply.

2.3 Phase-Sensitive Detection Electronics

The PSD electronics differ from the AD electronics in that they make use of only the CR aspects of the SC/CR and the differential input amplifier high pass filter   (See Figure 2-3). This modification bypasses most of the SC module. Typical circuitry for this "piggy-backed" system is shown in Figure 2-5. While the AD circuit is not shown here, it remains intact and the PSD system is added on to expand the capabilities of the ECFM.
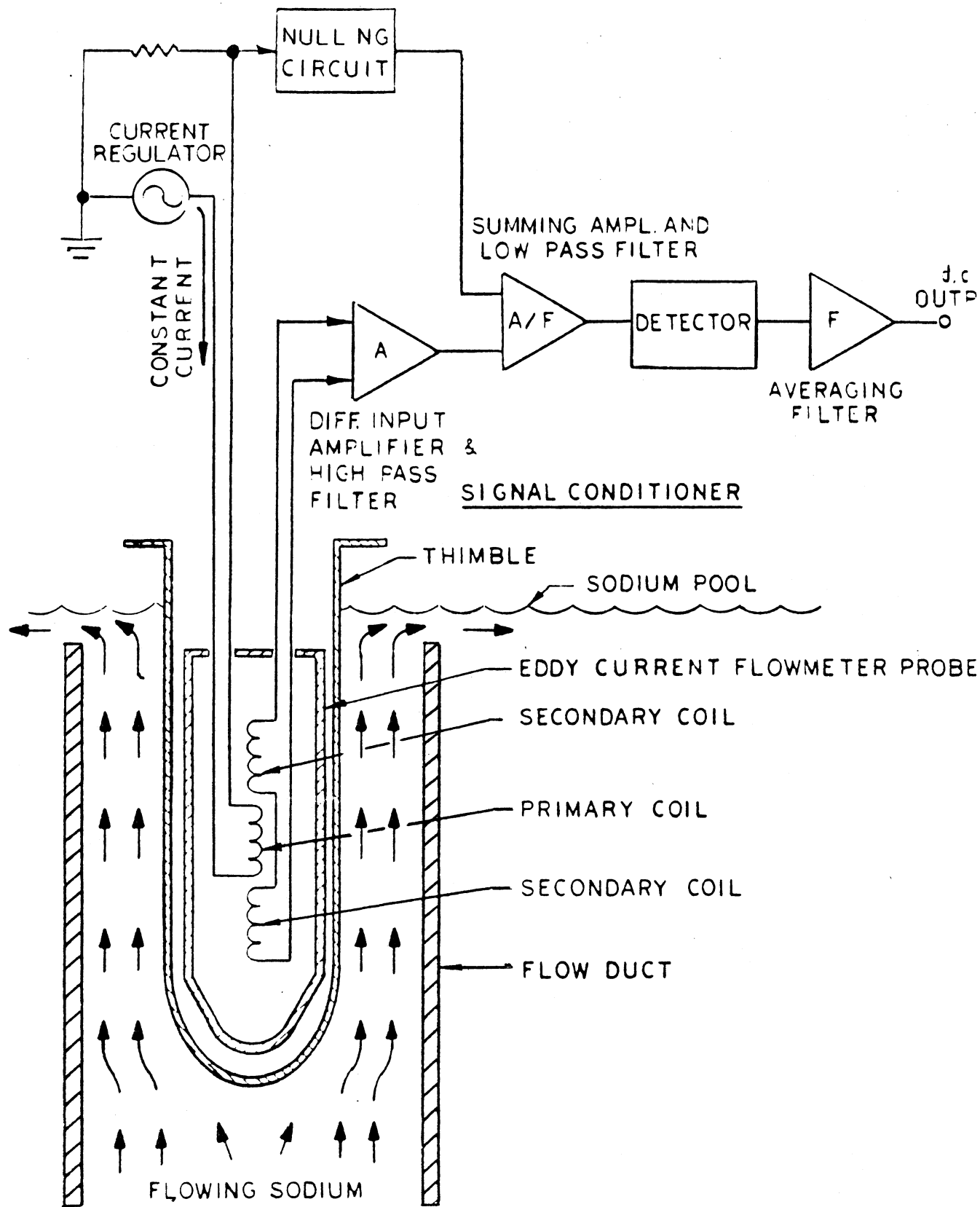
FIGURE 2-3

FUNCTIONAL BLOCK DIAGRAM
OF A SINGLE ECFM CHANNEL
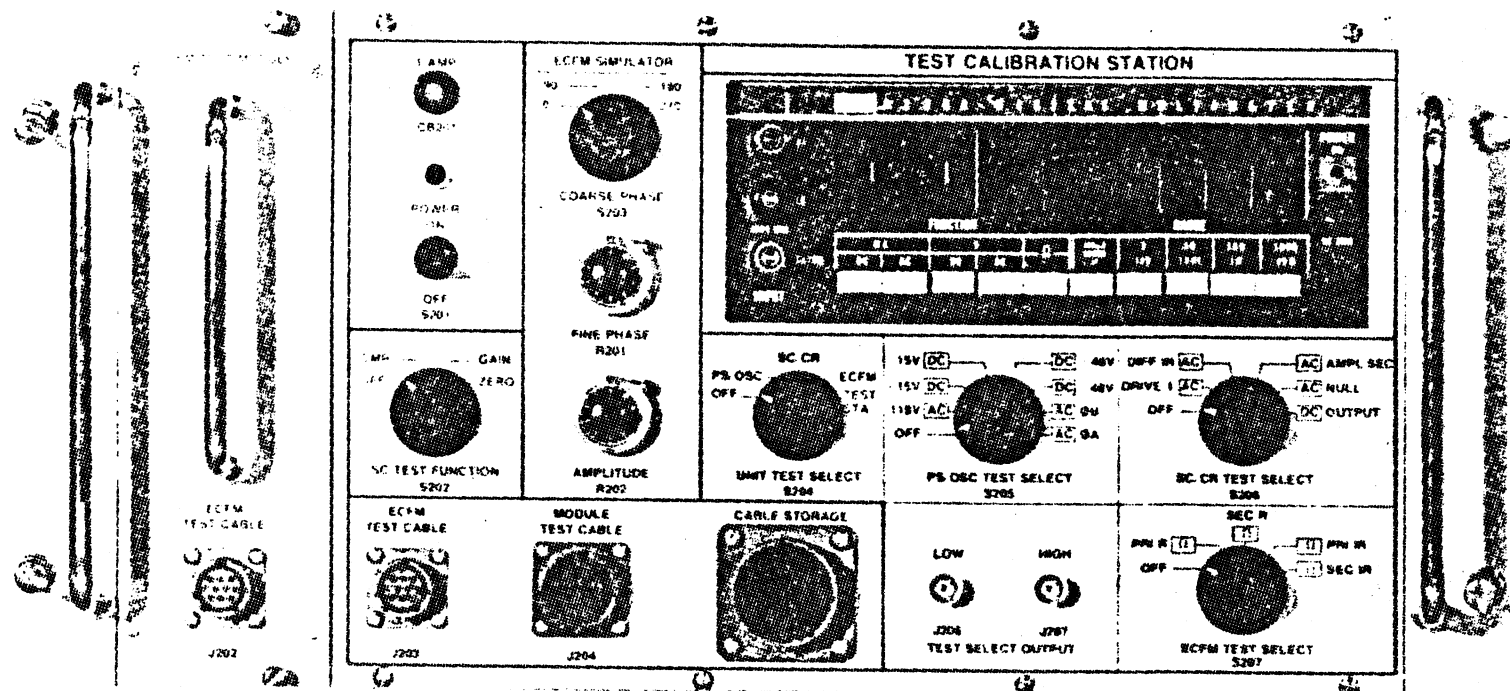
FIGURE 2-4   Test/Calibration Station
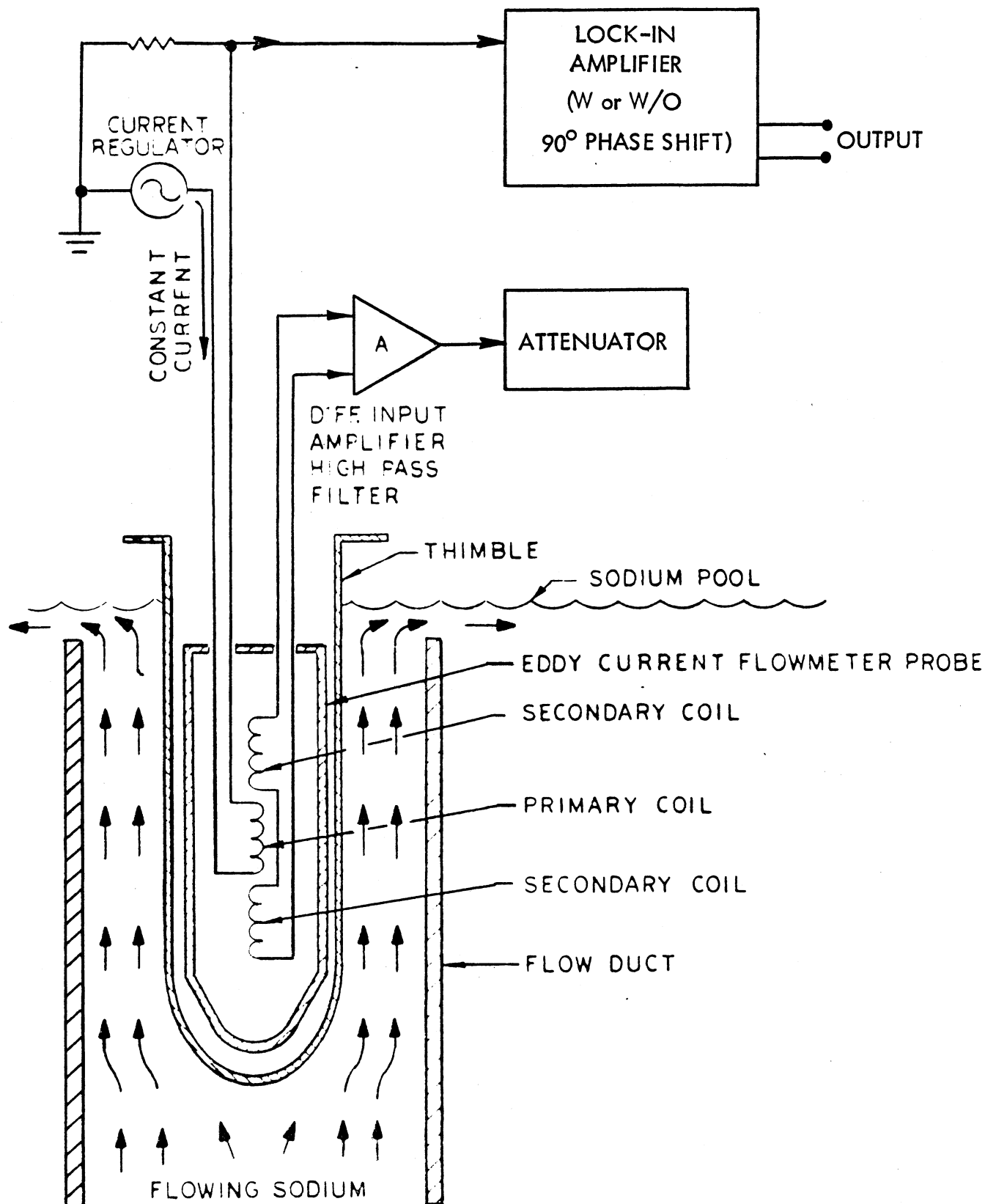
FIGURE 2-5

FUNCTIONAL BLOCK DIAGRAM
OF A SINGLE ECFM CHANNEL

14

Several components are common to both systems; namely, the CR, the differential input amplifier/high pass filter and the test calibration module. The additional components used in PSD are a lock-in amplifier and an ohmic attenuator to provide appropriately scaled inputs for the amplifier.

The PSD electronics are of two types: The first, used on all subassemblies except the Row 2 FOTA (HF011), employs a Princeton Applied Research (PAR) Model 128 A Lock-In Amplifier (see Figure 2-6) to provide the flow signal output using the typical circuitry in Figure 2-5. The Row 2 FOTA employs a PAR Model 5204 Lock-In Analyzer (see Figure 2-7) which is basically two lock-in amplifiers with a 90° phase difference between the two channels. The output of this analyzer consists of two signals: one being the usual flow signal, the other being the component of the signal 90° out-of-phase with the flow signal. Analysis of PSD measurement theory in Section 3 explains the value of this configuration and of PSD itself for low flows.

The physical characteristics of the two lock-in amplfiers are detailed in Appendix A.

As a final hardware note, the calibration program employed PAR Model 120 Lock-In-Amplifiers which differ substantively in that they have a 20 mv setting, on which all calibration was performed, while both models used in the FFTF have a 25 mv setting. The differences are compensated by adjusting the resistance of the attenuators as described in Section 5.2.
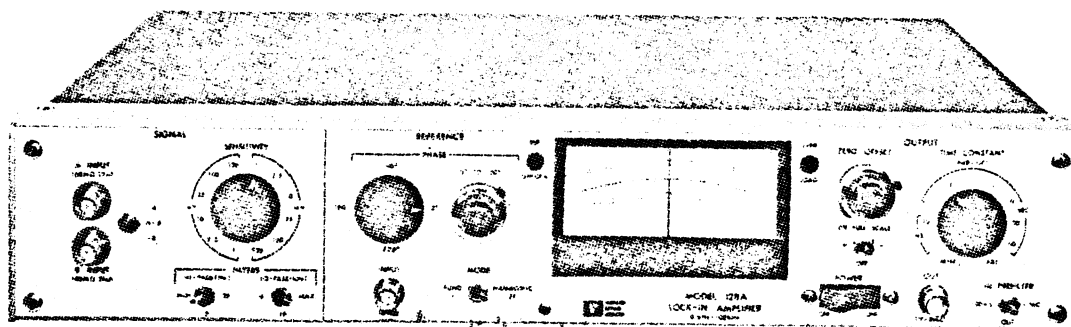
FIGURE 2-6   PAR Model 128A Lock-In Amplifier
The Princton Applied Research
(PAR) Model 128A Lock-In
Amplifier (Front View) is used
for all ECFM flow evaluation by
PSD except HF011. Specifications
are presented in Appendix A.
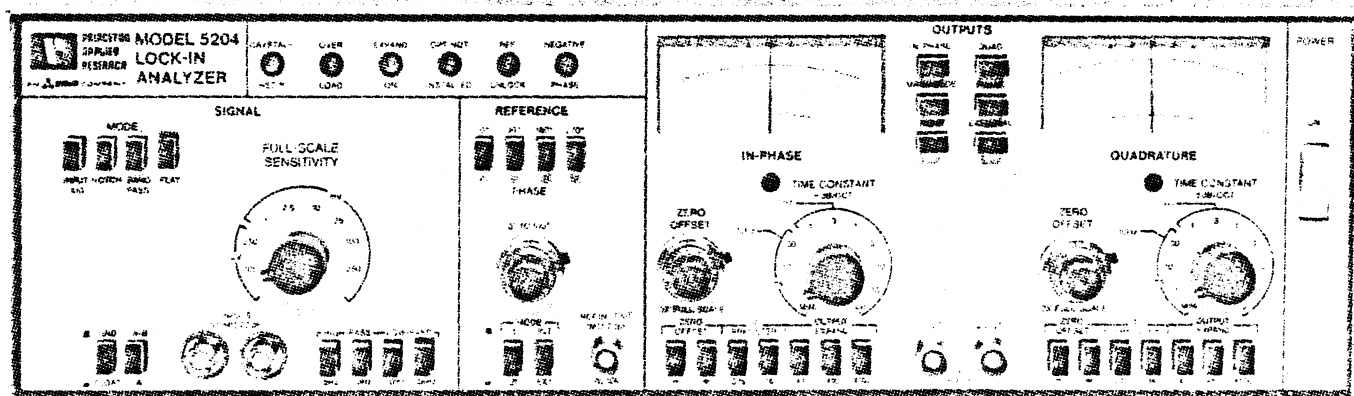
FIGURE 2-7 PAR Model 5204 Lock-In Analyzer
The Princeton Applied Research
(PAR) Model 5204 Lock-In Analyzer
used by HF011 in FFTF Acceptance
Testing. This analyzer acts as
two Lock-In Amplifiers.
Specifications are given in
Appendix A.

3.0 ANALYSIS

This section presents a simplified version of the theory of ECFMs. Both AD and PSD are described in order to provide the motivation for PSD. Error sources are very important in any measurement technique and Section 3.4 presents a discussion of several error sources which are present in flow measurement. Finally Section 3.5 reports the results of the calibration program and discusses errors remaining in the flow signal.

3.1 ECFM

A detailed discussion of the theory of operation of the ECFM is presented in both Appendix B and in Reference 7. Figure 2-3 provides a schematic picture of the operation of an ECFM immersed in flowing sodium.

An alternating current (in this case 1000 Hz) is applied to the primary coil. The choice of frequency is influenced by the conductor resistivity, the use a thimble (dry) or director immersion (wet), and considerations such as lead-to-lead coupling in the electronics. The sodium penetration decreases with increasing frequency and at 1000 Hz the thimble alone attenuates the signal by 40%. (See Refernce 8.) The alternating current flowing in the primary induces eddy currents in the sodium which, when the sodium velocity is zero, are parallel to a plane normal to the axis of the coil, symmetric with respect to the plane in magnitude, but flow in opposite directions. If the sodium has a velocity along the axis of the coil, then the upstream eddy currents develop a damping term which is essentially bilinear in velocity and conductivity, thus introducing a skew in the EM field in the direction of flow. When the eddy currents are imbalanced by the sodium flow, a different emf is induced in each of the secondary coils. The difference in the two emfs becomes the flow signal.

There are some problems involved, in that this signal has non-flow components which arise from the variation in sodium conductivity with temperature, thermal changes in the coils (both secondary and primary), variations in permittivity of the thimble and the sodium etc. The dominant temperature variation in the non-flow component is usually the conductivity of the sodium although changes in the thimble and the environment can bias the low flow values in both phase and amplitude.

18

The sum of the secondary coil emfs will contain the same information except that, to first order, the flow dependence will be eliminated. Thus the temperature dependence of the signal is enhanced. This fact has been used to provide a correction for the temperature effects and improvement in the linearity for linear variable differential transformer (LVDT). (See Reference 9). In fact, when the sum of the emfs is used, it is possible to use the ECFM as a high speed temperature measuring device with good accuracy (5°F). Reference 10 is a series of papers on just this topic.

3.2 Amplitude Detection

This technique of flow measurement assumes the non-flow components are not important and ignores the Phase, ϕ, of the flow signal. The first assumption of AD is that, while there is temperature dependence in the flow signal, all flow lines cross at a single point, S, in an amplitude-phase (v-ϕ) plot at the point corresponding to zero flow.

The second assumption is that S also corresponds to the origin of the v-ϕ plot. Thus the assumed form of a v-ϕ plot is that pictured in Figure 3-1.

It is clear from examining this figure that the amplitude (distance from the origin) of the flow signal for a fixed flow is independent of the temperature and vanishes when the flow vanishes. When one assumes the relationship of flow to signal is linear (a very good assumption in this case) only a gain is necessary to convert the flow signal to appropriate flow units.

In fact, both assumptions are violated to some extent by real ECFMs. Figure 3-2 represents typical v-ϕ plots for ECFMs. In Figure 3-2a the flow signals have all crosed at a single point, S, but it is not the origin and it is not zero flow. Had it been zero flow, one could have translated the origin to the zero flow point and obtained Figure 3-1. The AD calibration procedure translated the origin to zero flow rather than to S. Either of these choices seems to be on equal footing, and nulling the amplitude at zero flow is easier than measuring from S (which first must be determined). The consequences of the two choices are shown

$$x = V_{AC} \cos \phi$$
$$y = V_{AC} \sin \phi$$
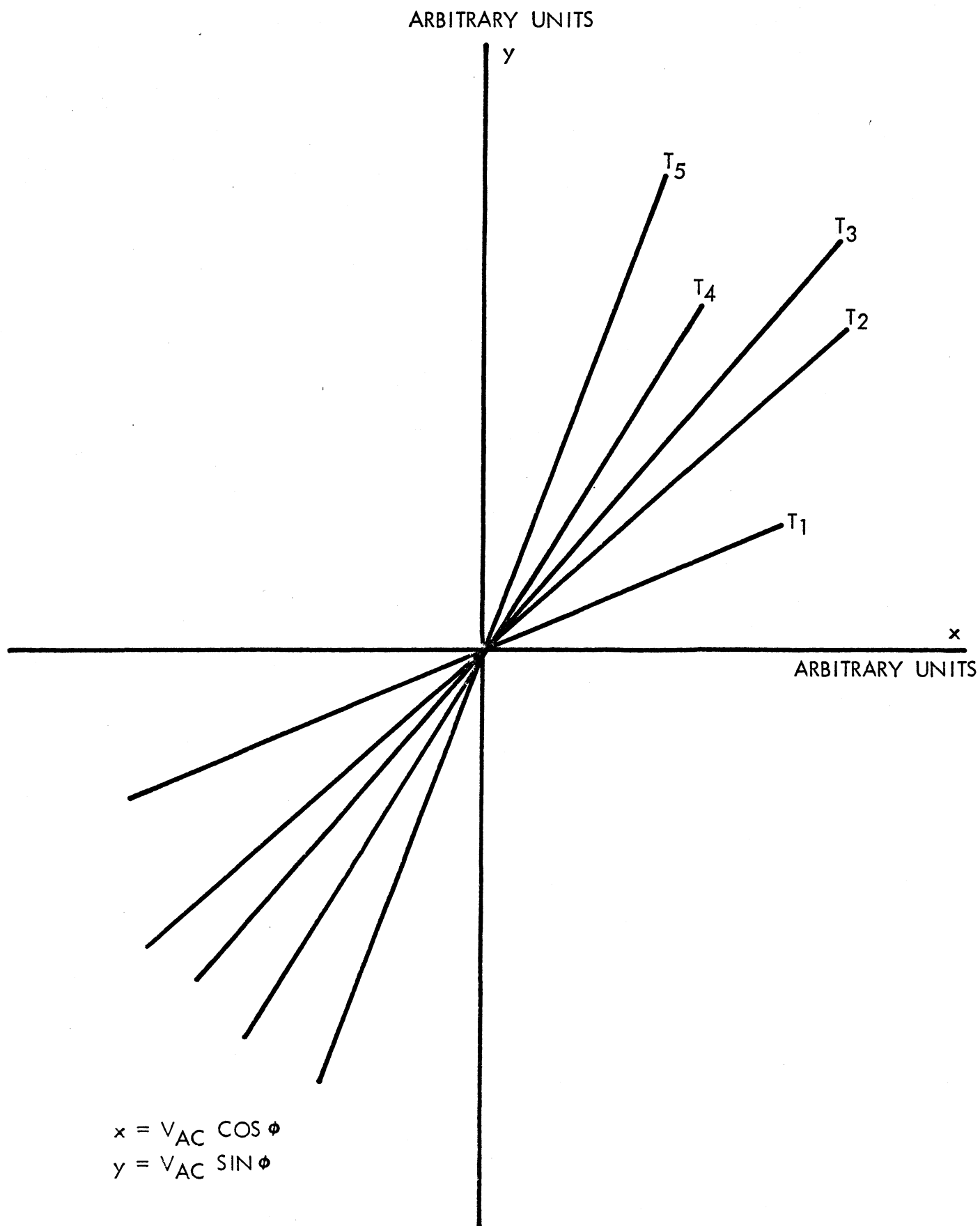
FIGURE 3-1   IDEAL ECFM Amplitude-Phase Plot
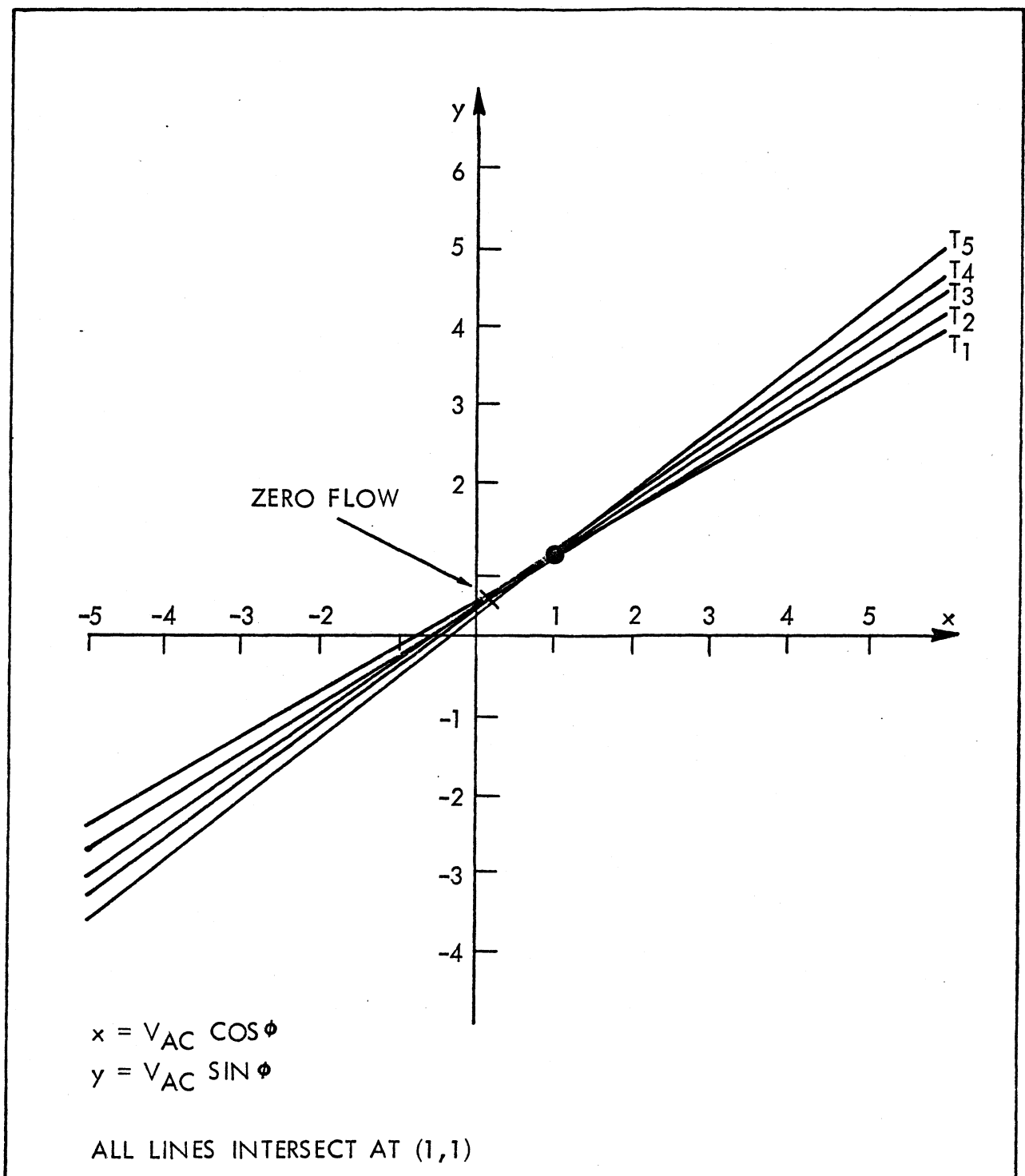
FIGURE 3-2a   Realistic ECFM Amplitude-Phase Plot

HEDL 7902-043.2

in Figure 3-3a. Note that nulling to zero flow has produced a family of curves, whereas measuring from S has produced on straight line with a non-zero intercept. When nulling to zero flow, one is given the impression that some nonlinear, temperature-dependent, flow-dependent effect is entering at low flows. It is in fact just an artifact of the nulling process.

If there were no point S, one could get two distinct types of situations, Figure 3-2a and 3-2c, which correspond to Figures 3-3b and 3-3c when one examines the flow signal versus flow. Type b could be improved somewhat by measuring from an approximate S value, however, Type C is double valued! Nothing can be done to resolve the ambiguity at low flow using AD. Note that if the AD were to null to S in Type b a double-valued result would result.

Use of AD for higher flow is quite reliable, but the matching of the secondary coils in the ECFM is not done sufficiently well to use AD in the low flow regime. Moreover, it may not be feasible to perform matching to the level of accuracy required by low flows.

3.3 Phase-Sensitive Detection

PSD was instituted on several ECFMs at the FFTF to ameliorate the difficulties caused by the inability of AD-calibrated ECFMs to provide the necessary low flow data. PSD, in essence, measures the distance from a line perpendicular to the reference flow line (usually 400°F) and calculates the flow from the quantity. Ideally a flowmeter should be such that the flow lines for different temperature never cross. This means that the line perpendicular to the reference flow line is perpendicular to all flow lines and the distance from the line is dependent only on flow, not on temperature.

If the ideal situation were obtained, then while the flow measurements would have no temperature dependence, the change in the distance from the origin to the flow line (an easily obtained quantity) would be dependent only on the temperature. Thus it could act as a high-speed, high accuracy temperature measuring device with little post-processing of the signal.

There were approximately 140 ECFMs available at HEDL which had been calibrated using AD. For each flowmeter a complete file of V_{AC} and ϕ
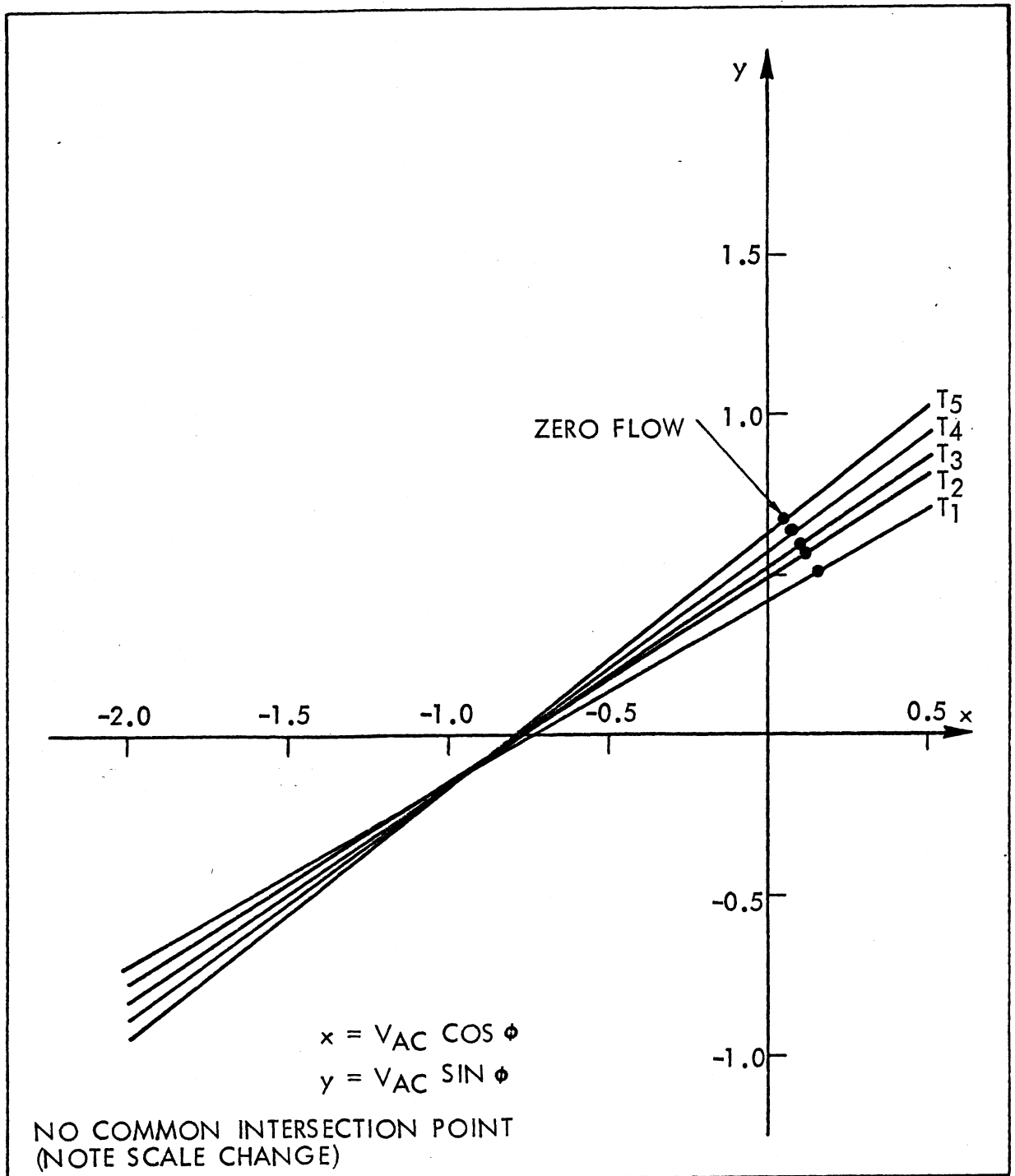
FIGURE 3-2b Realistic ECFM Amplitude - Phase Plot

HEDL 7902-043.4

23
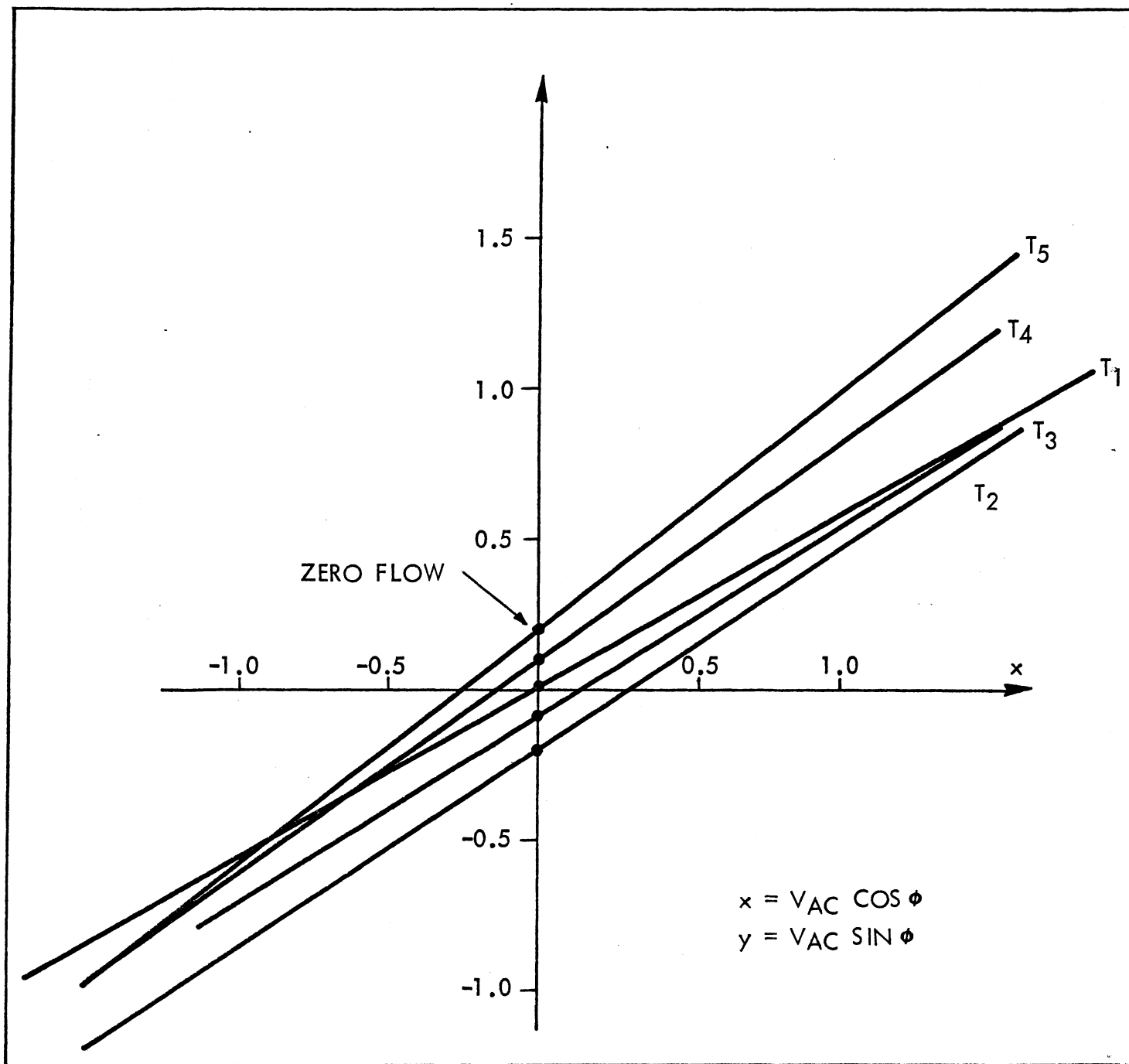
FIGURE 3-2c Realistic ECFM Amplitude - Phase Plot
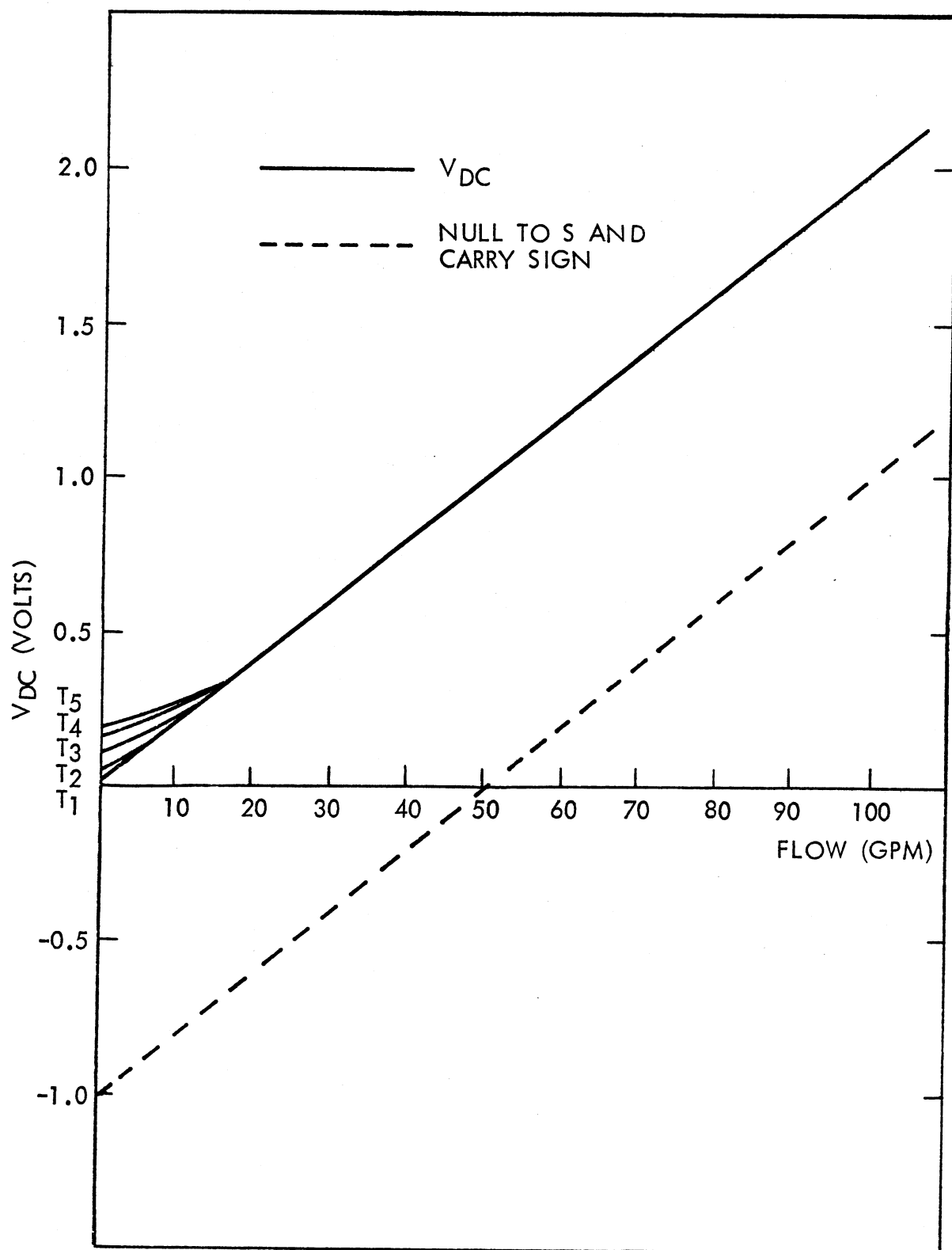
HEDL 7902-043.

FIGURE 3-3a V_{DC} Versus Flow for Amplitude Detection

HEDL 7902-043.6
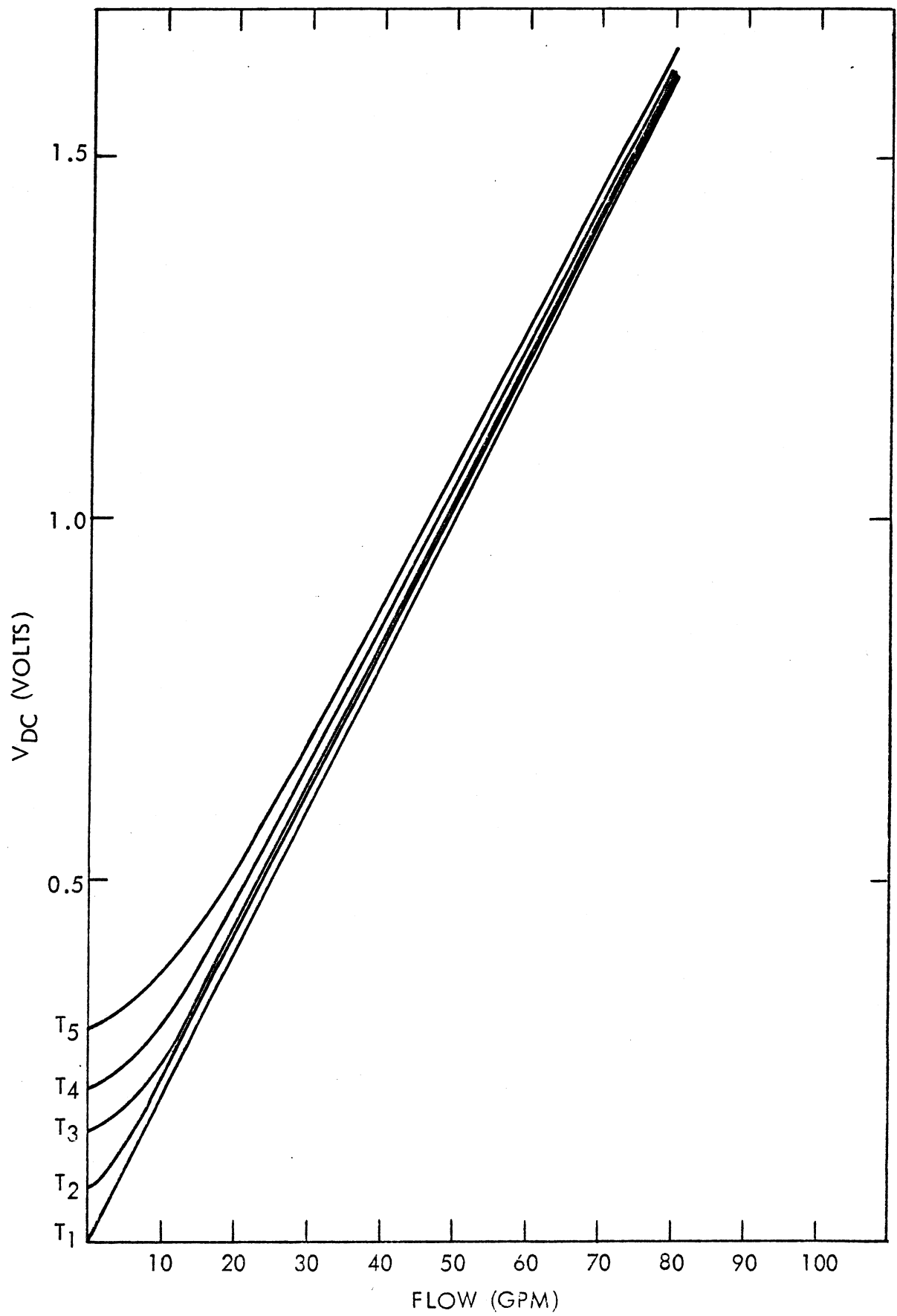
FIUGRE 3-3b V_{DC} Versus Flow for Amplitude Detection

HEDL 7902-043.7
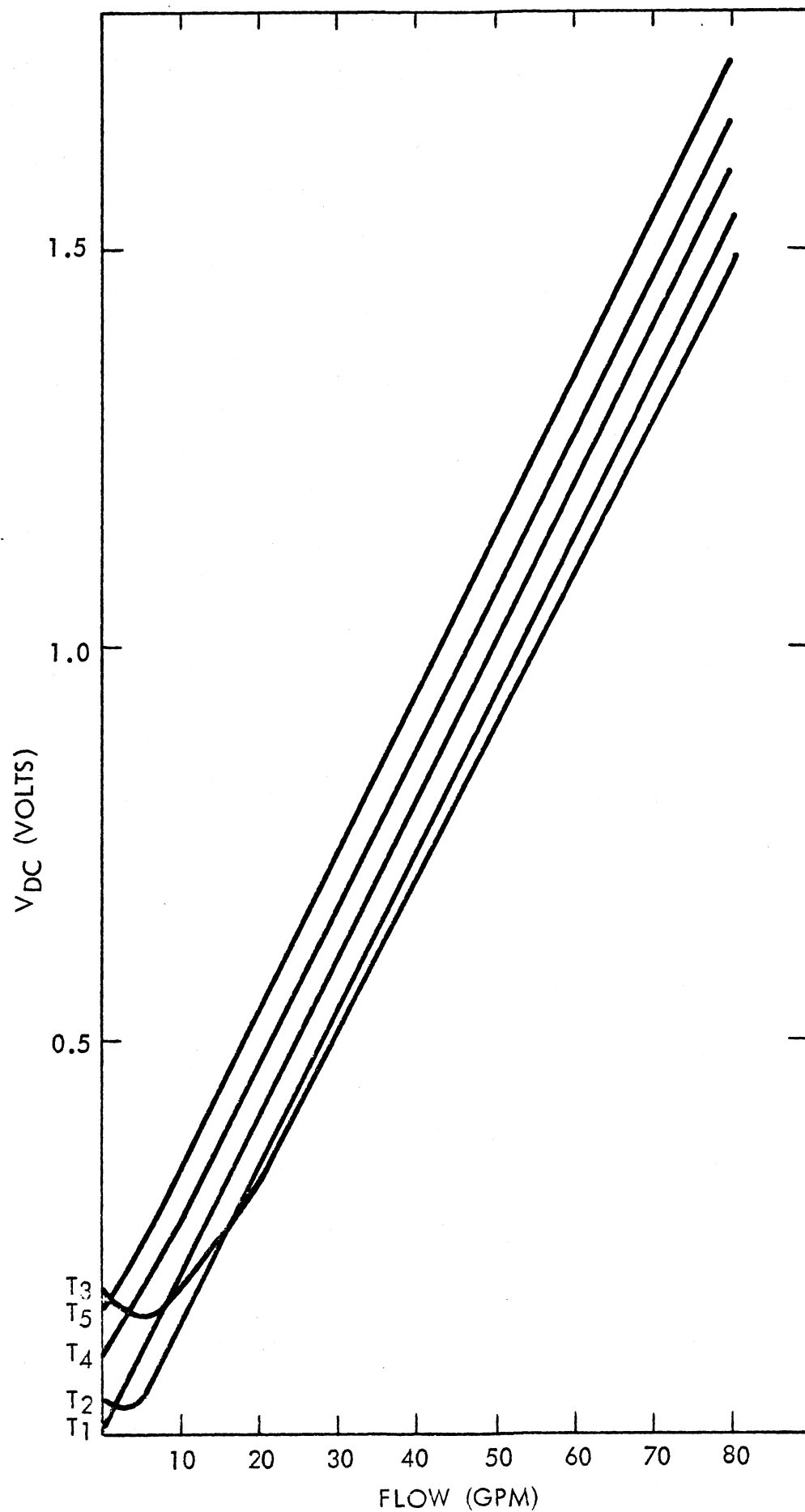
FIGURE 3-3c V_{DC} Versus Flow for Amplitude Detection

was available. Selection of ECFMs for use in low flow measurement was based on the criteria that the fixed low-flow line and the fixed temperature reference line be nearly orthogonal and that the data scatter be minimal.

In order to set up the perpendicular line using PSD, two flows (at a minimum) must be measured to find their in-phase (I) and quadrature (Q) components at each flow. The I and Q components are at 90° to one another so that the amplitude (V_{AC}) from the origin (as opposed to V_{DC}, the amplitude from the zero flow reference temperature point) is related to the two components by,

$$V_{AC} = (I^2 + Q^2)^{1/2} \tag{3.1}$$

Any two flow measurements must give the same value for Q if Q is to represent the perpendicular distance from the origin to the flow line. Figure 3-4a shows this situation for two flows W_1 and W_2. Figure 3-4b shows the case in which the two Q-components are not the same. They are measured along the same direction but they are of different length. The solution is to rotate the direction of measurement of the Q-component by an angle (θ) until the Q-components at both are equal. (See Figure 3-5.) The angle between the Q-component and the line along which V_{AC} is measured is called β. Therefore, for Q_1 to be equal to Q_2,

$$V_{AC_1} \cos (\beta_1 + \theta) = V_{AC_2} \cos (\beta_2 + \theta). \tag{3.2}$$

The unknown voltages V_{AC_1} and V_{AC_2} are eliminated by the relationship,

$$I_n = V_{AC_n} \sin \beta_n. \tag{2.3}$$

Using the angle sum formula for cosines and Equation 3.3 gives,

$$I_1 (\cot \beta_1 \cos \theta - \sin \theta) = I_2 (\cot \beta_2 \cos \theta - \sin \theta) \tag{3.4}$$

or

$$\theta = \tan^{-1} \left(\frac{Q_1 - Q_2}{I_1 - I_2} \right). \tag{3.5}$$

From the two flows one can ascertain the proper Q-component, which is obtained by changing the measurement angle by an amount θ. The new Q is,

$$Q = V_{AC_1} \cos (\beta_1 + \theta) \tag{3.6}$$

28

FIGURE 3-4a Relationship of V_{AC} and Q for Two Flow Readings when Q has bee Properly Adjusted.
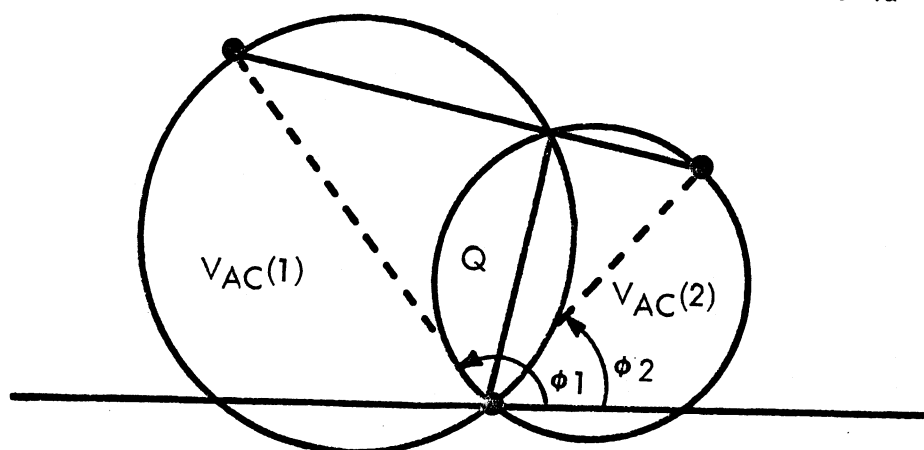
FIGURE 3-4b Variation of Q with Flow When Q has not been Properly Adjusted.
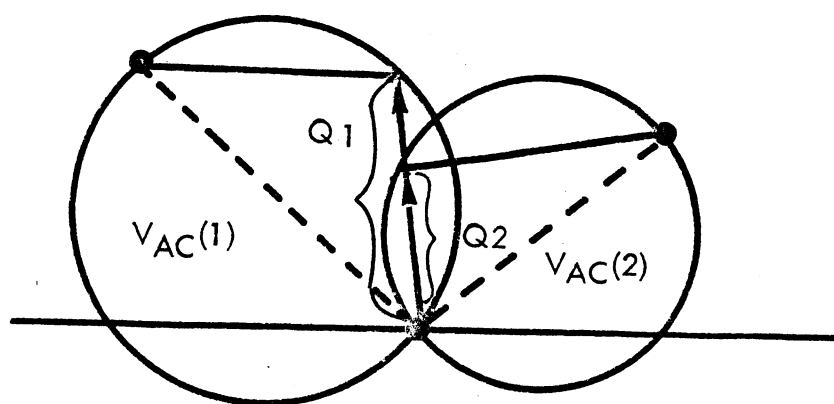
HEDL 7902-043.11
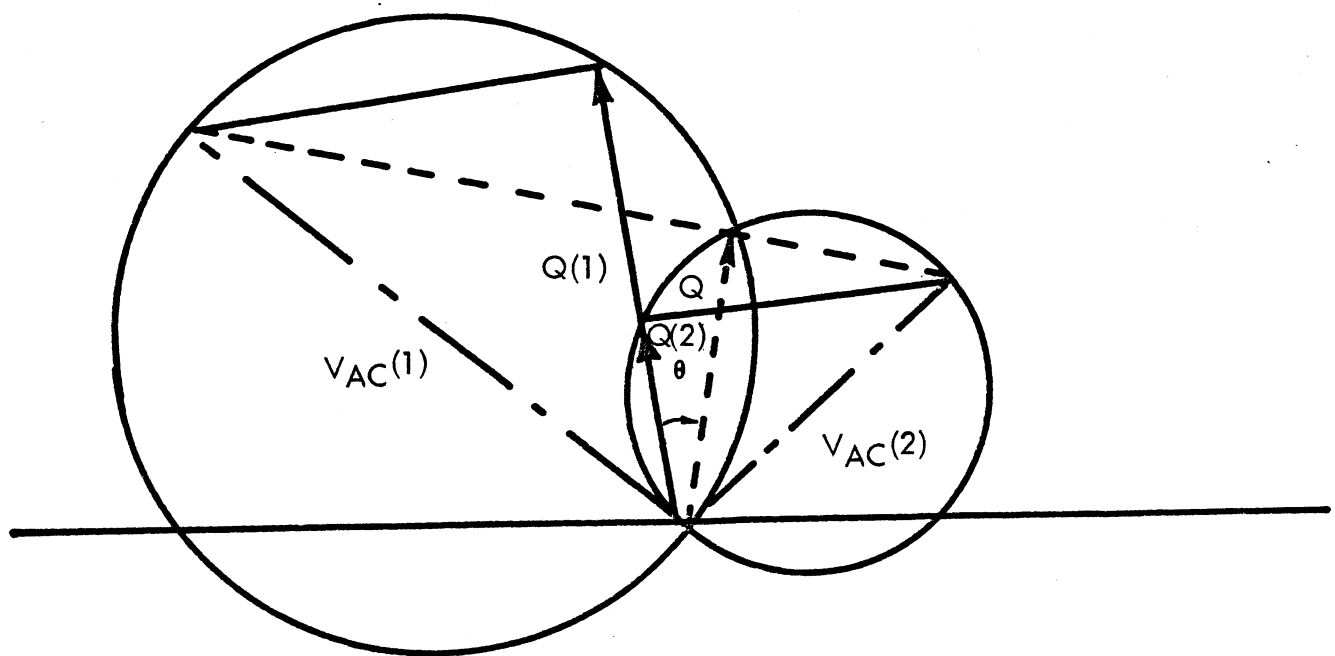
FIGURE 3-5 Rotation of the Direction of Measurement of Q by an Angle
θ to Make Q Flow-Independent.

HEDL 7902-043.9

which, making use of Equation 1.3, becomes

$$Q = \sqrt{I_1^2 + Q_1^2} \; \cos(\beta_1 + \theta) \qquad (3.7)$$

In Figures 3-4 and 3-5 one flow point is on either side of the quadrature vector. A more common occurrence is to have both flow points on the same side of Q. The procedure for finding Q is unchanged, however the readings obtained in this case will seem hard to interpret at first glance. A valuable tool for avoiding this confusion is the graphical method. This method gives an approximate value for Q which can be used to verify the more precise algebraic solution outlined above.

Plot the flow point, given by the quadrature and in-phase components for each flow on a Q-I grid. Connect the two flow points with a straight line. A line from the origin, perpendicular to the flow line, is the correct Q. Figure 3-6 shows the graphical method.

Error arising from the fact that the flow lines do cross one another are small, because the correction is dependent on the sine of the crossing angle, which is small. Thus all of the realistic cases in Figures 3-2 can be treated with a high degree of accuracy using PSD.

3.4 Error Sources

In addition to the errors introduced by the lack of an ideal ECFM (which may be processed out) there are certain error sources which can give rise to errors that limit the ultimate accuracy of the flow measurement. There are three basic sources: (1) hardware-related biases, (2) electronics-biases, and (3) noise, each of which will be discussed in the next three sections.

3.4.1 Hardware Biases

This category of biases includes the thimble related environment changes, the sodium channel changes, wire routing changes, etc. The net effect of these changes is to alter V_{AC} and ϕ in such a fashion that a rotation and a shift of the flow/temperature grid on the v-ϕ plot occurs. The sensitivities ($\frac{\partial I}{\partial W}$ and $\frac{\partial I}{\partial T}$) can be affected by these changes. When the ECFM is setup in the FFTF, only two flows are required and if one is known (i.e., zero flow), the shift and rotation of the flow/temperature grid can be processed out during the setup. The sensitivity changes, though small, will remain.
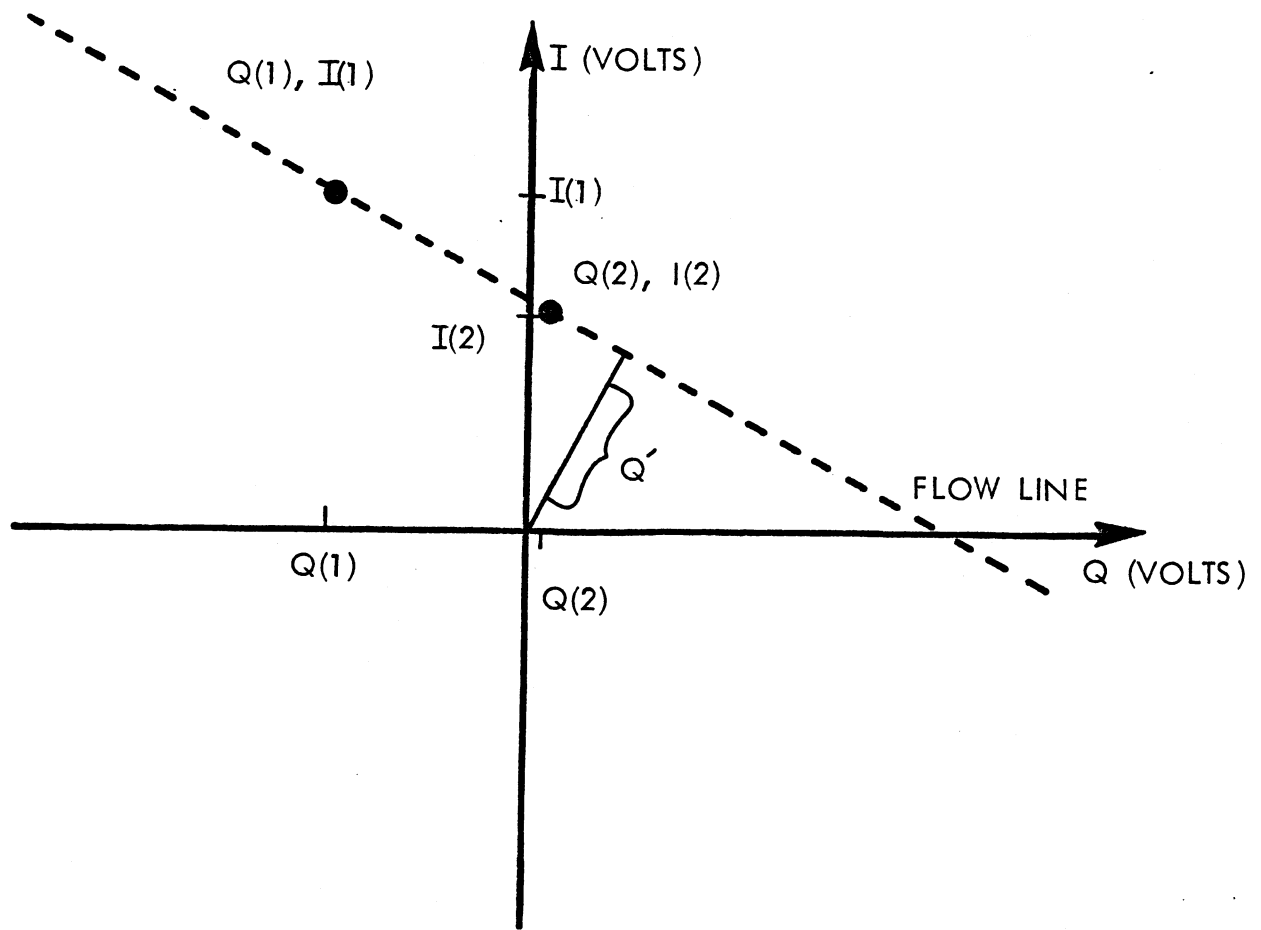
FIGURE 3-6   Graphical Method for Obtaining Q.

The length Q' is an estimate of the correct quadrature Q, given two sets of measurements [Q(1), I(1)] and [Q(2), I(2)], at different flows. The new coordinate system is obtained by rotating the old system until the Q value becomes Q1. The rotational angle will be determined better at flow #1, because $|Q(1) - Q'| > |Q(2) - Q'|$. After rotation, all Q-values will be constant.

HEDL 7902-043.8

3.4.2 Electronics Biases

After the calibration program, variations in the electronics components were observed (see Table 5-1). In the calibration program a PAR Model 120 lock-in amplifier was used in conjunction with external attenuation and Signal Conditioning/Current Regulator Modules (SC/SR), the latter being calibrated to plant specifications. (See Reference 10.) The variations in the components are scaled by the input voltage column and represent a small error on the order of 1/4 GPM at zero flow. In plant calibration includes compensation for these variation. In effect the sensitivities ($\frac{\partial I}{\partial W}$ and $\frac{\partial I}{\partial T}$) are also perturbed, but again, only very slightly.

3.4.3 Noise

The TTL facility and the recording apparatus constitute a generator of random signals of a variety of frequencies and amplitudes. An analysis of the noise on the measured data is probably the best estimate of this error (see next section). It will be present in the FFTF as well as the TTL.

3.5 Calibration Results

This section presents a summary of the results of processing the ECFM calibration runs at the TTL using the PSD. The discussion addresses the biases which arose in repeat runs when the test thimble and the electronics were changed, the noise level on the data and the flow/temperature calibration curves for each ECFM. For S/N 172, which is in the Row 2 FOTA and has both I and Q output, both the temperature and flow calibrations are reported.

The ECFM response obtained in the TTL may differ from the ECFM response in the FFTF. The effect on the calibration curve can be expressed in terms of the changes which can occur in the v-ϕ plot. Three separate changes to the calibration grid can occur: (1) it can be rotated around the origin in the v-ϕ plot, (2) it can be scaled and (3) it can be translated with respect to the origin.

The rotation is easily adjusted out during the setup of the quadrature. The scaling has not occurred during test station changes at TTL and is not expected to enter in any significant way.

The translation with respect to the origin has occurred during testing at the TTL. When the quadrature vector is adjusted, there is a residual difference between the length of the in-phase vector at zero flow in the two cases. Such differences will almost certainly occur when the ECFMs are calibrated in the FFTF. Two solutions present themselves: (1) select zero flow for one of the two flows used in the setup and establish procedures for obtaining zero flow, or (2) use a Kalman filter to process out the bias in the flow data after-the-fact.

3.5.1 Calibration Curves

The summary of the flow calibration curves for the ECFMs calibrated at the TTL are presented in Tables 3.1 to 3.15. These curves are functions of both temperature and flow. While the voltage biases for each run are included, the absolute bias is a function of many variables and will be redetermined in the plant. The temperature sensitivity of the bias is also a function of the environment.

The calibration curves are straight lines and satisfy;

$$\text{Flow} = (V_{DC} - \text{Bias})/\text{Slope} \qquad (3\text{-}8)$$

where V_{DC} is the in-phase component I,

$$\text{Slope} = S1 + S2 \cdot T, \qquad (3\text{-}9)$$

and

$$\text{Bias} = B1 + B2 \cdot T \qquad (3\text{-}10)$$

The values of S1, S2, B1 and B2 are included in Tables 3.1 to 3.15. Several tables show different signs for S1 for different runs. This is a result of the relative phase setting on the lock-in amplifier and as a matter of convention all of these parameters are multiplied by the sign of S1. Table 3.16 is a summary of parameters. Note that all of the parameters listed in Table 3.16 are scaled by a factor of 10. This difference is due to a change in amplifier gain between the TTL and the FFTF. As described in the next paragraph, several runs were discounted because of obvious data acquisition errors.

Table 3.1

S/N 052 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	.404926	.030161	.504612
	500.0	.348626	.030347	.512748
	600.0	.294221	.030197	.579480
	700.0	.242743	.029889	.510724
	800.0	.258666	.030155	.322982
	900.0	.187046	.029754	.602076
	1000.0	.094759	.028569	.368891
	1100.0	-.009830	.027804	.379466

B1 =   .627486   S1 = .031972

B2 =   -.0005331223   S2 = -.0000031496

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	.726265	.030086	.161921
	600.0	.649766	.030529	.223428
	700.0	.610819	.030238	.167526
	800.0	.563427	.030038	.197729
	900.0	.535142	.029281	.174214
	1000.0	.486676	.029423	.139064
	1100.0	.462778	.028033	.216970

B1 = .878950   S1 = .031860

B2 = -.0003850504   S2 = -.0000027984

Table 3.2

S/N 064   Parameters

T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
400.0	-2.568879	.032198	.229671
600.0	-2.772457	.032167	.218910
700.0	-2.866239	.032581	.198361
800.0	-2.940135	.032583	.209953
900.0	-2.977041	.031044	.436393
1000.0	-3.013686	.030752	.262611
1100.0	-3.035866	.029937	.495312

B1 =-2.361937   S1 =   .034255

B2 = -.0006619543   S2 = -.0000033672

Table 3.3

S/N 078   Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	2.188090	-.031698	-.218712
	600.0	2.241499	-.032069	-.192551
	700.0	2.184301	-.031365	-.260619
	800.0	2.126020	-.031545	-.232035
	900.0	2.152527	-.030803	-.357274
	1000.0	2.332331	-.030313	-.848971
	1100.0	2.480885	-.029544	-.342618

B1 = 1.999355   S1 = -.033570

B2 = .0003109407   S2 = .0000032093

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	2.146267	-.031146	-.106323
	600.0	2.245697	-.031372	-.162133
	700.0	2.273608	-.031151	-.163994
	800.0	2.283862	-.031305	-.102806
	900.0	2.261030	-.029935	-.327723
	1000.0	2.229798	-.029733	-.209881
	1100.0	2.179137	-.028967	-.378781

B1 = 2.199941   S1 = -.033144

B2 = .0000399663   S2 = .0000033454

Table 3.4

S/N 081 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	.410214	.032570	.222756
	600.0	.398231	.033076	.255634
	700.0	.396138	.032933	.236419
	800.0	.393234	.032531	.285982
	900.0	.381666	.032131	.152998
	1000.0	.395459	.030983	.245714
	1100.0	.392174	.030308	.302498

B1 = .415375   S1 = .034841

B2 = -.0000255475   S2 = -.0000035194

Run #2	T°F	Bias* (V)	Slope * (V/GPM)	RMS * (GPM)
	400.0	.103007	.018785	.202367
	600.0	.083521	.018436	.401982
	700.0	.036582	.018577	.541246
	800.0	-.034214	.018064	.149819
	900.0	-.029699	.017627	.744082
	1000.0	.120951	.017115	1.185363
	1100.0	.177189	.016776	1.053693

B1 = .021728   S1 = .020277

B2 = .0000554978   S2 = -.0000030103

*An extra 5KΩ resistor in the circuit introduced a factor of 0.6 in this run.

Table 3.5

S/N 098 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-1.311786	.028660	1.053677
	500.0	-1.366640	.028993	1.226408
	600.0	-1.400477	.028789	1.204226
	700.0	-1.426069	.029917	3.007165
	800.0	-1.413824	.028758	.370252
	900.0	-1.428041	.028385	.414818
	1000.0	-1.439349	.027707	.218730
	1100.0	-1.491043	.027271	.319585

B1 = -1.258869   S1 = .030214

B2 = -.0002010465   S2 = -.0000022048

Run #2	T°F	Bias* (V)	Slope* (V/GPM)	RMS (GPM)
	400.0	1.066116	-.018344	-.175282
	600.0	1.147484	-.018264	-.153425
	700.0	1.177093	-.019053	-.142548
	800.0	1.182087	-.018385	-.092633
	900.0	1.200562	-.018347	-.122953
	1000.0	1.222890	-.017859	-.232888
	1100.0	1.257483	-.017709	-.229225

B1 = .984941   S1 = -.019065

B2 = .0002471134   S2 = .0000009996

*An extra 5KΩ resistor in the circuit introduced a factor of 0.6 in this run.

Table 3.6

S/N 109 Parameters

T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
400.0	.064128	.031058	.185080
600.0	.082627	.030825	.156914
700.0	.079259	.030689	.233051
800.0	.086858	.030424	.318283
900.0	.106634	.030055	.508100
1000.0	.166253	.029039	.292469
1100.0	.188966	.028874	.347757

B1 = -.028108   S1 = .032769

B2 = .0001766325   S2 = -.0000033496

Table 3.7

S/N 110 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.715633	.030730	.482525
	600.0	-.814390	.032592	.354225
	700.0	-.843053	.032730	.521336
	800.0	-.878454	.032705	.799776
	900.0	-.942039	.032877	.684958
	1000.0	-1.048316	.033717	.651696
	1100.0	-1.190856	.034785	.674861

B1 = -.424000   S1 = .029110

B2 = -.0006299533   S2 = .0000047936

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.517290	.031326	.106633
	600.0	-.433507	.031325	.173329
	700.0	-.383485	.030671	.216978
	800.0	-.348473	.030742	.233291
	900.0	-.305033	.030165	.175701
	1000.0	-.268285	.029655	.231682
	1100.0	-.193402	.028739	.190746

B1 = -.698843   S1 = .033206

B2 = .0004440772   S2 = -.0000036031

Table 3.8

S/N 128 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	.747313	.028916	.149029
	600.0	.839853	.029053	.176245
	700.0	.892686	.028328	.213210
	800.0	.920184	.028088	.248617
	900.0	.956047	.027646	.285951
	1000.0	.989685	.027294	.155110
	1100.0	1.046236	.026563	.276405

B1 = .591794   S1 = .030732

B2 = .0004089895   S2 = -.0000034972

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	.516283	.030220	.152294
	600.0	.599973	.030503	.248662
	700.0	.654381	.030121	.333847
	800.0	.691739	.029823	.210730
	900.0	.725340	.029425	.171227
	1000.0	.746044	.029018	.229188
	1100.0	.789418	.028160	.222994

B1 = .372474   S1 = .031967

B2 = .0003847023   S2 = -.0000029992

Table 3.9

S/N 156 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-1.013324	.029825	.202318
	600.0	-1.009467	.029705	.292939
	700.0	- .998643	.029732	.255655
	800.0	- .986815	.029762	.187907
	900.0	- .955683	.029250	.236706
	1000.0	- .934050	.029047	.294872
	1100.0	- .912731	.027993	.292973

$B1 = -1.093765$ $\qquad$ $S1 = .031086$

$B2 = .0001537525$ $\qquad$ $S2 = 0.0000022345$

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.826294	.028951	.189323
	600.0	-.798583	.029287	.188993
	700.0	-.766750	.029135	.203400
	800.0	-.733726	.028763	.252994
	900.0	-.693084	.028374	.191550
	1000.0	-.645439	.027620	.184455
	1100.0	-.609235	.027029	.181090

$B1 = -.980050$ $\qquad$ $S1 = .030786$

$B2 = .0003249526$ $\qquad$ $S2 = -.0000029715$

Table 3.10

S/N 158 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.334092	.030159	.178307
	600.0	-.323246	.030187	.172948
	700.0	-.312447	.029578	.248640
	800.0	-.304404	.029603	.222979
	900.0	-.286557	.029105	.422616
	1000.0	-.283594	.028865	.626448
	1100.0	-.268628	.027740	.670678

B1 = -.377100   S1 = .031847

B2 = .0000957699   S2 = -.0000032175

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.506052	.030641	.197586
	600.0	-.528715	.030659	.166237
	700.0	-.512115	.030574	.232369
	800.0	-.490360	.030323	.234835
	900.0	-.528134	.030240	.474143
	1000.0	-.554172	.029015	.343209
	1100.0	-.560294	.028459	.311398

B1 = -.469497   S1 = .032426

B2 = -.0000715208   S2 = -.0000031041

Table 3.11

S/N 164 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.931465	.029393	.135195
	600.0	-.960698	.029673	.154130
	700.0	-.965268	.029166	.200688
	800.0	-.984598	.029088	.238926
	900.0	-.976959	.028542	.222246
	1000.0	-.921906	.028149	.240597
	1100.0	-.863095	.027371	.197002

B1 = -1.001817   S1 = .031105

B2 = .0000743151   S2 = -.0000029735

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-1.238576	.030790	.185950
	600.0	-1.264099	.031049	.175565
	700.0	-1.261235	.030462	.333368
	800.0	-1.266589	.030475	.332485
	900.0	-1.269469	.030400	.508013
	1000.0	-1.253502	.029670	.269943
	1100.0	-1.231074	.028796	.312279

B1 = -1.259242   S1 = .032343

B2 = .0000054818   S2 = -.0000026839

Table 3.12

S/N 172 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	1.165144	.023597	.196426
	600.0	1.172185	.023638	.165362
	700.0	1.151381	.025190	.154781
	800.0	1.132190	.023827	.101073
	900.0	1.098150	.023856	.128713
	1000.0	1.068585	.023542	.108390
	1100.0	1.035932	.022705	.155161

B1 = 1.274438   S1 = .024674
B2 = -.0001995452   S2 = -.0000011578

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	1.220693	.032743	.216341
	600.0	1.234435	.034537	.531979
	700.0	1.239034	.033577	.238634
	800.0	1.236476	.032913	.184115
	900.0	1.226639	.031881	.454185
	1000.0	1.176964	.031866	.301639
	1100.0	1.109343	.030626	.342830

B1 = 1.313488   S1 = .035644
B2 = - .0001365151   S2 = -.0000038844

Run #3	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	1.245072	.031472	.202183
	600.0	1.282226	.031303	.234432
	700.0	1.265343	.031024	.233118
	800.0	1.215923	.031303	.160429
	900.0	1.145447	.031380	.528557
	1000.0	1.091266	.029388	.406395
	1100.0	1.023844	.029730	.302421

B1 = 1.458393   S1 = .032913
B2 = -.0003526593   S2 = -.0000026885

Table 3.13

S/N 191 Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	.148762	.031281	.294969
	600.0	.137557	.032008	.302299
	700.0	.136618	.032107	.334061
	800.0	.141750	.032364	.156915
	900.0	.163834	.030361	.359169
	1000.0	.179851	.031299	.290575
	1100.0	.192289	.030343	.403654

$B1 = .100691$ $S1 = .032716$

$B2 = .0000719682$ $S2 = -.0000016824$

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	.342747	.031638	.218153
	600.0	.352039	.033061	.191972
	700.0	.380906	.032602	.331962
	800.0	.445790	.031913	.263979
	900.0	.503451	.031648	.354667
	1000.0	.395286	.030736	.755003
	1100.0	.246027	.030416	.586130

$B1 = .390580$ $S1 = .033789$

$B2 = -.0000123296$ $S2 = -.0000026381$

Table 3.14

AOTA Parameters

Run #1	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.024788	.104802	1.886903
	500.0	-.032325	.103106	1.553797
	600.0	-.026994	.099308	1.362831
	700.0	-.008825	.094951	1.091018
	800.0	-.002788	.090816	.741955
	900.0	.039932	.084975	.512219
	1000.0	.074112	.0799912	.254024
	1100.0	.112484	.074534	.301678

B1 = -.135426   S1 = .125005

B2 = .0002023695   S2 = -.0000445925

Run #2	T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
	400.0	-.135508	.115320	.214064
	600.0	-.089470	.106955	.206181
	700.0	-.067363	.102078	.202657
	800.0	-.043745	.096650	.094982
	900.0	.005329	.090968	.157114
	1000.0	.047434	.084646	.180501
	1100.0	.085842	.077930	.211687

B1 = -.280185   S1 = .138483

B2 = .0003206936   S2 = -.0000536057

48

Table 3.15

S/N 201 Parameters

Run #1

T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
400.0	-.580719	.033842	.216978
600.0	-.602511	.034111	.376711
700.0	-.594228	.033035	.299516
800.0	-.568129	.031688	.298276
900.0	-.564002	.032363	.272746
1000.0	-.537951	.031391	.234378
1100.0	-.515972	.030429	.228228

$B1 = -.649188$ $S1 = .036417$

$B2 = .0001056007$ $S2 = -.0000051024$

Run #2

T°F	Bias (V)	Slope (V/GPM)	RMS (GPM)
400	.626337	-.032737	-.497113
600	.668855	-.034142	-.327199
700	.671996	-.034292	-.208642
800	.673330	-.034122	-.145910
900	.662631	-.033580	-.258667
1000	.632122	-.002688	-.190443
1100	.595858	-.029190	-.652081

$B1 = .681859$ $S1 = -.036129$

$B2 = -.0000439791$ $S2 = .0000040282$

49

TABLE 3.16

CALIBRATION CURVE PARAMETERS

S/N	S1 $(\times10^{+2})$ (Volt/GPM)	S2 $(\times10^{+7})$ (Volt/GMP/°F)	B1 $(\times10)$ (Volts)	B2 $(\times10^{+5})$ (Volts/°F)
052	.319	-2.97	0.75	-4.59
064	.343	-3.37	-2.36	-6.62
078	.334	-3.28	-2.10	-1.75
081	.343	-4.27	0.26	-2.26
098	.310	-1.94	-1.45	-3.06
109	.328	-3.35	-0.03	1.77
110	.332	-0.36	-0.70	4.44
128	.313	-3.25	0.48	3.97
156	.309	-2.60	-1.04	2.39
158	.321	-3.16	-0.42	-0.84
164	.317	-2.83	-1.13	0.40
172	.343	-3.29	1.37	-2.45
191	.333	-2.16	0.25	0.30
194 (AOTA)	1.385	-53.61	-0.28	3.21
201	.363	-4.57	-0.67	0.75

50

The 400°F to 700°F runs on ECFM S/.Ns 052, 098 and 194 (AOTA) were all
run at the same time and the run suffered a computer failure producing two
sets of data which led to the anomalous behavior in the rms column.
Run #1 for S/N 110 and for S/N 172 contain bad data also.

3.5.1.1 Temperature and Flow Calibration

The ECFM in the Row 2 FOTA (HF011) is Serial Number 172 and is attached
to the Model 5204 Lock-in Amplifier. This amplifier provides both Q and I
output. Simultaneously. A test run (Run 3C) at the TTL using flows of
approximately 20 gpm and 200 gpm was used to find the flow and temperature
dependence of the Q vector for S/N 172. Table 3.17 displays the results of
this run, which may be summarized as follows:

$$I = (S1 + S2 \cdot T) \cdot Flow + (B1 + B2 \cdot T) \tag{3-11}$$

and

$$Q = (T1 + T2 \cdot T) \cdot Flow + (C1 + C2 \cdot T) \tag{3-12}$$

where I and Q are the in-phase and quadrature vectors; S1, S2, B1 and B2
are given in Table 3.16 for S/N 172 and T1, T2, C1 and C2 are defined in
Table 3.18.

Note that B1 and C1 are both functions of the location of the absolute
zero flow and are subject to change. Note also, the factor of 10 scaling
between TTL results and those of the FFTF. Thus the values of B1 and C1
to be used in the FFTF will be derived from the zero flow values of Q and I
in the plant.

Solve Equation (3-11) and (3-12) for flow and T (temperature in °F)
to obtain a pair of solutions,

$$T_\pm = 1/2 \ (\xi - \beta \pm \sqrt{\beta^2 - 4\alpha})/\alpha \tag{3-13}$$

and

$$Flow_\pm = (I_p - B1 - B2 \cdot T_\pm)/(S1 + S2 \cdot T_\pm) \tag{3-14}$$

where

$$\alpha \triangleq T2 \cdot B2 - S2 \cdot C2$$

$$\beta \triangleq B2 \cdot T1 - S1 \cdot C2 - T2 \cdot (I - B1) + S2 \cdot (Q - C1)$$

and

$$\gamma \triangleq (Q - C1) \cdot S1 - (I - B1) \cdot T1$$

TABLE 3.17

FLOW AND TEMPERATURE DEPENDENCE OF Q FOR S/N 172

Temperature (°F)	Flow (GPM)	Quadrature (Volts)
407.8	20.2	0.9322
398.8	200.5	0.9319
598.8	20.2	1.3796
598.8	198.7	1.95F9
698.9	20.2	1.6224
700.4	199.2	2.5105
800.6	20.4	1.8962
800.2	201.3	2.9830
898.7	20.0	2.1631
897.3	201.3	3.4450
996.2	20.1	2.3490
997.4	201.0	3.9230
1092.0	20.4	2.5117
1098.0	200.1	4.2150
1098.0	20.3	2.5196

TABLE 3.18

PARAMETERS FOR QUADRATURE DEPENDENCE ON FLOW AND TEMPERATURE

	T1 (Volts/GPM)	T2 (Volts/GPM/°F)	C1 (Volts)	C2 (Volts/°F)
TTL	-4.58×10^{-3}	1.29×10^{-5}	9.95×10^{-2}	2.07×10^{-3}
FFTF	-4.58×10^{-4}	1.29×10^{-6}	9.95×10^{-3}	2.07×10^{-4}

The appropriate choice of solutions corresponds to the negative root in Equation (3-13).

3.5.2 Conclusions

The implementation of the PSD flow measuring electronics in the FFTF allows flow measurement accuracies in the low flow regime (< 75 gpm) of approximately ±1 gpm. The success of the linear fit to the data is somewhat dependent on the low sodium velocities being measured (see Appendix B) and on the increased sensitivity of the flow signal at low flows resulting from the removal of all constant, non-flow signals by the PSD electronics.

The largest errors produced were a result of spurious data or of data recording errors. Highly repetitious measurements in the plant environment will suppress many of the larger errors and the permanent attachments to the DDH & DS, the on-line data handling and storage computer at the FFTF, should help to minimize recording errors.

The additional instrumentation on the Row 2 FOTA (HF011) provides, in addition to accurate flow measurement, fast temperature measurements with a sensitivity of about 2 millivolts/°F. An accuracy of 10 millivolts (not unreasonable) in the output voltage (relative to previous readings) would allow for rapid temperature tracking with a ±5°F uncertainty band. Thus the installation on HF011 can provide flow measurement and temperature measurement with accuracies of ± 1 gpm and ± 5°F, respectively. The effects of rapid thermal transients have not been investigated and might indicate the need for post-processing of the data to account for thermal lags in the ECFM thimble.

The AOTA has considerably higher velocities at the same flow. The repeat run, unlike the other ECFMs, was made in the same thimble, as only one AOTA test station existed. The first run suffered from the computer failure and is far less believable. The second run shows the excellent accuracy of the AOTA with an rms error of 0.21 gpm or less. This high level of linearity provides quite accurate flow measurements.

54

4.0 PLANT PROCEDURES

This section treats the plant requirements for setting up the PSD-equipped ECFMs. The procedures vary with fueled assemblies and with unfueled assemblies because of their drastically different flow rates. Finally a procedure for checking for bias shifts after a few thermal cycles is outlined in Section 4.2.

4.1 Phase-Sensitive Detector Setup

The in-plant setup of the PSD electronics consists of setting the correct attenuation and of obtaining a value for Q, the quadrature vector, which is independent of the flow. The description of the quadrature setup in the TTL given in Section 3.3 applies equally well to in-plant setup since setting the quadrature does not require knowledge of the flow value. Simulated in-plant quadrature setups were performed at the TTL in which the quadrature vector for a flowmeter was obtained using unknown flows. The results of the test indicate the knowledge of the true flow values made no difference in obtaining Q. Appendix C contains the detailed procedure for the field calibration and setup.

4.1.1 Fueled Assemblies

Fueled assemblies are orificed to provide flows of about 500 gpm with all three primary pumps at full power. Three pony motors provide about 10% flow or 50 cpm. Prior to operation, the fueled assemblies produce no decay heat to speak of and it is possible to obtain nearly zero flow with an isothermal core. Hence with the fueled assemblies, the two plant flow conditions required for setup are three pony motors and no pumps. The advantage of these two flow rates are: 1) the TTL calibration was performed use 2 and 60 gpm and, 2) the zero flow reading provides an absolute calibration of the in-phase component, thereby lessening the uncertainty caused by the environmental feedback.

4.1.2 Reflectors

Most of the comments concerning the fueled assemblies apply to the reflector assemblies also. The only difference is the orificing in the reflectors: They carry about 35 gpm with three primary pumps. Thus in

order to accurately calibrate the reflector   ECFMs, the two plant flow
conditions should be design flow and no pumps, respectively.

4.2 Bias Shift Checks

The stability of an ECFM appears to increase after it has undergone
a few thermal cycles. In order to check for shifts in the flow zero and
in the quadrature vector, the setup procedure should be performed again
following the maximum isothermal (MIST) test in the ATP.

5.0 PHASE-SENSITIVE ELECTRONICS CALIBRATION

The PSD electronics have been calibrated in the Standards Laboratory at HEDL
prior to being installed at the FFTF. The calibrations necessary before
and after arrival at the FFTF are treated in this section.

5.1 Standard In-Laboratory Calibration

The lock-in amplifier calibration involves adjusting the tuning of the
signal amplifier of each lock-in amplifier to a high level of accuracy so
that a 25 mv ± 0.2% sinusoidal input at 1 KHz with less than 0.5% total
harmonic distortion produces 1.000 volt ± 0.2% at the output.

After each amplifier has been adjusted on the 25 mv scale, the attenuation
ratios for the 2.5 mv to 250 mv ranges are recorded for each amplifier.

The procedure for this calibration is reproduced in Appendix C.

5.2 In-Field Calibration

Following calibration of the lock-in amplifiers by the Standards Lab
and installation of the amplifiers in the FFTF, the attenuators were adjusted
to provide full scale reading for the lock-in amplifier when a 3 mv signal
at the system 1 KHz frequency was fed into the SC/CR, which in turn provided
a 3.000 V_{AC} signal (1 KHz frequency) at the AMPL SEC (Amplified Secondary
Coil Voltage) output connector located on the front of the SC/CR module.
The attenuator adjustment (ADJ) potentiometer was adjusted until the lock-in
amplifier, whose phase had been adjusted to obtain a maximum in-phase
(zero quadrature) singal (phase shifts through the SC/CR amplifier require prior
adjustment of the phase switch and dial to get the maximum signal sensitivity),
gives a V_{DC} output corresponding to the average value obtained from Table 5-1
for the ECFM S/N being calibrated.

The signal attenuator design standard is reproduced in Appendix C.

TABLE 5.1.a

CHARACTERISTICS OF TTL ELECTRONICS

Ident No.	SC/CR S/N 5541-	Lock-In Amplifier & Attenuator	V_{AC}	V_{DC}
I	0062	612953	3.0780	9.2785
II	0062	612480	3.0780	9.0780
III	0062	701584	3.0780	9.0680
IV	0019	612953	3.0440	9.1110
V	0019	612480	3.0455	8.9090
VI	0019	701584	3.0455	8.9000
VII	0002	612953	3.0280	9.0450
VIII	0002	612480	3.0280	8.8415
IX	0002	701584	3.0285	8.8300
X	0044	612953	3.0065	9.0650
XI	0044	612480	3.0065	8.8465
XII	0044	701584	3.0065	8.8465
XIII	0043	612953	3.0065	9.0485
XIV	0043	612480	3.0065	8.8460
XV	0043	701584	3.0065	8.8700
XVI	0044	612953 +5K	3.0075	5.4040
XVII	0062	612953 +5K	3.0790	5.5380

TABLE 5.1.b

TABLE OF CALIBRATION RUNS VERSUS ELECTRONICS IDENT. NO.

S/N	I.D. (1)	I.D. (2)
052	XI	XIV
064	I	XIII
078	II	XIV
081	XVI	I
098	XVI	XV
109	I	XV
110		XIV
128	XV	I
156	II	XIV
158	XV	I
164	XV	I
172	XIII	VII
191	VII	VII
AOTA	XVII	XVII
201	VII	VII

6.0 REFERENCES

1. Letter, J. W. Mitchell to W. M. Jacobi, "GPL-2 Instrument S/A Testing - Preliminary Report," W/FFTF 721426, March 1, 1972.

2. D. R. Pederson, et al., "Flowmeter Calibration Report - SLSF Flowmeters," ANL/RAS 76-16 , April 1976.

3. V. DeVita, "Calibration Report for HEDL Eddy Current and PM Flowmeters - H-3-42621 and H-3-42670," LMEC TI-12-LME-009, October 1977.

4. Letter, T. T. Anderson to W. B. Klingler, "Field Installation and Operating Instructions for the FC/T Module," Argonne National Laboratory, March 10, 1977.

5. Standard RDT C-4-7, "Eddy Current Probe Type Flow Sensor for Liquid Metal Service".

6. Standard, RDT C-10-5, "Eddy Current Power Supply and Signal - Conditioning Electronics."

7. M. Hirayama, "Theoretical Model of an Eddy Current Flowsensor," IEEE Transactions on Nuclear Science NS-24, 2021 October 1977.

8. L. E. Fort, Private Communication.

9. K. Ara, "A Differential Transformer with Temperature and Excitation Independent Output," IEEE Transactions on Nuclear Science, IM-21, 249, August 1972.

10. G. Hughes, "Electrical Conductivity Fluctuations in High Temperature Liquid Metals," Journal of Physics E: Scientific Instruments 5, 349, 1972 .

    J. D. McCann, "Fast Response Temperature Sensor for Use in Liquid Sodium, "Journal of Physics E: Scientific Instruments 9, 298, 1975 .

    B. J. Farrington and G. Hughes, "A Theoretical Analysis Applied to Electromagnetic Instruments Used in Liquid Sodium," Central Electricity Generating Board, Berkeley, Report RD/B/N2751, 1975 .

    B. S. Farrington and G. Hughes, "Performance of an Electromagnetic Temperature Sensor in Liquid Sodium," Journal of British Nuclear Energy 16, 347, October 1977 .

APPENDIX A

This Appendix contains the specifications for the following ECFM Components:

- PAR Model 128A Lock-In Amplifier
- PAR Model 5204 Lock-In Analyzer

PAR MODEL 128A SPECIFICATIONS

SIGNAL CHANNEL

FREQUENCY RANGE: 0.5 Hz - 100 KHz

SENSITIVITY: 1 μV to 250 mV rms full scale in a 1-2.5-10 sequence.

INTERNAL NOISE: Less than 10 nV/Hz$^{1/2}$ at 1 KHz.

SYSTEM GAIN STABILITY: Less than 0.1%/°C.

DETECTOR BIAS: Adjustable from 0 to ±15 V by inserting divider resistors on internal preamplifier board.

SIGNAL CHANNEL: Single-ended or true differential, switch-selectable.

INPUT IMPEDANCE: 100 megohms in parallel with 20 pF.

COMMON MODE REJECTION: Better than 100 dB at 1 KHz.

MAXIMUM COMMON MODE VOLTAGE: 3 V pk-pk to 20 KHZ, -6 dB/Octave above.

MAXIMUM INPUT SIGNAL: 1000 times full scale up to a maximum of 1.8 V pk-pk before overload.

HI-PASS FILTER: A front panel switch sets the high pass characteristics to < 0.5 Hz (MIN. position), 5 Hz or 50 Hz. These values can be easily changed in the field to suit the application.

LOW-PASS FILTER: A front panel switch sets the low pass characteristics to 100 Hz, 10 KHz or >100 KHz (MAX. position). These values can be easily changed in the field to suit the application.

TUNED SIGNAL CHANNEL OPTION (128A/98): Provides a switch-selectable choice of a flat response or of a tuned bandpass (or notch charactersitic) at a set frequency with a Q of 5. The frequency can be adjusted over a 3:1 frequency range by means of a potentiometer, accessible from the rear panel, and can be changed to any frequency within the range of approximately 0.5 Hz to 100 KHz by changing capacitors mounted on solderless component clips on the board.

REFERENCE CHANNEL

FREQUENCY RANGE: 0.5 Hz - 100 KHz. No range switching or tuning required.

MODES OF OPERATION: Fundamental (f) - the Model 128A locks onto any external reference signal of the proper input characteristic. Harmonic (2f) - in this mode, the 128A will respond at the second harmonic of the external reference frequency, maximum input frequency is 50 KHz.

INPUT REQUIRED: The reference channel will phase lock to virtually any external voltage waveform of at least 100 mV pk-pk amplitude and which crosses its mean only twice each cycle. The minimum pulse duration (for asymmetrical waveforms) is 100 ns. The front panel Reference Unlock lamp indicates the presence of a proper reference input. When using a sine wave reference, best phase accuracy is achieved at 1 V rms.

ACQUISITION TIME: The time required for the reference channel lock to a changed reference signal is typically 2 seconds/octave. Below 5 Hz the acquisition time increases to 10 seconds/octave.

PHASE ADJUSTMENT: A calibrated ten-turn potentiometer provides 0 - 100° phase shift. The phase shift accuracy is better than 0.2° over the entire frequency range. Resolution is 0.1°. A four-position quadrant switch provides 90° phase shift increments accurate to 0.2°.

PHASE-SENSITIVE DETECTOR

DYNAMIC RESERVE: Asynchronous signals with amplitudes corresponding to 1000 times full scale can be applied without overload. Dynamic reserve can be greatly increased by modification 128A/70, 128A/98, and proper setting of high pass, low pass controls.

A-3

FILTER TIME CONSTANTS: 1 ms to 100 seconds plus an External position and a Minimum time position (less than 1 ms). The external position allows capacitance to be added via a rear panel connector to obtain any desired time constant. A dc Pre-Filter switch is provided which inserts an additional 0.1 or 1 second time constant filter. When used in conjunction with any of the standard time constant settings, it provides a 12 dB/octave rolloff rate.

DC OUTPUT ZERO STABILITY: Better than 0.1%/°C, 0.1%/24 hours at constant temperature.

OUTPUT VOLTAGE: ±1 V full scale.

ZERO OFFSET: Calibrated ten-turn potentiometer allows up to ±10x full scale signal to be suppressed.

OUTPUTS

METER READOUT: Zero-center taut-band meter to monitor dc output.

RECORDER: ±1 V full scale at both a front panel BNC connector and a rear panel double banana jack for driving a recorder.

GENERAL

OVERLOAD: A front panel lamp indicates overload at all critical points in the instrument.

AMBIENT TEMPERATURE RANGE: The unit can be operated at temperatures ranging from 15°C to 45°C.

AUXILIARY POWER OUTPUT: Regulated ± 15 V at 20 mA available at a rear panel connector.

A-4

POWER REQUIREMENTS: 100-130 or 200-260 V ac; 50-60 Hz; 12 watts. Unit can also be powered from batteries by supplying ±20 to 30 V dc to a rear panel connector. Batteries must be able to supply at least 250 mA.

SIZE: 17-3/4" W x 3-1/2" H x 14" D (45 cm W x 9 cm H x 36 cm D).

WEIGHT: 14 lbs (6.4 kg).

PAR MODEL 5204 SPECIFICATIONS

SIGNAL CHANNEL

FREQUENCY: 0.5 Hz - 100 KHz

SENSITIVITY: 8 full-scale ranges from 100 microvolts to 250 millivolts in a 1-2.5-10 sequence. Three output expansion ranges of X1, X10 and X100 increase the overall sensitivity to 1 µV full scale.

INPUT: Single-ended or differential input, floating or grounded.

INPUT IMPEDANCE: 100 megohms shunted by 25 picofarads.

COMMON MODE REJECTION: Better than 100 dB at 1 KHz.

MAXIMUM COMMON MODE VOLTAGE: 3 V pk-pk to 20 KHZ -6 dB/octave above 20 KHz.

MAXIMUM INPUT SIGNAL: 650 millivolts rms sine wave before overload (1.8 V pk-pk).

DETECTOR BIAS: Adjustable from 0 to ±15 volts by inserting bias resistors on the internal preamplifier board.

HI PASS FILTER: A front panel switch sets high pass characteristics to <0.5 Hz (both switches out), 5 Hz, or 50 Hz. These values can be changed in the field to suit the application.

LO PASS FILTER: A front panel switch sets low pass filter characteristics to 100 Hz, 10 kHz, or max (greater than 100 kHz). These values can be changed in the field to suit the application.

INTERNAL NOISE: Less than 10 nV/Hz$^{1/2}$ at 1 kHz (see noise figure contour).

SYSTEM GAIN STABILITY: Better than 0.1%/°C.

REFERENCE CHANNEL

FREQUENCY RANGE: 0.5 Hz to 100 kHz. no range switching or tuning required.

MODES OF OPERATION:

Fundamental (f): The reference channel locks onto any external reference signal having the proper reference characteristics (see below).

Harmonic (2f): The reference channel locks onto the proper external reference signal and responds to the second harmonic of the external reference.

INPUT REQUIRED: The reference channel phase locks to virtually any external voltage waveform having amplitude excursions of at least 50 millivolts on each side of the mean crossing the mean only twice each cycle. Minimum pulse duration (for an asymmetrical waveform) is 5 microseconds. The front panel reference unlock lamp indicates the absence of a proper reference input. When using a sine wave reference, the best phase accuracy is achieved at 1 volt rms.

PHASE ADJUSTMENT: A calibrated ten-turn potentiometer provides 0-100 degree phase shift. The accuracy is within 0.2 degree and the resolution is 0.1 degree. A four-position quadrant switch provides 90 degree phase shift increments accuraate to 0.1 degree.

PHASE NOISE: Less than 0.1 degree (at 1 kHz; 0.1 sec, 12 dB/octave).

ACQUISITION TIME:

0.5 Hz to 50 Hz - 15 sec (typical)
50 Hz to 100 kHz - 2 sec (typical)
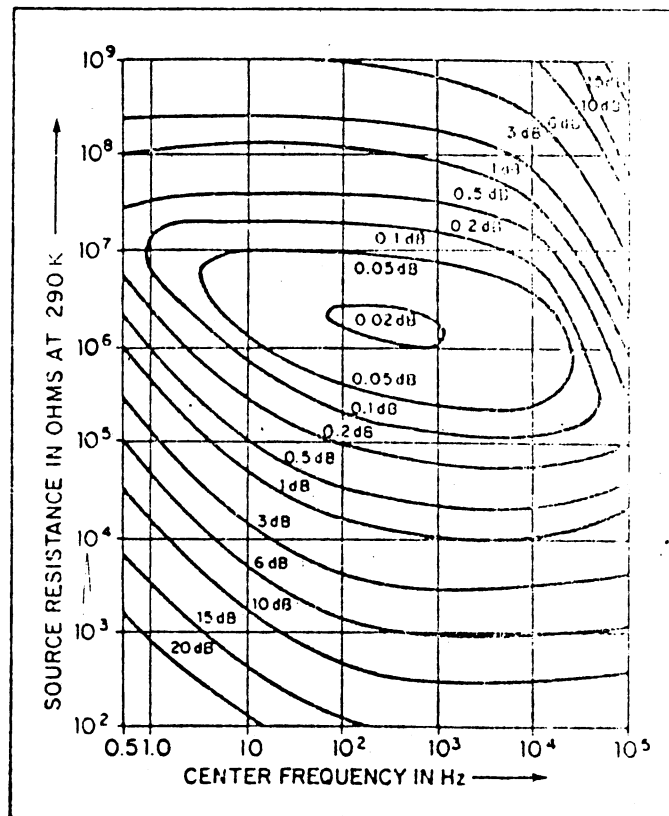
OUTPUTS

METER READOUT: Two zero-center meters provide full-scale indication for
a full scale input as determined by the input sensitivity switch and the
output expand switch settings. The left meter can be switched to monitor
the in-phase signal or, if the appropriate option is installed, the vector
magnitude or computed noise. The right meter can be switched to monitor
the quadrature signal or, if the option is installed, the computed phase
of the signal with respect to the reference signal. A third position
allows the righr meter to monitor an external dc signal such as that available
from the optional ratio output.

RECORDER OUTPUT: Front and rear panel BNC connectors are provided in
parallel to interface to all standard recorders.

Provided with PNNL-26202

OUTPUT VOLTAGE: 1 volt through 600 ohms.

METER SENSITIVITY (External Mode): 1 volt full scale. (100 µA meter movement through 10 kilohms.)

GENERAL

AMBIENT TEMPERATURE RANGE: Units can be operated at temperatures ranging from 15°C to 45°C.

AUXILIARY POWER OUTPUT: Regulated ±15 volts at 20 mA available at rear panel connector.

POWER REQUIREMENTS: 100 to 130 or 200 to 260 volts ac; 50-60 Hz; 35 watts. Units can also be powered from batteries by supplying ±24 V to ± 30 V and +8 V dc to a rear panel connector. Batteries must be able to supply at least 1 A.

SIZE: 17-1/2" W x 5-1/2" H x 19-1/2"D (44.5 cm W x 13.9 cm H x 49.5 cm D).

WEIGHT: 25 lbs (11.4 kg).

APPENDIX B

This appendix provides a detailed calculation of the behavior of the induced EMFs in an ECFM made of three single loop coils. This simplification does not affect the applicability of the qualitative results but does invalidate them for quantitative purposes.

Maxwell's field equations for the general case in which the medium is moving with a velocity, $\vec{V}$, are:

$$\vec{\nabla} \times \vec{H} = \vec{J} + \sigma \, (\vec{E} + \vec{V} + \vec{B}) + \frac{\partial \vec{D}}{\partial T} \tag{B.1}$$

$$\vec{\nabla} \times \vec{E} = \partial \vec{B}/\partial T \tag{B.2}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{B.3}$$

$$\vec{\nabla} \cdot \vec{D} = \rho \tag{B.4}$$

where the only addition caused by the moving medium is the $\sigma \vec{V} \times \vec{B}$ term in Equation (B.1).

The divergence of $\vec{B}$ vanishes so , without loss of generality, $\vec{B}$ can be expressed in terms of a vector potential A,

$$\vec{B} = \vec{\nabla} \times \vec{A} \tag{B.5}$$

Where A is not unique since it can be replaced by any vector function which differs from it by the gradient of some scalar function. This ambiguity does not reflect itself in the final answer and so is not considered.

Making use of Equations (B.1) - (B.5) along with the relation of D to E and B to H,

$$\vec{D} = \epsilon \, \vec{E}, \tag{B.6}$$

$$\vec{B} = \mu \, \vec{H}, \tag{B.7}$$

B-1

which are valid in an isotropic, homogeneous medium. The following
differential equation for A may be written when the driving current is
sinusoidal;

$$\vec{\nabla} (\vec{\nabla} \cdot \vec{A}) - \nabla^2 \vec{A} = \mu \vec{J} - \mu (\sigma + i \omega \epsilon) \frac{\partial \vec{A}}{\partial T} + \mu \sigma \vec{V} \times (\vec{\nabla} + \vec{A}) \quad (B.8)$$

which simplifies for the case in which V is parallel to the Z-axis of
the coil, since the current and vector potential are in the θ direction.
Hence, one can write,

$$\vec{V} = V \hat{Z} \quad (B.9)$$

$$\vec{A} = A \hat{\theta} \quad (B.10)$$

$$\vec{J} = J \hat{\theta} \quad (B.11)$$

where the caret denotes a unit vector and Equation (B.8), expressed in cylindrical
coordinates becomes,

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial A}{\partial r} \right) + \frac{\partial^2 A}{\partial Z^2} - \mu \sigma V \frac{\partial A}{\partial Z}$$

$$= \left(\frac{1}{r^2} + i \omega \mu \sigma - \omega^2 \mu \epsilon \right) A - \mu J. \quad (B.11)$$

The assumption of a single loop coil of radius a at $Z = Z_0$ leads to,

$$J = J_0 \, \delta (r-a) \, \delta (Z-Z_0). \quad (B.12)$$

This choice means that the solution for A is the Green function and can be
used to create the general solution. Throughout, the assumption of
invariance with respect to θ has been tacitly assumed. Define A as the
product of two functions,

$$A (r, Z) \triangleq \phi (r) \psi (Z). \quad (B.13)$$

The resulting equations for ϕ and ψ can be obtained by inserting Equation (B.13) in Equation (B.11).

$$\frac{1}{\phi(r)\,r}\,\frac{\phi\,d}{dr}\left[r\,\frac{d}{dr}(r)\right] - \frac{1}{r^2} - \omega\,\mu\,(i\,\sigma - \omega\,\varepsilon) \qquad (B.14)$$

$$= -\frac{1}{\psi(z)}\left[\frac{d^2\,\psi(z)}{dz^2} - \mu\,\sigma\,v\,\frac{d\,\psi\,(z)}{dz}\right]$$

$$-\frac{\mu\quad J_0}{4(z)\quad(r)}\,\delta\,(r-a)\,\delta\,(z-z_0)$$

In order to solve Equation (B.14), it is necessary to consider the solution for $r > a$ (outside at the coil) as well as for $z > z_0$ and $z < z_0$. For these cases, the two components can be separated and written as,

$$\frac{d^2\,\psi}{dz^2} - \mu\,\sigma\,v\,\frac{d\,\psi}{dz} = C\,\psi \qquad (B.15)$$

$$\frac{1}{r}\,\frac{d}{dr}\left(r\,\frac{d\phi}{dr}\right) - \frac{\phi}{r^2} = [\,C + \omega\,\mu\,(i\,\sigma - \omega\,\varepsilon)\,]\,\phi \qquad (B.16)$$

Because these are second order differential equations each possesses two solutions. The choice of solution is dictated by the boundary conditions. The solution of Equation (B.16) is a linear combination of first-order modified Bessel functions, however only K_1 survives because I_1 is irregular at infinity. Equation (B.15) is solved by making the ansatz that

$$\psi = e^{-imz} \qquad (B.17)$$

which results in

$$M^2 - i\,\sigma\,\mu\,v\,M + C = 0 \qquad (B.18)$$

Choose C to simplify Equation (B.18),

$$C = (\alpha^2 + i\,\sigma\,\mu\,v\,\alpha) \qquad (B.19)$$

which results in one solution, $M = -\alpha$. The second solution is obtained from,

$$M - \alpha - i \sigma \mu v = 0 \qquad\qquad\qquad (B.20)$$

Again applying the appropriate boundary conditions, ψ becomes

$$\psi(z) = \psi_0 \, e^{\, i\alpha \, (z-z_0)} \qquad\qquad z < z_0 \qquad (B.21)$$

$$\psi(z) = \psi_0 \, e^{\, -i\alpha \, (z-z_0)} \; e^{\sigma\mu v \, (z-z_0)} \qquad\qquad (B.22)$$
$$z > z_0$$

This two solution match at $z = z_0$ as they should both remain finite in their respective regimes and the jump in the first derivative at $z = z_0$ is $\sigma \mu v \, \psi_0$ as it should be.

The choice of C given by Equation (B.19), results in a solution for ψ of,

$$\psi(r) = \psi_0 \cdot K_1 \, (\alpha^1 r) \qquad\qquad\qquad (B.22)$$

where

α^1 is given by,

$$\alpha^1 \triangleq \sqrt{\alpha^2 + \mu \, (i \, \sigma \, v \, \alpha + \omega \, (i \, \sigma - \omega \, \varepsilon))} \qquad (B.23)$$

The final solution is obtained by integrating over the arbitrary parameter σ,

$$A(r, z) = A_0 \int_{-\infty}^{\infty} K_1 \, (\alpha^1 \, r) \, e^{\, i\alpha \, (z-z_0)} \, d\alpha \quad z \geq z_0 \qquad (B.24)$$

$$A(r, z) = A_0 e^{\sigma\mu v \, (z-z_0)} \int_{-\infty}^{\infty} K_1 \, (\alpha^1 \, r) \, e^{\, -i\alpha \, (z-z_0)} \, d\alpha \quad z < z_0 \qquad (B.25)$$

Where A_o is an arbitrary normalization for A.

The voltage induced in the secondary coils is given by,

$$V = \oint E \cdot ds = 2 \pi b E_\theta = -2 \pi b \frac{\partial A}{\partial t} = -2 \pi bi\omega a \qquad (B.26)$$

where b is the radius of the secondary loops (b > a). Thus the EMF in the loop which is upstream of the primary ($z = z_1$) is given by,

$$V_{us} = -i \cdot b \, \bar{A} \, \omega \, e^{\sigma\mu v (z_1 - z_0)} \int_{-\infty}^{\infty} K_1 (\alpha' r) e^{-i\sigma (z_1 - z_0)} \qquad (B.27)$$

Where $\bar{A}$ is a new normalization. The downstream loop ($z = z_2$) sees an EMF of,

$$V_{ds} = -i \cdot b \, \bar{A} \, \omega \int_{-\infty}^{\infty} K_1 (\alpha' r) e^{i\sigma (z_2 - z_0)} \, d\alpha \quad , \qquad (B.28)$$

When $\sigma\mu v (z_1 - z_0)$ is not large and when $z_1 - z_0 = z_0 - z_2$. These two potentials can be related approximately by,

$$V_{us} \overset{\sim}{=} V_{ds} [1 + \sigma \mu v (z_1 - z_0)] \qquad (B.29)$$

Hence, in the limit that σ and μ are constant and the expansion is valid, the difference of V_{us} and V_{ds} is proportional to the sodium velocity, v,

$$V_{ds} - V_{us} = V_{ds} (z_0 - z_1) \sigma \mu v \qquad (B.30)$$

Fluctuations in V_{ds}, σ, μ and nonlinearities in V_{us} can lead to significant temperature dependent effects. (V_{ds} is not independent of V since it appears in α'.) Self-compensating flowmeters use the difference and the sum to eliminate V_{ds}. Thus they measure R, defined as the difference of the two potentials over the sum, which reduces to,

$$R = \frac{1 - e^{\sigma\mu v (z_1 - z_0)}}{1 + e^{\sigma\mu v (z_1 - z_0)}} \simeq \sigma\mu v (z_0 - z_1)/2 \qquad (B.31)$$

under the assumption of $\sigma\mu v (z_1 - z_0)$ being small. This self-compensated flowmeter sees a more linear relationship between R and flow.

In order to avoid the approximation of a small argument for the exponential, it is possible to examine the natural logarithm of the ratio of V_{ds} to V_{us},

$$\ln (V_{ds}/V_{us}) = \sigma\mu v (z_0 - z_1) \tag{B.32}$$

Pure temperature variations affect σ and μ. Because of these effects, one can see that variations in $\sigma\mu v$ and in α' (see Equation (B.23) will have much less effect on Equations (B.31) and (B.32) than on Equation (B.30).

APPENDIX C

This appendix consists of the relevant procedures and standards for the PSD electronics:

- Setup and calibration procedure for the PAR Model 128A and 5204 Lock-In Amplifiers.

- ECFM Lock-In Amplifier System Attenuator Design.

- Field Calibration and Setup Procedure for the ECFM - Phase Sensitive Detectors.

SET UP AND CALIBRATION PROCEDURE FOR THE
PAR MODEL 128A AND 5204 LOCK-IN AMPLIFIERS

J. L. Stringer
November 21, 1978

I.   <u>GENERAL</u>

These procedures cover the modifications, operational checks, and calibration for the PAR Models 128A/98 and the 5204/98 Lock-In Amplifiers. In all cases the amplifiers are new "just received" equipment whose proper operation and specific function calibration must be performed before the equipment is installed at FFTF.

II.   <u>EQUIPMENT MODIFICATION</u>

A.   <u>Modifications for both 128A and 5204</u>

1. Install the rack mounting brackets on all instruments using the 07-5204-35 kit on the 5204 and brackets supplied by J. L. Stringer for the 128A's.

2. Install any hardware required to support the rear of the instrument cabinet required for mounting in the FFTF cabinets.

3. Remove the rubber feet from the bottom of all instrument chassis.

B.   <u>For only the 128A</u>

Install a BNC connector in one of the rear chassis holes (selection TBD by J. L. Stringer) and connect it in parallel with the OUT connector on the front panel.

C.   <u>For only the 5204</u>

Install a locking collet on the "Tuned Amplifier" frequency selecting patentiometer shaft (rear panel). Lock collet will be supplied by J. L. Stringer.

III. INITIAL OPERATION CHECK

Both 5204 and 128A model lock-in amplifiers were purchased with only the "TUNED AMPLIFIER OPTION" no other options are installed.

A. For the 128A

Perform the instrumentation of the Section II initial checks section of the Operation and Maintenance Manual (OMM) with the following selections:

Paragraph 3.3 (3)   Set tracking rate switch to FAST.

3.3 (4)   1kHz was the ordered frequency.

3.3 (5)   Skip Option not installed.

3.3 (8)   These units were to have their gain trimmed at the factory for a full scale indication on the 25 mV range, thus, the error may be (1% to 2%) larger than expected by this instruction.

B. For the 5204

Perform the instructions of Section III of the OMM "Initial Checks" with the following selections:

° Perform only the paragraph 3.3 and 3.4 instructions.

° Only the Tuned Amplifier option is installed.

IV. CALIBRATION

The calibration of the two lock-in amplifier models shall be performed only after the Initial Operation checks of the Section III have been completed and shall be performed in the sequence listed in this section.

1. Test Equipment

(a)   H/P model 650B Sinewave Oscillator or equivalent with an adjustable amplitude and frequency with a 50 ohm output impedance.

(b)   50 ohm or 75 ohm switch selected attenuator which can provide attenuation down to a 1db resolution.

(c) Digital voltmeter such as a Fluke model 3200A or equivalent.

(d) Two BNC shorting plugs.

(e) Interconnecting cables.

(f) Frequency counter with an accuracy at 1 kHz to ±0.5 Hz or better.

(g) General purpose oscilloscope.

2. **Preliminary Steps**

(a) Remove the top cover, which is secued by four screws, two on each side.

(b) Check and, if necessary, adjust the mechanical zero of the panel meters. Then plug in the Model 128A or 5204 turn on the power and allow a fifteen minute warm up minimum.

(c) Connect the BNC shorting plugs to both inputs.

3. **Procedure for the 128A**

Some of the instructions in this procedure will refer to the OMM for the 128A amplifier.

3.1 **Power Supply Check**

On the power supply board, check for: (a) +15.5V ±0.1V at the positive end of capacitor C309, (b) -15.5V ±0.2V at the negative end of capacitor C310, and (c) +5V ±0.2V at the positive end of capcitor C312. If these voltages are not within the allowed variation notify J. L. Stringer (2-3418) before continuing.

Reference the OMM Section 6.4 and schematic on page VII-11.

3.2 Amplifier Control Settings:

Input Selector Switch: A
Sensitivity: 25 mV
Lo Pass Switch: 10 kHz
Hi Pass Switch: 50 kHz
Phase
        Switch: 270°
         Dial: 90° (9:00)
Reference Mode Switch: f (fund.)
Time Constant: 0.3 sec.
DC Prefilter: OUT
Zero Offset
        Switch: OFF (center position)
         Dial: 0.00 (fully counter clockwise)
Fast/Slow Switches (located on Ref. board): FAST

3.3 Test Configuration (See Figure 1).

3.3.1 Connect the test system together as shown in Figure 1 except that one digital voltmeter (DVM) can be used for all measurement. Connection points should be provided in the test set up to allow quick connection of the DVM from point-to-point (BNC connectors)

3.3.2 Set the oscillator to 1 kHz ± 0.5 Hz with a nominal amplitude of 0.5 Vac Rms. (should always be within ±5%).

3.3.3 Set the attenuator output to give 25 mVac ± 0.2% (requires approximately 26 db of attenuation) indication on the digital voltmeter.

3.4 Set Up the Tuned Amplifier and Lock-In Amplifier Gain.

3.4.1 Tuned Amplifier Switch Settings (Amplifier Board)

        (a) Selective/Flat Switch: Selective
        (b) Notch/Bandpass Switch: Notch

Refer to OMM page IV-13, Figure IV-14.

3.4.2 Connect the oscilloscope to the Sig. Mon. BNC connector on the rear panel and set the oscilloscope to view a steady 1 kHz waveform.

3.4.3 Alternately adjust the tuned amplifier Freq. Adj. potentiometer (rear panel hole) and the NULL potentiometer (side wall hole) to obtain a minimum amplitude signal on the oscilloscope. These controls interact so several iterations will be necessary to obtain the best minimum.

NOTE: These controls should have been preset by the vendor for 1 kHz.

3.4.4 Set the Notch/Bandpass switch to Bandpass.

3.4.5 Adjust the Phase Dial (and Phase Switch if required) for peak (maximum) output voltage (Vdc) on the panel meter and Digital Voltmeter.

3.4.6 Adjust the Model 128A GAIN CAL. trim poteniometer, R143, for exactly +1.000 Vdc $\pm$ 0.0001 Vdc on the Digital Voltmeter. Refer to OMM page V-2, Figure V-1 for the location of R143.

3.5 Sensitivity Range Calibration

This step determines the gain sensitivities of the adjacent attenuator ranges (250 mV, 100 mV, 10 mV and 2.5 mV).

3.5.1 Set the Sensitivity Switch to the 250 mV position.

3.5.2 Set the attenuator for a nominal 6 db of attenuation and adjust the oscillator amplitude to give a reading of 250 mV $\pm$ 0.05 mV at the attenuator output.

3.5.3 Read the Model 128A output (Vdc) on the Digital Voltmeter and record this reading versus the input voltage. The output voltage should be 1.00 Vdc ± 0.02 Vdc. If not call to the attention of J. L. Stringer 2-3418.

3.5.4 Set the attenuator for a nominal 14 db of attenuation and adjust the oscillator amplitude to give a reading of 100 mV ± 0.05 mV.

3.5.5 Set the amplifier sensitivity to 100 mV and record the 128A Output voltage reading on the Digital Voltmeter versus the input voltage. Voltage should be 1.00 Vdc ± 0.02 Vdc.

3.5.6 Repeat steps 3.5.4 and 3.5.5 for the following sensitivity switch settings and inputs.

Sensitivity	Input	Attenuator
10 mV	10 mV ± 0.5 mV	34 db
2.5 mV	2.5 mV ± 0.5 mV	46 db

3.5.7 Return the Sensitivity switch to 25 mV.

This completes the calibration of the 128A Lock-In Amplifier.

4.0 Procedure for the 5204

Some of the instruction in this procedure will refer to the OMM for the 5204 amplifier.

4.1 Power Supply Check (DO NOT ADJUST)

In the OMM on Page VII-15 the circuit diagram 11092 and circuit board layout are shown for the power supply boards. Refer to these diagrams for the measurement locations.

4.1.1 Connect a Digital Voltmeter (DVM) across diode CR306 and verify a reading of + 15.00 Vdc ± 0.04 Vdc.

4.1.2 Connect the DVM across diode CR307 and verify a reading of
- 15.00 Vdc $\pm$ 0.04 Vdc.

4.1.3 Connect the DVM across capacitor C304 and verify + 5.0 Vdc
$\pm$ 0.2 Vdc.

NOTE: If any of the voltages fall outside the limits call
J. L. Stringer (2-3418) for further Instruction and
stop the calibration.

4.2 Amplifier Control Settings

4.2.1 Front Panel:

Mode: Notch
Float/Ground: Float
A/A-B: A
Sensitivity: 25 mV
High Pass: 50 Hz
Low Pass: 10 kHz
Phase (Reference)
    Push Button Depressed: 270°
    Dial: 90° (9:00)
    f/2f: f
    EXT/INT: EXT
In-Phase
    Zero Offset Dial: Fully CCW
    Zero Offset PB: OFF (Both released)
    DC Prefilter PB: 0.1 Sec (depressed)
    Output Expand PB: X1 (depressed)
    Time Constant: 0.3 sec.
Meter PB
    In-Phase: depressed
    Quadrature: depressed

Quadrature

    Zero Offset dial: Fully CCW

    Zero Offset PB: Off (both released)

    DC Prefilter PB: 0.1 sec (depressed)

    Output Expand PB: X1 (depressed)

    Time Constant: 0.3 sec.

4.2.2 Rear Panel

Tuned Amplifier

    Range Switch: 1 kHz

    Multiplier: Near 1 (subject to final tuning)

4.3 Test Configuration (See Figure 1)

4.3.1 Repeat Steps 3.3.1 through 3.3.3

4.3.2 Connect a DVM to the In Phase (I) Output BNC.

4.4 Set up the Tuned Amplifier and Lock-In Amplifier Gain

4.4.1 Adjust the Tuned Amplifier Range and Multiplier controls set up in 4.2.2 to achieve a decreased level on the In Phase meter and DVM.

4.4.2 Alternately adjust the Multiplier and Notch Depth controls to get the smallest indication on the In Phase meter. Increase the measurement sensitivity by first operating the output expansion PB to X10 then to X100 and finally move the Sensitivity switch to 10 mV, 2.5 mV, etc., until no further decrease can be achieved or the overload light becomes illuminated.

4.4.3 Return the Sensitivity switch to 25 mV and the Output Expand PB to X1 (depressed).

4.4.4 Depress the Bandpass pushbutton the In Phase (I) meter should indicate near full scale and the Quadrature (Q) meter should indicate near zero.

4.4.5 Move the phase dial to get the best zero on the Q meter and a maximum reading on the I meter and DVM.

> NOTE: Use the Q meter Output Expand ranges of X10 and X100 to complete the final adjustment, then return the Output Expand to X1.

4.4.6 Referring to pages VII-12 and VII-13 for the schematic and parts location on the Signal Amplifier Board, adjust R143 Gain Adj. potentiometer to give an output on the I meter of 1.000 Vdc ± .0001 Vdc.

4.4.7 Depress the 180° phase pushbutton and change the DVM to the Q meter output. Verify that the Q output voltage is 1.000 Vdc ± 0.0005 Vdc.

4.4.8 Return the DVM to the I meter output and depress the 270° Phase pushbutton.

This completes setting up the gain of the 5204 for the 25 mV sensitivity range to an accuracy ± 0.2%.

4.5 Sensitivity Range Calibration

This step determines the relative gain sensitivities of the adjacent attenuator ranges (250 mV, 100 mV, 10 mV and 2.5 mV).

4.5.1 Set the Sensitivity switch to the 250 mV position.

4.5.2 Set the attenuator for a nominal 6 db of attenuation and adjust (trim) the oscillator amplitude to give a reading of 250 mV ± 0.05 mV at the attenuator output.

4.5.3 Read the I meter output (Vdc) on the DVM and record the reading versus the input voltage. The output voltage should be within 1.000 Vdc ± 0.020 Vdc.

4.5.4   Set the attenuator for a nominal 14 db of attenuation and
trim the oscillator amplitude to give a reading of 100 mV
± 0.05 mV.

4.5.5   Set the 5204 sensitivity switch to 100 mV and read the I meter
output (Vdc) on the DVM and record this reading versus the input
voltage. This voltage should be within the range of 1.000
Vdc ± 0.020 Vdc.

4.5.6   Repeat steps 4.5.4 and 4.5.5 for the following sensitivity
switch settings and inputs.

Sensitivity	Input	Attenuator
10 mV	10 mV ± .05 mV	34 db
2.5 mV	2.5 mV ± .05 mV	46 db

4.5.7   Return the Sensitivity switch to 25 mV.

This completes the calibration of the 5204 Lock-In Amplifier.

FREQUENCY
COUNTER
ACCURACY:
1000. H_z ± 0.1 H_z

DIGITAL
VOLTMETER
ACCURACY:
± 0.5% AT 1k H_z

SINEWAVE
OSCILLATOR
Zo = 50Ω
0.5 Vac ± 5% 0.1k H_z + 0.5 H_z

AMPL. SENS. RANGE	ATTEN. SETTING (db)
0.250	6
0.100	14
0.025	26
0.010	34
0.0025	46

DIGITAL VOLTMETER
ACCURACY - @25 mV,
1k H_z -± 0.2%

STEP
ATTENUATOR

● SIG. INPUT   ○ REF. INPUT
P A R
128A OR 5204
LOCK-IN AMPLIFIER   Q● $\left(\begin{array}{c}5204\\ONLY\end{array}\right)$
I ●

DIGITAL VOLTMETER
VDC ACCURACY
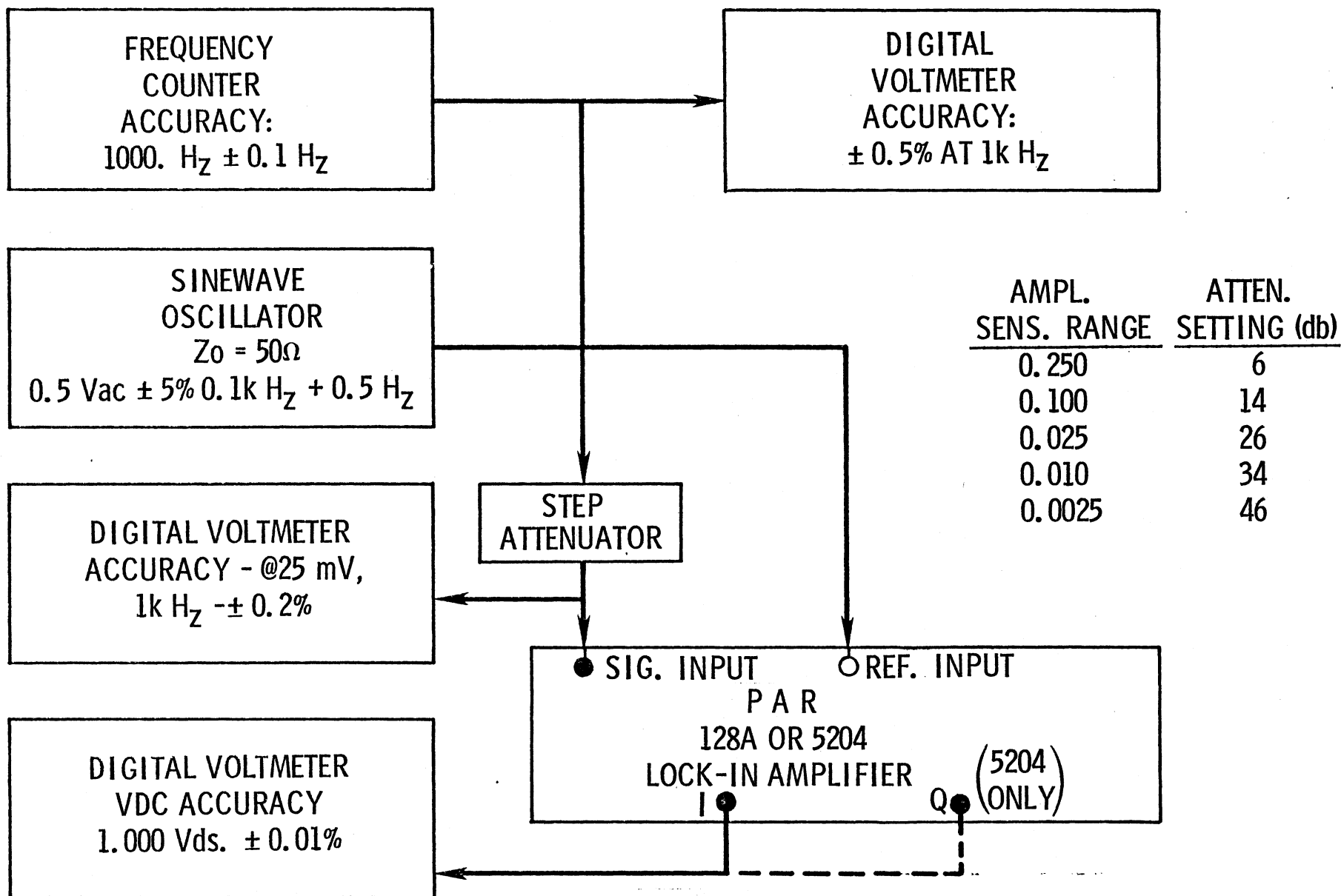1.000 Vds. ± 0.01%

FIGURE 1   HEDL 7904-152.1

SYSTEM ATTENUATOR
ECFM LOCK-IN AMPLIFIER DESIGN

J. L. Stringer
December 4, 1978

I. **DESIGN DECISIONS:**

1. Since the new PAR lock-in amplifiers have a 25 mV sensitivity range rather than 20 mV and a 1.000 Vdc output rather than 10.00 Vdc, it was decided to design the attenuator to match the 25 mV input signal, but allow the factor of 10 reduction in the output (no choice).

2. The gain errors from the original calibration of the ECFM's for the lock-in amplifier/attenuator combinations for each chanel is + 1.1%, (-) .79%. The gain error between channels (Attenuator/Amplifier No. 1; Attenuator/Amplifier No. 2) is (+) 1.3%, (-) .78%.

3. The tolerance of the 10k ohm buffer resistor in the FFTF-ECFM-SC/CR module is ± 5%.

4. From these data the total variation which must be accomodated by the attenuator is:

$$\pm\ 5\%,\ \pm\ 1.3\%,\ \pm\ 1.1\%$$

Linearly combining these variations gives

$$\pm\ 7.4\%$$

as the variation range for the adjustment, and is the design goal.

5. A variation of ± 10% was used to make the initial design choices.

6. The final design choices were made for the components available from Rockwell Stores.

7. A circuit design was chosen to make the attenuator input and output impedances nearly contant near the values used for the calibration attenuators.

8. The circuit ground will be carried separate from chassis ground to be consistant with the grounding practices in use at FFTF and the floating input on the PAR amplifiers.

II. CIRCUIT DESIGN (Nominal Values)
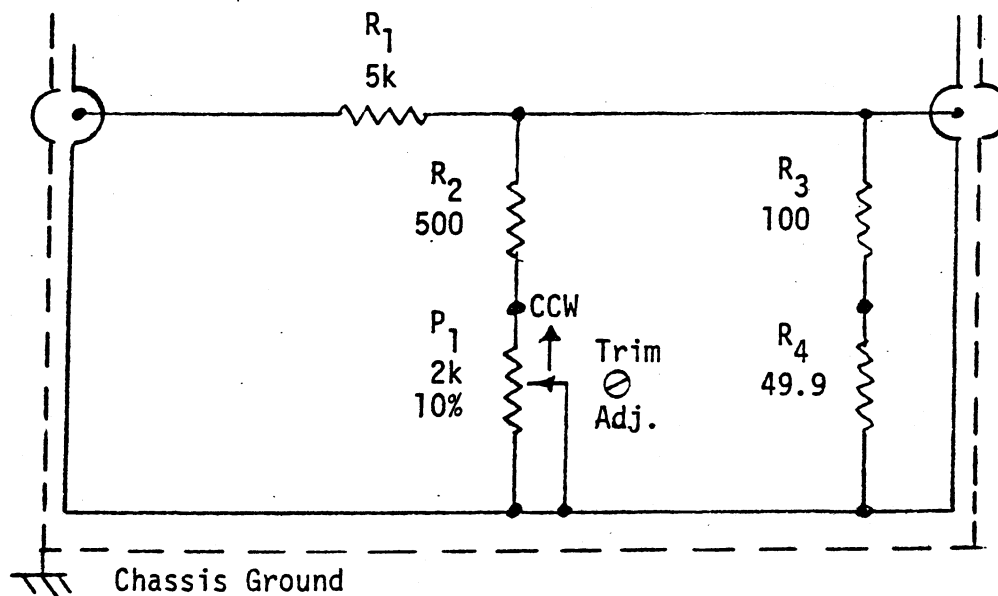
Chassis Ground
All resistor values in ohm
All resistors are 1/4 w, 1%, metal film
Potentionmeter is cermet, 20 turn

The nominal setting of P_1 to give an output of 0.0250 volts for a 1.000 V input is $P_{1,0} = 382$ ohms.

FIGURE 1

The equation for the nominal attenuator is:

$$\frac{Vo}{Vin} = n = \frac{\dfrac{R_s (R_2 + P_1)}{R_s + R_2 + P_1}}{\dfrac{R_s (R_2 + P_1)}{R_s + R_2 + P_1} - R_1}$$

where: $R_s = R_3 + R_4$

Evaluating with the nominal values gives

$$R_s = R_3 + R_4 = 100 + 50 = 150 \ \Omega$$

and

$$R_2 + P_1 = 500 + 382 = 882 \ \Omega$$

and

$$\frac{R_s(R_2 + P_1)}{R_s + R_2 + P_1} = \frac{150(500 + 382)}{150 + 500 + 382} = 128.2 \ \Omega$$

then

$$\frac{V_o}{V_{in}} = \eta = \frac{128.2}{5000 + 128.2} = .0250$$

This result can be interpreted to mean, when 1 volt is applied to the attenuator input .0250 volts is applied to the amplifier input.

The nominal input impedance of the attenuator is

$$5000 + 128.2 = 5.1282k \text{ ohms} \pm 1\%$$

The ECFM calibration attenuator nominal input impedance was 5.10k ohms $\pm$ 1%.

The nominal output impedance of this attenuator design is

$$\frac{(128.2)(5000)}{128.2 + 5000} = 125 \text{ ohms} \pm 1\%$$

The nominal output of the ECFM calibration attenuator was

$$\frac{(100)(5000)}{100 + 5000} = 98.0 \text{ ohms} \pm 1\%.$$

CIRCUIT VARIATION RANGE

Note the following circuit components and their tolerances.

R_1 = 5000 Ω, ± 1%

R_2 = 500 Ω, ± 1%

R_3 = 100 Ω, ± 1%

R_4 = 50 Ω, ± 1%

P_1 = 2000 Ω ± 10% and ∿ 2 Ω residual resistance

$R_3 + R_4$ = 150 Ω, ± 1%

The attenuator circuit can be redrawn as

FIGURE 2

Variation Analysis:

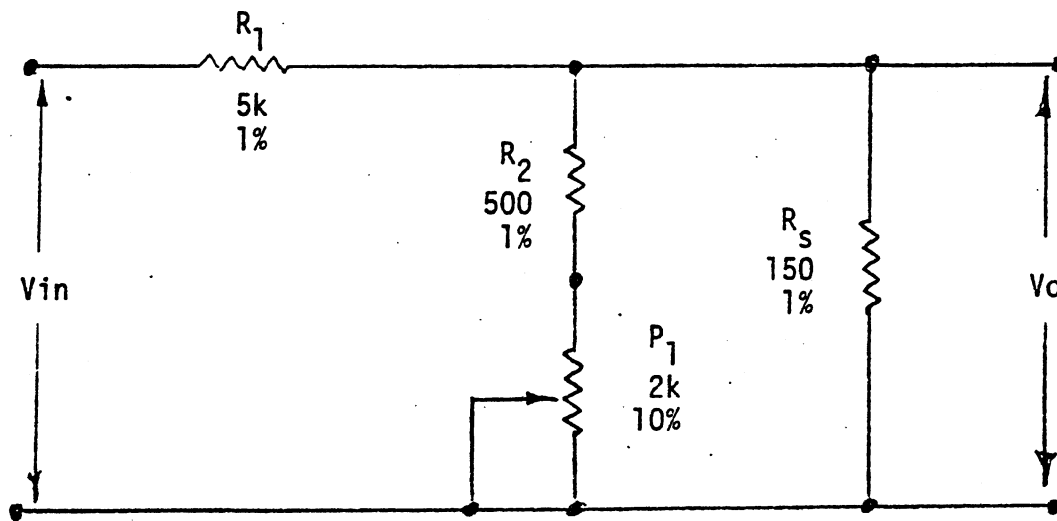The various circuit element combinations will be calculated for the maximum and minimum variation around the nominal attenuator value of 0.0250.

The minimum output voltage of the R_1, R_s circuit branch ocurrs when

R_s = 148.5 (- 1%) ohm

R_1 = 5050 (+ 1%) ohms

The maximum output voltage of the R_1, R_s circuit branch ocurrs when

R_s = 151.5 (+ 1%) ohms

R_1 = 4950 (- 1%) ohms.

The R_2, P_1 circuit branch just modifies the R_s circuit value, thus, when the R_2, P_1 circuit has its maximum value the parallel combination of R_s and $(R_2 + P_1)$ will have its maximum value, and when $(R_2 + P_1)$ has its minimum value the parallel combination of R_s and $(R_2 + P_1)$ will have its minimum value.

Thus, only four cases need to be calculated. These are:

CASE I:

$R_s = 148.5 \, \Omega$ $\eta(R_1, R_s) = $ minimum

$R_1 = 5050 \, \Omega$ $R_2 + P_1 = $ minimum (Adj. High)

$R_2 = 495 \, \Omega$

$P_1 = 1800 \, \Omega$

$$R_p = \frac{R_s \, (R_2 + P_1)}{R_s + R_2 + P_1} = \frac{148.5 \, (2295)}{148.5 + 2295} = 139.5 \, \Omega$$

$$\frac{V_o}{V_{in}} = \frac{R_p}{R_1 + R_p} = \frac{139.}{139.5 + 5050}$$

Minimum (+) variation %

$$\frac{.02688 - .02500}{.02500} \times 100 = +7.52\%$$

CASE II:

$R_s = 151.5$ $\eta(R_1, R_s) = $ maximum

$R_1 = 4950$ $R_2 + P_1 = $ maximum (Adj. High)

$R_2 = 505$

$P_1 = 2200$

$$R_p = \frac{R_s \, (R_2 + P_1)}{R_s + R_2 + P_1} = \frac{151.5 \, (505 + 2200)}{151.5 + 505 + 2200} = 143.5 \, \Omega$$

$$\frac{V_o}{V_{in}} = \frac{R_p}{R_1 + R_p} = \frac{143.5}{4950 + 143.5} = .02817$$

Max (+) variation %

$$\frac{.02817 - .02500}{.02500} \times 100 = + 12.7\%$$

CASE III:

$R_s = 148.5$ $n (R_1, R_s) = minimum$

$R_1 = 5050$ $R_2 + P_1 = minimum \text{ (Adj. High)}$

$R_2 = 495$

$P_1 = 2$

$R_p = \dfrac{R_s (R_2 + P_1)}{R_s + R_2 + P_1} = 114.3 \ \Omega$

$\dfrac{Vo}{Vin} = \dfrac{R_p}{R_1 + R_p} = \dfrac{114.3}{5050 + 114.3} = .02213$

Maximum (-) variation %

$$\dfrac{.02213 - .02500}{.02500} \times 100 = -11.48\%$$

CASE IV:

$R_s = 151.5$ $n (R_1, R_s) = maximum$

$R_1 = 4950$ $R_2 + P_1 = maximum \text{ (Adj. High)}$

$R_2 = 505$

$P_1 = 2$

$R_p = \dfrac{R_s (R_2 + P_1)}{R_s + R_2 + P_1} = 116.5$

$\dfrac{Vo}{Vin} = \dfrac{R_p}{R_1 + R_p} = \dfrac{116.6}{4950 + 116.6} = .0230$

Minimum (-) variation %

$$\dfrac{.0230 - .0250}{.0250} \times 100 = - 8.0\%$$

Thus, the minimum positive attenuation variation value is + 7.52% while minimum negative attenuation variation value is - 8.0%.

SUMMARY

The positive and negative adjustment limits with the component tolerance chosen bracket the expected ± 7.4% system variation and should provide the long term stability that is necessary for the system operation.

FIELD CALIBRATION
AND SET UP PROCEDURE FOR
THE ECFM - PHASE SENSITIVE DETECTORS

J. L. Stringer
December 13, 1978

GENERAL

This procedure is focused on setting the PSD external attenuator to the TTL calibration gain requirements for the specific ECFM sensor being calibrated, and to adjust the phase space position of the in-phase PSD component to coincide with the sensor's flow vector.

PROCEDURE

1.0 Preliminary

1.1 Equipment Required

    a. Interconnecting cables and adapters.

    b. FLUKE - DVM in the ECFM test section for Vac measurements.

    c. Hand calculator SR-50, TI-30 or equivalent.

    d. Portable DVM with resolution and accuracy to 1 mVdc on a 1-2 Vdc full scale range.

1.2 Equipment Warm Up

The equipment shall have been turned on for 30 minutes following the last 2 to 3 minute duration without power prior to performing the procedural steps.

The attenuator calibration procedures shall be performed without power interruption.

1.3 Assumptions

1.3.1 This procedure assumes that the Model 128A's and 5204[1] have completed the gain calibrations in the Standards Laboratory[2], have been installed in the appropriate ECFM cabinets at FFTF and[3]

that the systems are interconnected per the connection diagram of Figure 1.

1.3.2 These procedures can be performed only following compilation and certification of FTRTA - ECFM - SC/CR module gain adjustment to a procedure equivalent to that of paragraph 5.4.1.4 (Gain Adjust) page 59 of OHM-092-00-002, Vol. 1.

1.4 Initial Control Settings

a. Model 128A

Input Selector Switch: A
Sensitivity: 25 millivolts
Lo Pass Switch: 10 kHz
Hi Pass Switch: 50 Hz
Phase:
       Switch: 270°
       Dial: 90° (9:00)
Reference Model Switch: f (fundamental)
Time Constant: 3.0 sec.
DC Prefilter: Out
Zero Offset:
       Switch: Off (Center Position)
       Dial: 0.00 (full ccw)

b. Model 5204
Front Panel

Mode: Bandpass (PB depressed)
Float/Ground: Float (PB depressed)
A/A-B: A (PB depressed)
Sensitivity: 25 mV
High Pass: 50 Hz (PB depressed)
Low Pass: 10 kHz (PB depressed)
Phase (Reference)
       PB: 270° (depressed)
       Dial: 90° (9:00)

Mode (reference)

    2f/f: f (PB released)

    Ext/Int: Ext (PB depressed)

In-Phase

    Zero Offset Dial: fully ccw

    Zero Offset PB: Off (both released)

    DC Prefilter PB: Off (both released)

    Output Expand PB: X1 (depressed)

    Time Constant: 3.0 sec.

In-Phase Meter

    In-Phase PB: Depressed

Quadrature Meter

    Quadrature PB: Depressed

Quadrature

    Zero Offset Dial: Full ccw

    Zero Offset PB: Off (both released)

    DC Prefilter PB: Off (both released)

    Output Expand PB: X1 (depressed)

    Time Constant: 3.0 seconds

Rear Panel

Tuned Amplifier Range Switch: 1kHz

2.0 Calibrate the PSD Attenuator/Lock-In Amplifier

2.1 Verify that the flowsensor is installed and connected to the correct SC/CR module position.

2.2 Verify that the PSD system is interconnected per Figure 1 and that power has been turned on for at least 30 minutes.

2.3 Verify that the ECFM-SC/CR module/flowsensor have been energized for at least 30 minutes, and has been calibrated to the requirements of paragraph 1.3.2.

2.4 Verify that the Lock-In Amplifier controls are setup per paragraph 1.4 for the appropriate Lock-In module.

2.5 Verify that the REF UNLOCK light in the Reference Section of the Lock-In Amplifier is <u>not</u> illuminated.

2.6 Connect the Test and Readout (T&R) cable between the Module Test Cable connector J204 on the Test/Cal Station and the Selected SC/CR module test connector.

2.7 With the T&R cable attached, remove the SC/CR module from its operating position and insert it fully into the Test Station test slot.

2.8 Set Test/Cal Station controls as follows:

Control/Switch	Position
Unit Test Select	SC/CR
SC/CR TEST SEL	AMPL SEC
SC TEST FUNCTION	GAIN
AMPL CONTROL	400 (4.00 mV)
DMM	10 V-AC

2.9 Verify that the DMM reads $\pm$ 3.03 Vac ($\pm$ 1%) with the cable to J3 SC/CR disconnected. Record this reading 3.   Vac.

2.10 Reconnect the cable to J3 (AMPL SEC) on the SC/CR module and note that the DMM reading drops to 1.02 Vdc $\pm$ .07 Vdc.

2.11 While monitoring the OUT DC voltage with portable DVM (2 Vdc max, 100% overage of output) adjust the dial phase control and the course switch or pushbutton controls to achieve a maximum in-phase output voltage and/or a zero quadrature voltage.

NOTE: The quadrature output for the Model 5204 is read from the Q output connector directly. For the Model 128A change the course phase dial by 90° leading or lagging and read the DVM output while adjusting the phase dial to get zero Vdc.

2.12 Return the Lock-In Amplifier course phase controls to display the maximum in-phase signal. Record the final phase readings. Switch _____, Dial _____.

2.13 Adjust the associated PSD attenuator section, adjust potentiometer to get a Vdc output from the Lock-In Amplifier determined in the following manner.

Multiply the voltage reading obtained in step 2.9 by the gain number associated with the ECFM probe being calibrated listed in the gain number column of Table I.

For example:

If the step 2.9 voltage is 3.04 and the Gain Number from Table I is 0.302 the Vdc output voltage will be:

3.04 x .302 = 0.918 Vdc

2.14 When the Lock-In Amplifier reads the calculated output voltage stop the adjustment, remove the adjustment tool, and cover the adjustment hole with an appropriate label which includes the ECFM No., and SC/CR No., serial number of associated Lock-In Amplifier, and the final output voltage measured.

2.15 Return the SC/CR module to its correct panel location and disconnect the T&R cable.

2.16 This completes the PSD attenuator calibration for this channel.

2.17 Continue to repeat the procedure steps until eleven PSD attenuator sections are adjusted.

2.18 Proceed to setting up the PSD detector in the direction of the flow vector section 3.0.

3.0 Lock-In Amplifier Phase Adjustment For Flow Measurement

3.1 Verify that the flowsensor is connected to the correct SC/CR module position, PSD attenuator and Lock-In Amplifier.

3.2 Verify that the PSD system is connected according to Figure 1.

3.3 Verify that power has been applied to both the SC/CR module and the Lock-In Amplifier for at least 30 minutes.

3.4 Verify that section 2.0 of this procedure has been completed for this PSD system.

3.5 Verify that the Lock-In Amplifier controls are set up per paragraph 1.4 for the appropriate Lock-In module.

3.6 Verify that the REF UNLOCK light in the reference section of the Lock-In Amplifier is <u>not</u> illuminated.

3.7 Set up the Switch/Pushbutton and dial phase settings determined in the TTL calibration for the ECFM selected. These settings are listed in Table I for the selected ECFM.

3.8 Set the reactor sodium flow past the ECFM's to zero (all pumps off).

3.9 Observe the in-phase (IP) and quadrature (QP) ($\pm$ 90°) signal magnitude and polarities, with the portable DVM, and adjust the phase switch and dial settings to get the magnitudes and polarities for IP and QP listed in Table I.

3.10 Record these magnitudes and phase settings in Section I of Addendum I.

3.11 Repeat the procedure step 3.1 through 3.10 for all the Lock-In Amplifier systems being set up.

3.12 Increase the flow by operating two or three (3 preferred) of the primary system pony motors.

3.13 Without performing any adjustments on the phase of the Lock-In Amplifier, record the IP and QP output voltages in Section I of Addendum I for the maximum flow.

NOTE: This procedure may not be adequate for those flowsensors positioned over the reflector position. A procedure addition may result from the field measurements being made.

3.14 Following completing steps 3.7 through 3.13 for all amplifiers transfer the voltage values recorded in Section I of Addendum I to the l_1, l_2, q_1, and q_2 values of Addendum II according to the following:

l_1 = IP at 3 pony motor flow, 400°F.

q_1 = QP at 3 pony motor flow, 400°F.

l_2 = IP at zero flow, 400°F.

q_2 = QP at zero flow, 400°F.

3.15 Perform the calculations indicated on Addendum II to get the correct 3 pony motor flow value for the QP voltage setting. Also, graph the l_1, l_2, q_1, and q_2 values and graphically verify the calculated value.

3.16 Record the QP calculated value in Section II Addendum I.

3.17 Repeat steps 3.14 through 3.16 for all the Lock-In Amplifier systems being set up.

3.18 While the three pony motor flow continues set the phase switch on the selected lock-in system to measure QP, and slowly adjust the phase dial to get as near to the calculated QP value as possible over a 5 minute time period.

3.19 Record the IP and QP voltage values in Section II of Addendum I.

3.20 Repeat steps 3.18 and 3.19 for all lock-in systems.

3.21 If possible lower the flow back to that used in step 3.9 and 3.10 and record the QP and IP output voltage in Section II of Addendum I as zero flow.

3.22 Repeat step 3.21 for all lock-in systems.

3.23 Resume 3 pony motor or selected flow.

3.24 Remove the DVM from the outputs.

3.25 Verify that the course phase switch is set to display the IP vector component on the meter and that the output connector is connected to the DDH and DS input.

3.26 This completes set up of the Lock-In Amplifier system after MIST operation.

ADDENDUM I

LOCK-IN AMPLIFIER/ECFM SET UP

Date:_____ Trial Run No.:_____ ECFM No.:_____

Reactor Position:_____ ECFM SC/CR No.:_____

DDH & DS Channel No.:_____ Lock-In Amp/Attn. No.:_____/_____

NA Temp.:_____ °F, Name and Initial:_____
                                        Calibrator

Section I

Na Flow - 3 pony motors   IP = _____ Vdc (° ±   °)
  @400°F   QP = _____ Vdc (° ±   °)

_____

Na Flow - near Zero   IP = _____ Vdc (° ±   °)
  @400°F   QP = _____ Vdc (° ±   °)

_____

Section II   CALCULATED

                                 QP = _____ Vdc

_____

Na Flow = 3 pony motors   IP = _____ Vdc (° ±   °)
  @400°F   QP = _____ Vdc (° ±   °)

_____

Na Flow = near Zero   IP = _____ Vdc (° ±   °)
@400°F (Check Of QP)   QP = _____ Vdc (° ±   °)

Date:_____ Trial Run No.:_____ ECFM No.:_____

Reactor Position:_____ ECFM SC/CR No.:_____

DDH & DS Channel No._____ Lock-In Amp/Attn. No.:_____/_____

Na Temp.:_____°F, Name and Initial:_____
                                            Calibrator

$$1_1 = \underline{\hspace{3cm}} \qquad q_1 = \underline{\hspace{3cm}}$$

$$1_2 = \underline{\hspace{3cm}} \qquad q_2 = \underline{\hspace{3cm}}$$

Calculate: (Observe Algebraic Sign Laws)

$$\sqrt{1_1^{\,2} + q_1^{\,2}} \quad =$$

$$\Theta = \tan^{-1} \frac{1_1}{q_1} \quad =$$

$$\emptyset = \tan^{-1} \left(\frac{q_1 - q_2}{1_1 - 1_2} \right) \quad =$$

$$QP = \sqrt{1^2 + q_1^{\,2}} \quad \cos(\Theta + \emptyset)$$

$$QP = \underline{\hspace{5cm}}$$

TABLE I

ECFM No.	Reactor Position	Gain Number	Phase Setting IP SW-Dial	Phase Setting QP SW	IP Voltage 0 gpm/60 gpm	QP Voltage 0 gpm/60 gpm
052		0.294	0° + 8°	90°	.075/.256	.076/.074
064		0.302	180° + 5°	90°	-.217/-.034	.376/.375
078		0.294	0° + 10°	90°	.213/.027	.180/.178
081		0.301	0° + 8°	90°	.044/.236	.035/.035
098		0.295	0° + 3°	270°	-.130/.038	.263/.267
109		0.301	0° + 7°	270°	-.003/.187	.114/.114
110		0.294	0° + 8°	90°	-.049/.135	.043/.043
128		0.301	180° + 9°	270°	.054/.232	.115/.117
156		0.294	0° + 8°	270°	-.080/.092	.283/.286
158		0.294	0° + 8°	270°	-.031/.148	.265/.264
164		0.301	0° + 6°	270°	-.122/.062	.045/.044
172		0.299	180° + 8°	270°	.125/.309	.121/.121
191		0.299	0° + 6°	90°	.016/.204	.118/.118
194	AOTA	(TBD)	0° + 20°	270°	-.010/.674	.049/.049

TYPICAL CHANNEL WIRE
ROUTING

BNC CONNECTORS

AMPL SEC
J3
AC NULL
J4
DRIVE CURRENT
J5

COAXIAL CABLE RG/58 A/U

J2
SC/CR TEST

ATTEN #1 ADJ
IN   OUT

ATTEN #2 ADJ
IN   OUT

ATTEN #3 ADJ
IN   OUT

ATTEN #4 ADJ
IN   OUT

BNC CONNECTORS

SIGNAL
A
B
(PAR 128A)

90°
180°   0°
270°   REP

0° - 100°

-1   0   +1

ADJ
OFFSET

OUT

Q

TIME CONSTANT

FROM REAR PANEL OUT CONNECTOR

TO FFTF DDH & DS SYSTEMS

115 VAC

MODEL 5204 OVER
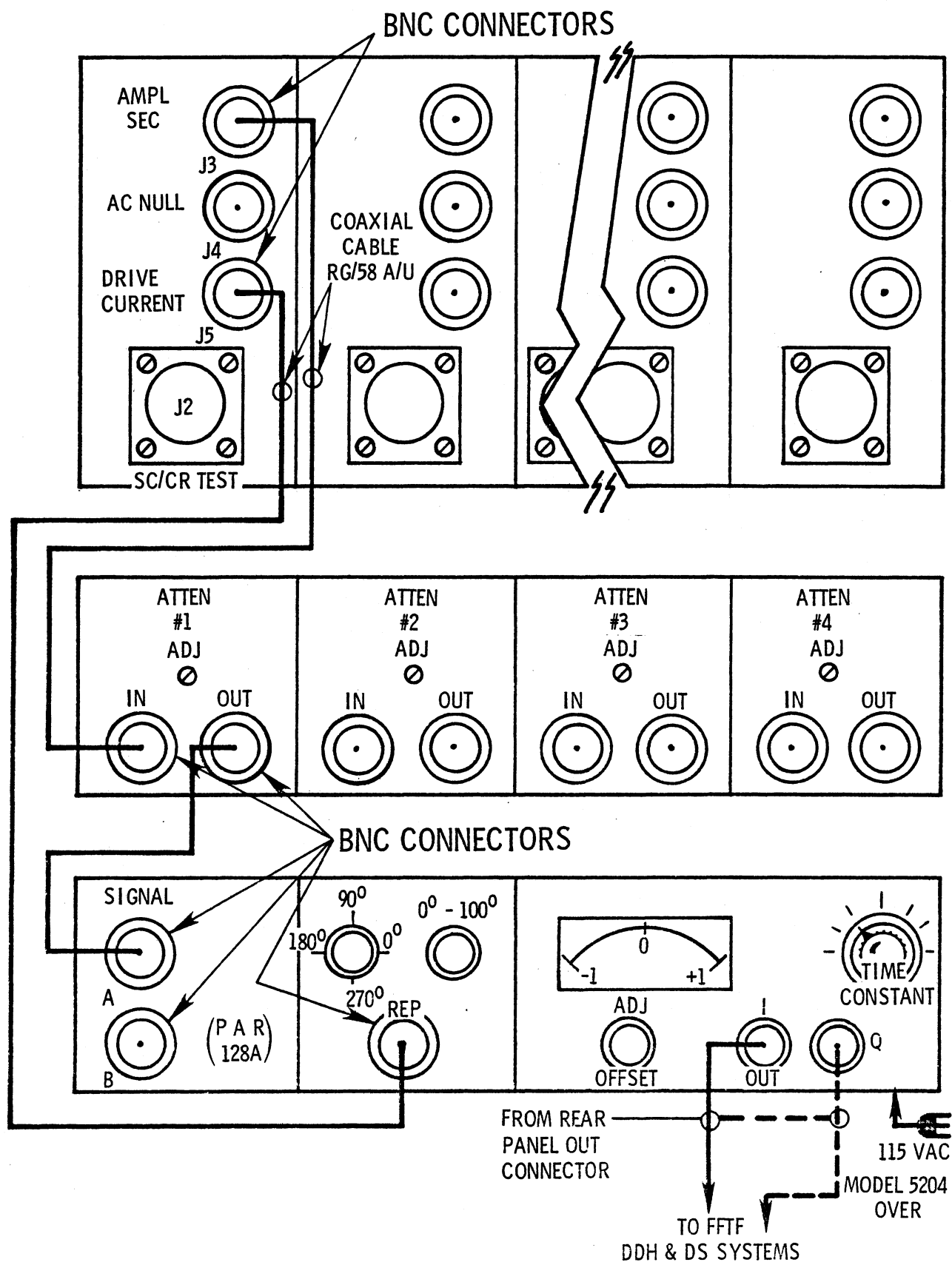
DISTRIBUTION

DOE/FFTFPO

Director (5)
G. D. Bouchey
T. L. King

HEDL

S. L. Additon	W/B-18
T. A. Basmajian	W/A-59
R. A. Bennett	W/B-43
P. B. Bourne	W/B-118
J. W. Connell	W/D-56
D. C. Corrigan	W/C-3
E. R. Cramer	W/B-48
A. D. Danko	W/D-18
L. V. Feigenbutz	W/C-6
L. F. Fort	W/D-56
W. M. Gajewski	W/B-82
C. W. Hoth	W/E-32
R. J. Jackson	W/E-32
H. G. Johnson	W/B-43
W. L. Knecht	W/D-66
W. J. McShane	W/B-12
D. E. Mahagin	W/A-59
W. T. Nutt (6)	W/B-18
R. J. Robinson	W/B-86
D. P. Schively	W/B-48
L. K. Severud	W/C-99
E. M. Sheen	W/A-56
D. E. Simpson	W/C-80
D. D. Stepnewski	W/C-75
J. L. Stringer (6)	W/A-56
W. L. Thorne	W/A-11
J. C. Tobin	W/B-33
R. P. Warrick	W/D-56
W. R. Wyckoff	W/D-56
M. W. Young	W/B-106

Central Files (10)
Publications and Services (2)