NBSIR 79-1933

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Robert E. Hebner, Jr.
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U.S. Department of Commerce
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Luther H. Hodges, Jr., *Under Secretary*
Jordan J. Baruch, *Assistant Secretary for Science and Technology*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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I. INTRODUCTION

The accepted techniques for measuring the high voltage pulses used for testing power system apparatus in the United States are described in the voluntary standard issued by the Institute of Electrical and Electronic Engineers, "High Voltage Testing Techniques," IEEE-4. This document is essentially the same as International Electrotechnical Commission Publication 60-3.

The basic assumptions underlying this standard are summarized in a publication[1] by the International Research Group Renardieres on Impulse Measuring Systems (IRR-IMS group). Basically, it is assumed that the measuring system can be modeled as a two terminal pair network. The relationship between the input and the output is

$$\begin{bmatrix} V_i\ (s) \\ I_i\ (s) \end{bmatrix} = [A] \begin{bmatrix} V_o\ (s) \\ I_o\ (s) \end{bmatrix} \qquad [1]$$

where V is the voltage, I is the current, the subscripts i and o refer to input and output respectively and s is the Laplace operator. Formally, the matrix A is represented as

$$[A] = \begin{bmatrix} A_{11}\ (s) & A_{21}\ (s) \\ A_{21}\ (s) & A_{22}\ (s) \end{bmatrix} \quad . \qquad [2]$$

The voltage transfer function, H(s), is defined as the voltage ratio when the output current is zero, i.e.,

$$H(s) = V_o(s)/V_i(s) = 1/A_{11}(s) \quad . \qquad [3]$$

The divider ratio, N, is then defined as

$$N = A_{11}(o) = \lim_{s\to 0} [A_{11}(s)] \quad . \qquad [4]$$

It should be noted that in some cases, e.g., capacitor dividers with a resistor in the low impedance element, A_{11} (s) may not be defined at zero. In this case, to represent the ratio as a single real number, A_{11} (s) must be frequency independent over the frequency range of interest. The assumption of frequency independence over the range of frequencies of interest is implicit because the divider must attenuate equally all frequencies contained in the input signal.

These fundamental considerations highlight two important facets of the calibration of impulse measurement systems:

- determination of the divider ratio -- a single real number by which output voltage is multiplied to determine the input voltage, and,

- verification that the transfer characteristics of the system are frequency independent over a sufficiently-wide frequency range so that this single real number is valid for the waveform to be measured.

The divider ratio can be measured using a variety of techniques which are generally, but not exclusively, based on comparison of the input and output voltages at a single frequency or a series of discrete frequencies.

The frequency dependence of $A_{11}(s)$ is generally determined in the time domain by measuring the response of the system to a voltage step. Obviously, the frequency dependence can also be measured in the frequency domain by performing measurements throughout all frequency ranges of interest. Because these latter measurements are difficult and time consuming[1], time domain measurements are generally performed.

The purpose of this investigation was to determine experimentally the adequacy of measurements of the response to a voltage step in large scale, practical measurement systems. There are valid technical reasons to question measurement accuracy in such systems. These are based on the fact that a practical measurement system is not well-correlated with the model outlined above. Obvious discrepancies include the following items:

- The measurement system is not an ideal two-terminal pair network. The constraint of current equality in the input terminal pairs and in the output terminal pairs cannot be easily realized, particularly because of ground currents which cannot always be confined to specified paths.

- Inductive and capacitive couplings among the pulse generating circuit, the measuring circuit beyond the divider terminals, and the divider itself introduce signals in addition to those specified at the terminals of the divider. (An unusual phenomenon in this category is the cavity resonance of the entire high voltage hall.[2] This resonance, however, was not observed in this investigation).

- It is not technically feasible to apply a voltage step directly between two widely separated input terminals. Leads, therefore, must be used to connect the terminals to a step generator. Because the lead geometries are different in the tests of the step response and the measurements of high voltage transients, the entire divider circuitry is modified. The significance of lead effects must be determined.

- The relatively small signals encountered in the determination of the step response may be contaminated by extraneous electro-magnetic interference.

These problems have long been recognized and a considerable amount of effort has been devoted to verifying that measurements with uncertainties of the order of a few percent can be performed. An area where inaccuracies of a few percent are difficult to attain is the measurement of impulses which are chopped on the front. As a demonstration of this exception, IEEE-4 describes a technique to correct the crest value of a front-chopped impulse in those cases in which the response time of the measuring system is more than 5% of the risetime of voltage pulse. Unfortunately, range of applicability of this correction is poorly documented. This fact is emphasized, as this is the only correction for which the standard explicitly suggests agreement between the parties involved before the correction is applied.

The approach taken in this investigation was to verify that all of the parameters in Duhamel's integral (also referred to as the convolution integral)[3,4] could be measured with sufficient accuracy to guarantee that corrections based on the measured response to a step would permit meaningful measurements of the voltage waveform. Duhamel's integral can be expressed as

$$N\, V_o\,(t) = \int_0^t \Theta'(\tau)\; V_i\;(t - \tau)\; d\tau, \qquad [5]$$

where τ is an integration variable, $\Theta'(\tau)$ is the time derivative of the unit step response, V_i is the input voltage, V_o the output voltage, and N is the divider ratio as defined in Eq. 4. This equation dictates the measurement program -- the input and output voltage, the divider ratio and the step response each must be measured.

Measurements of the divider ratio, the step response and the output voltage are conventional in a modern, high voltage test laboratory. It is assumed that the input can be determined from these three measurements. To verify this assumption, the input is also measured using a second divider which introduces only negligible distortion in the applied waveform. To provide evidence that the characteristics of this second divider are appropriate for the desired measurement, two low voltage checks are performed. First a low voltage (100-1000 V) ramp, having about the same time-to-crest as the high voltage pulse, is applied to the divider under test. The input and output voltages are measured with an oscilloscope. Using the same experimental setup, the test is repeated using the second divider to measure the input voltage. Comparison of these results provides information with which to judge the validity of the approach.

It should be noted that the low voltage tests using two dividers are technically difficult. The output voltages typically range from 0.01-0.1 V peak. Electromagnetic interference and ground impedance make measurements at this level challenging in an industrial high voltage laboratory.

This test protocol was originally developed and employed with mixed success by the IRR-IMS group for an experimental session in the summer of 1976 at the high voltage laboratory of Electricité de France.

Section II of this report describes the design, construction and testing of the resistor dividers, the ramp generator, and the step generator. The software used to evaluate the measurements is given in Section III. Section IV presents the results of tests performed at the high voltage laboratory of the Bonneville Power Administration. Section V summarizes the data analysis results. Finally, Section VI summarizes the results of the measurements and suggests possible implications.

II. APPARATUS

II.1 Divider Design, Construction, and Calibration

II.1.a Introduction

The basic design of the impulse divider had been developed by other workers.[5] In principle, the high impedance element is a non-inductive resistor having a resistance of approximately 10,000 Ω. The resistance distribution along the resistor is chosen to match approximately the capacitance distribution, which is controlled primarily through the choice of the size and position of the divider's guard ring(s). Two dividers were constructed -- one designed to measure standard lightning impulses up to about 350 kV peak and the other designed to measure standard lightning impulses up to approximately 1 MV peak. During the high voltage tests, it was only necessary to use the larger divider, so only it will be described in detail. The remainder of this subsection is a description of the design, construction, and calibration of this divider.

II.1.b 1 MV Divider

A photograph of the completed 1 MV divider is shown in Fig. 1. The high impedance element consists of three discrete resistors. Each resistor is nominally 1 meter long and 5 cm in diameter. To obtain a somewhat non-uniform resistance distribution, which approximately matches the capacitance distribution, the three resistors were designed to have nominal resistances of 2500 Ω, 3500 Ω, and 4000 Ω. It should be noted that a computer program has been developed to optimize the design of resistor dividers.[6] Because of the availability of design information for dividers of this size, however, it was not judged necessary to incur the expense of duplicating that program. The resistors were wound using resistance wire that had a resistance of 26.2 Ω/m. To obtain a non-inductive resistor, two nominally equal windings were used, wound in opposite directions one on top of the other and connected in parallel. Each winding consisted of more than 1000 turns; the exact number of turns depended on the desired resistance.

The resistors were wound using a lathe, so the actual resistance was determined by the available pitch settings. The completed resistors had values of 2729 Ω, 3483 Ω, 3945 Ω.

Fig. 1 The resistor divider, NBS-1, rated at one million volts.

The divider's low impedance element has a nominal resistance of 1 Ω and consists of two 2-Ω pieces of resistance wire connected in parallel. Each of the 2-Ω resistors is twisted to minimize its inductance.[3] With this low value of resistance, the effect of low-side capacitance (e.g., from cables or the measuring instrument) was judged to be negligible. This judgement is based on the maximum frequency which can be generated in the high voltage circuit, f_{max}. This frequency can be estimated[4] as

$$f_{max} = \frac{c}{4(h_G + h_C)} ,$$

where c is the speed of light, h_G is the height of the generator, and h_C is the height of the front capacitor. To calculate f_{max}, it was assumed $h_G = 2\ h_C$ which in general should overestimate f_{max}. In Fig. 2, the maximum frequency is superimposed on a plot of the calculated magnitude of low side impedance versus frequency (using the conservative assumption that low side capacitance is 1000 pF (equivalent to about 10 m of coaxial cable)). It should be emphasized that this plot does not constitute proof of measurement accuracy. It does, however, indicate that the design of the divider low-side is probably adequate for the measurement of the voltage pulses in a wide range of measurement applications.

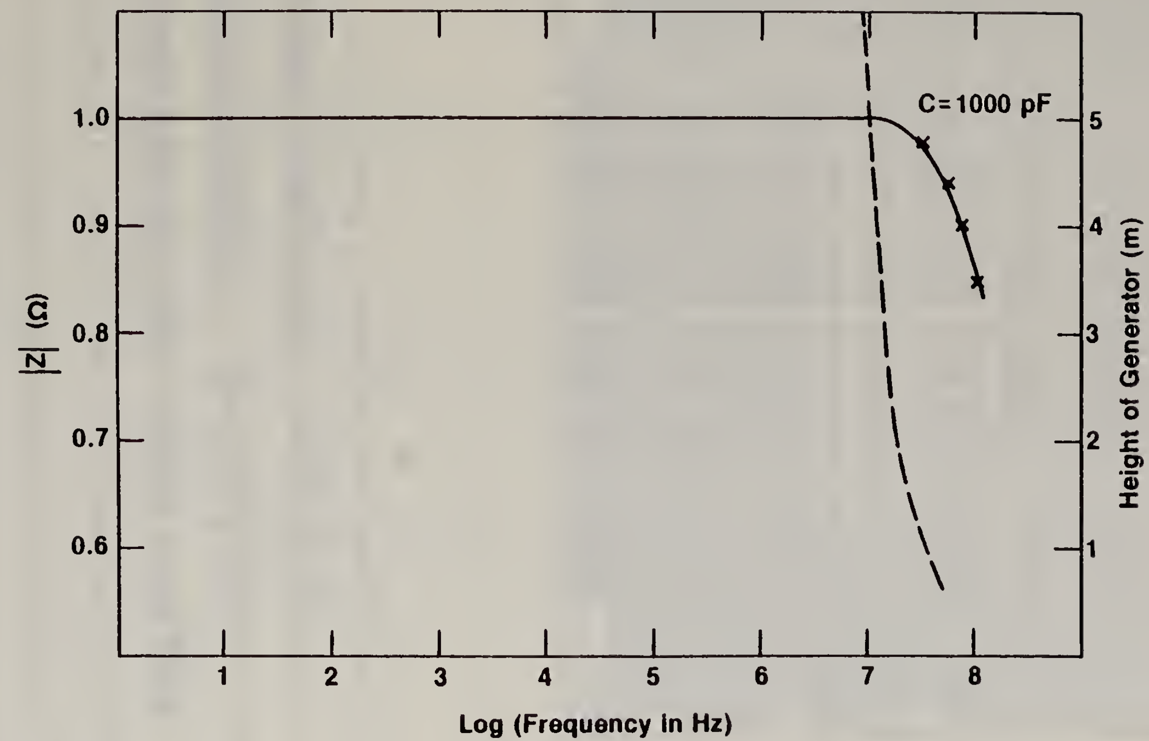


Fig. 2 Low-side impedance (solid line) as a function of frequency and theoretical maximum frequency (dashed line) as a function of generator height.

The design of the guard ring was done experimentally. The size was estimated from experience with other dividers of the same physical dimensions and voltage ratings. Low voltage tests were performed to document the relationship between the size of the guard ring and the response to a voltage step.

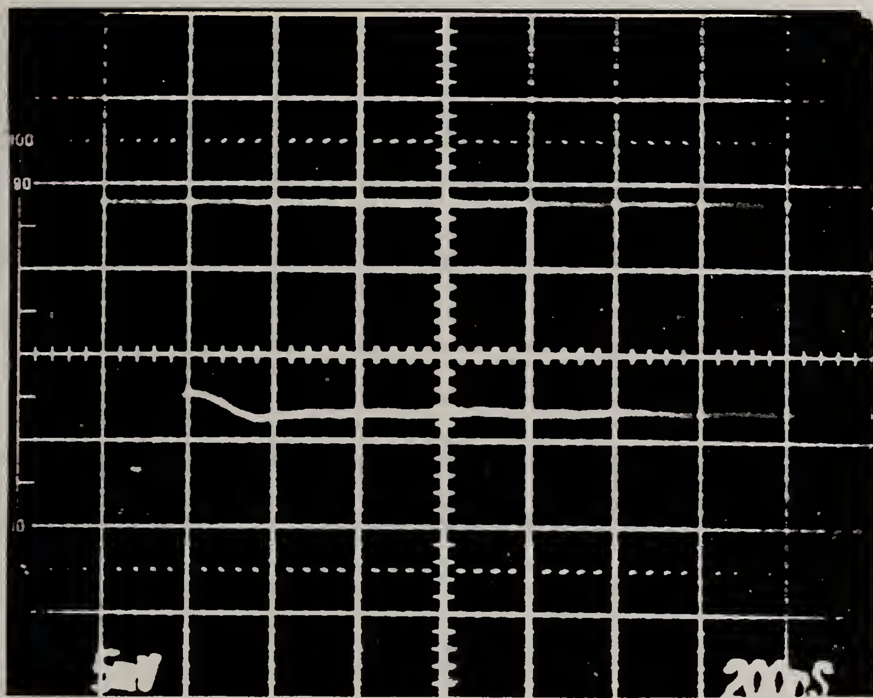
The divider was calibrated by four different methods, consisting of three low-voltage measurements:

- step-response
- dc voltage ratio
- resistances (plus calculation)

and one high voltage measurement:

- comparison with an electro-optic Kerr system, of the measurement of the peak value of a high voltage impulse.

A typical low-voltage step response is shown in Fig. 3. Average step height from such oscillograms with an applied voltage of 135.5 V was 12.80 mV, from which a divider ratio of 10590:1 was obtained. The uncertainty of this method was about ±1%, primarily attributable to errors in resolving the spacing of the traces on the photographic record. By digitizing the entire oscillogram and correcting for all distortion in the oscilloscope screen and photographic reproduction, it is, in principle, possible to reduce this uncertainty -- perhaps by as much as a factor of ten. In this case, the only correction applied was for errors in the vertical gain of the oscilloscope. For the position on the screen of the response shown in Fig. 3, this correction was negligible.



Applied Voltage: 135.5 V
Vertical Scale: 5 mV/Div
Horizontal Scale: 200 ns/Div

Fig. 3 Typical step response of NBS-1.

Non-negligible distortions were observed, however, for trace positions significantly higher or lower on the screen.

To check the overall performance of the divider, the response time was measured using five different values of the damping resistor (R_D in Fig. 5). These data are shown in Fig. 4. From a least-squares linear fit, the equivalent input capacitance[1] was found to be 95.8 pF with a standard deviation of 5 pF.

Measurement of the dc voltage ratio was performed using two digital voltmeters. Typical results are presented in the following table.

TABLE 1: DC VOLTAGE RATIO

V_{in} (volts)	V_o (volts)	Ratio
60.20	0.00567	10620
74.12	0.00698	10620
99.90	0.00940	10630
127.28	0.01198	10620
151.46	0.01425	10630
175.21	0.01649	10630

The resistances which must be measured in order to calculate the ratio are shown in the circuit of Fig. 5. In this figure, R_D is the damping resistor, R_H is the divider high-side resistor, R_L is the low-side resistor, R_T is the terminator resistor at the input to the oscilloscope, R_1 is the resistance of the center conductor of the coaxial cable connecting the divider with the oscilloscope and R_2 is the resistance of the shield of that cable. From this circuit,

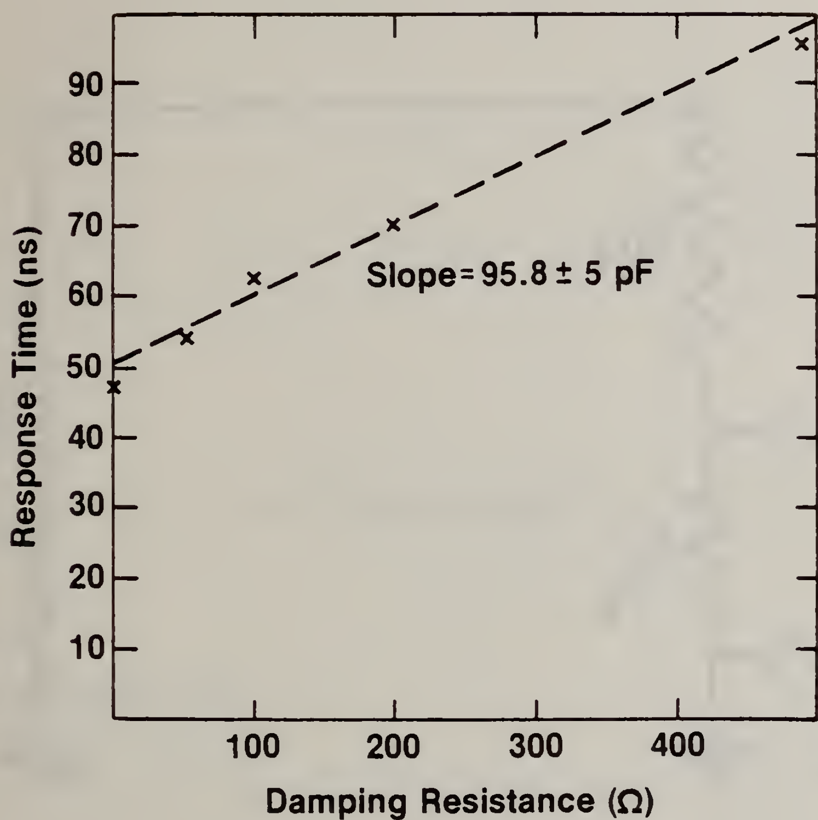


Fig. 4 Response time of NBS-1 as a function of damping resistance.

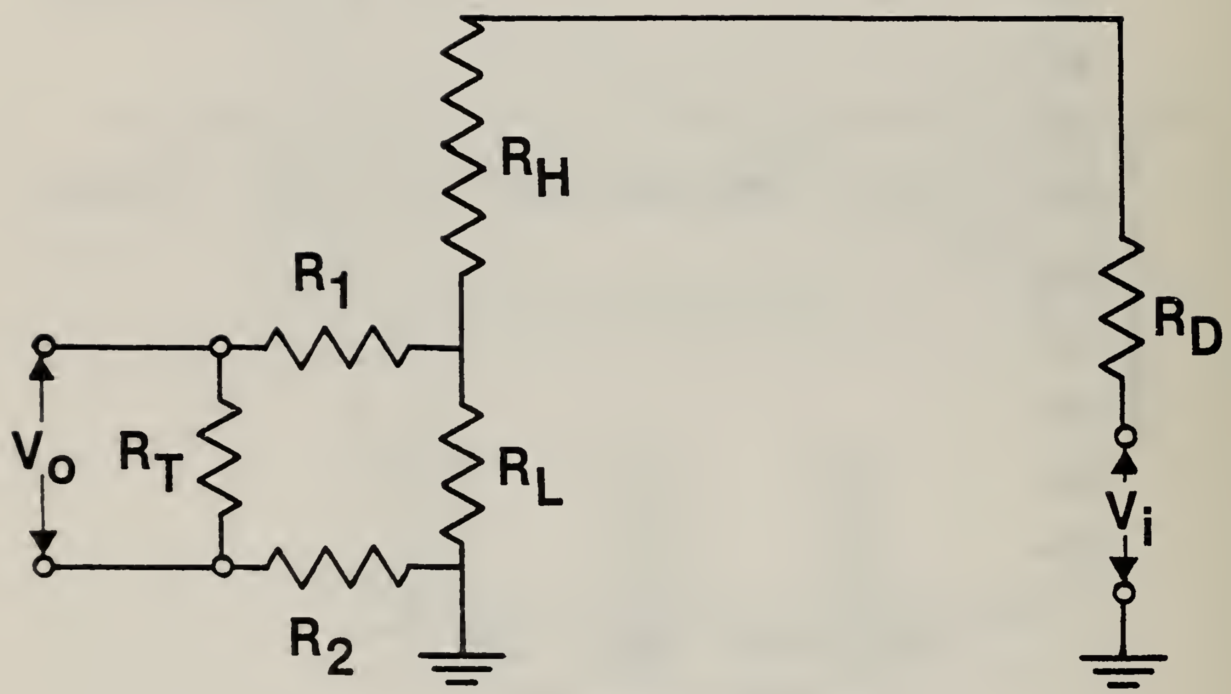


Fig. 5 Equivalent circuit of NBS-1 with damping resistor and cable termination.

$$V_{in}/V_o = (R_\tau/R_{\mathcal{L}})\ (R_1 + R_2 + R_T)/R_T, \qquad [6]$$

where

$$R_{\mathcal{L}} = R_L \ || \ (R_1 + R_2 + R_T), \qquad [7]$$

and

$$R_\tau = R_{\mathcal{L}} + R_H + R_D\ . \qquad [8]$$

The measured values were

$$\begin{aligned} R_\tau &= 10360\ \Omega \\ R_{\mathcal{L}} &= 0.977\ \Omega \\ R_1 + R_2 + R_T &= 50.34\ \Omega \\ R_T &= 50.26\ \Omega\ . \end{aligned} \qquad [9]$$

Calculations from these measurements yield a divider ratio of 10620:1, which agrees with Table 1 values.

The test circuit for the simultaneous measurement of the high voltage pulse using both an electro-optic Kerr system[1] and the divider is shown in Fig. 6. The pulse transformer provides an approximately rectangular pulse with a full-width at half maximum of about 6 μs. To perform an accurate measurement of the divider low-side peak voltage, a suppressed-zero technique is used. The response of the Kerr cell is shown in Fig. 7. The peak voltage applied to the cell is determined from the equation:

$$I/I_m = \sin^2 (\pi(V/V_m)/2) \quad , \qquad [10]$$

where I/I_m is the relative transmittance of the Kerr system, V is the applied voltage and V_m is a constant determined by the cell geometry and the properties of the electro-optic fluid.

Dividing this voltage by the measured peak of the divider output yielded a divider ratio of 10560:1, within 0.7% of the low voltage values discussed earlier. The applied voltage was approximately 150 kV peak during these tests. During the development and testing of various configurations of the low impedance element of the divider, a series of high voltage tests was performed using both the square wave and a 1.2 x 50 μs standard

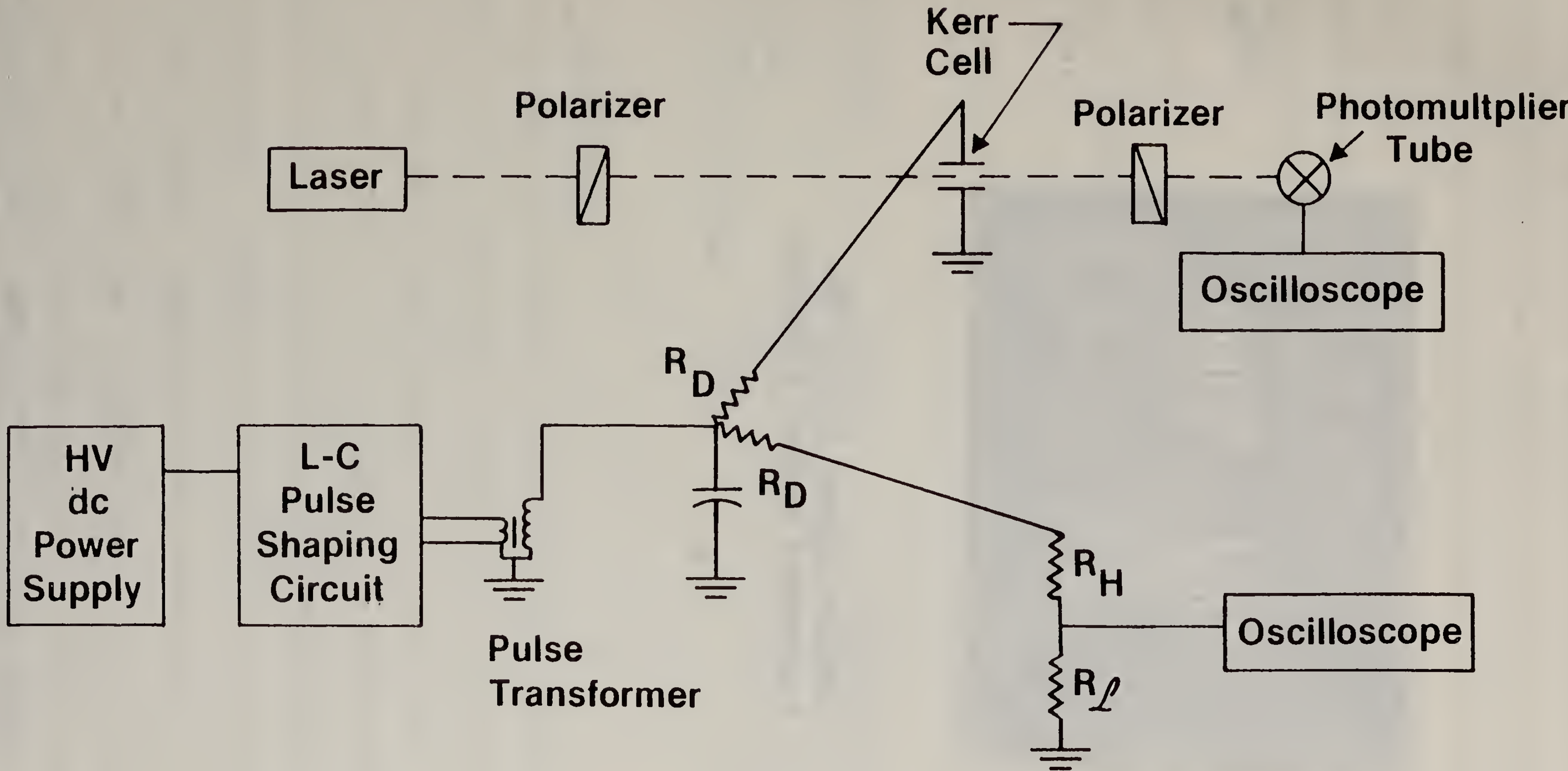
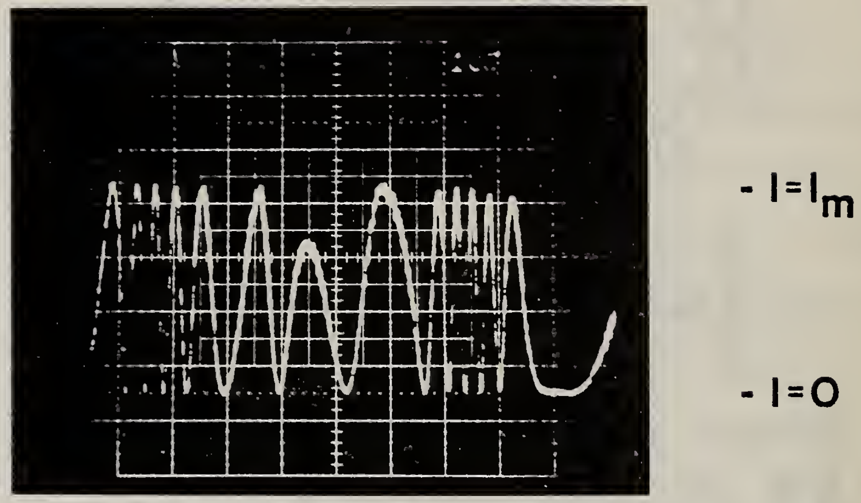


Fig. 6 Test circuit for high voltage calibration of NBS-1.



Vertical Scale: 50 mV/Div
Horizontal Scale: 1 μs/Div

Fig. 7 Typical response of Kerr system to high voltage pulse. I=Im is the maximum transmittance of the system while I=0 is the minimum.

lightning impulse. The choice was determined by convenience and availability of pulse sources, because it was assumed that the rates of change of both waveshapes were sufficiently slow that the measured ratio would be independent of pulse shape. While no systematic investigation of this assumption was performed, a spot check indicated that the divider ratios measured using the two waveforms differed by only about 0.1%.

The results of the four determinations of the divider ratio are shown in the following table:

TABLE 2: SUMMARY OF DIVIDER RATIO DETERMINATIONS

Measurement Method	Ratio	Deviation From Average %
dc voltage	10620:1	+0.2
resistance	10620:1	+0.2
step response	10590:1	-0.1
comparison with Kerr system	10560:1	-0.4

II.2 Ramp Generator

A voltage ramp with a nominal slope of 500 V/μs, chopped after approximately 1 μs ($V_0 \simeq 500$ volts), is required for the low-voltage calibration of the high voltage divider. The circuit used to generate this ramp is shown in Fig. 8. It is essentially a modification and optimization of an earlier circuit used in unpublished experiments at Electricité de France. Voltage, V, is furnished by a conventional low-current dc power supply. Capacitor, C,which serves as an "infinite" source during ramp generation, is charged slowly through resistor, R, which also serves to limit the power supply current after the circuit fires. Switching gap, G_1, is adjusted to break down when voltage V_1

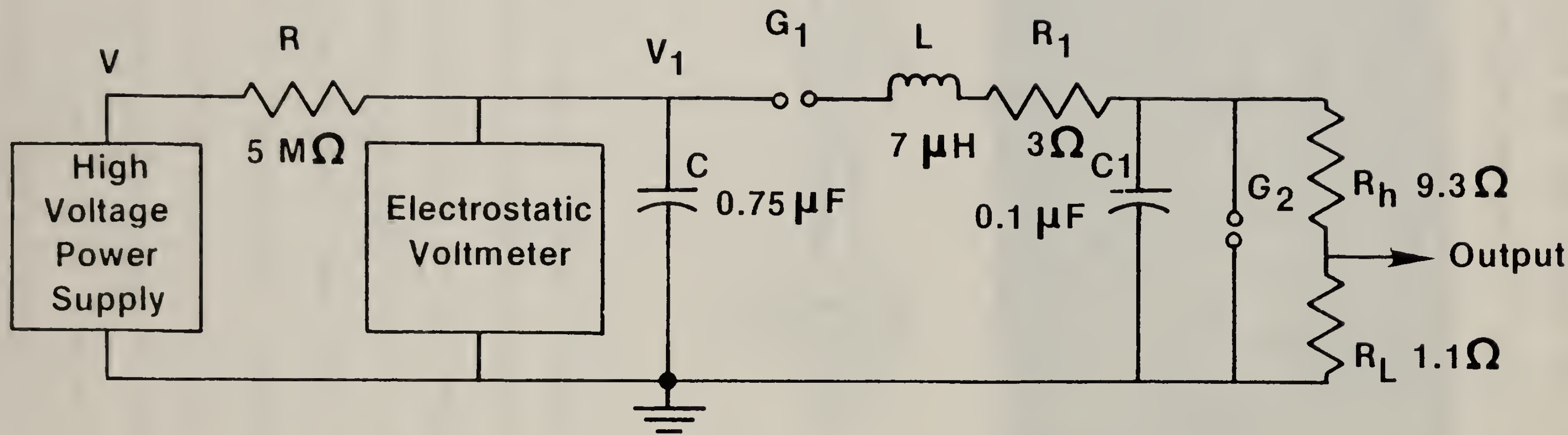


Fig. 8 Ramp generator circuit.

equals the desired value, usually about 10 kV. G_1 consists of two 2.5 cm brass spheres, operating in air. L, C_1, R_1, R_h and R_L act to generate and shape a ramp voltage across C_1 after G_1 fires. Gap G_2, similar in construction to G_1, chops the ramp at the desired voltage Output voltage V_o is applied directly to the divider under test, and to a storage scope (not shown) via two cascaded 10:1 attenuators.

Once placed in operation, the circuit functions as a relaxation oscillator, with a period determined by RC, V and the setting of gap G_1. The scope is triggered by a 30 cm diameter loop antenna placed 20-30 cm from gap G_1.

The response of the elemental circuit of Fig. 8 is easily calculated. With the valid assumption that the time constant RC is much larger than the ramp time, that C is much larger than C_1, and that G_1 fires instantaneously, output voltage is

$$V_o = V_1 R_L \left[1 - \varepsilon^{-at} \left(\cos bt + \frac{a}{b} \sin bt\right)\right] / (R_1 + R_2) \qquad [11]$$

and ramp slope is

$$\rho_o = \frac{dV_o}{dt} = V_1 R_L q \left(\varepsilon^{-at} \sin bt\right) / b(R_1 + R_2) \qquad [12]$$

where $R_2 = R_h + R_L$

$$a = p/2$$

$$b = \frac{\sqrt{4q - p^2}}{2}$$

and

$$p = (R_1/L) + (1/R_2C_1),$$

$$q = (R_1 + R_2)/R_2LC_1 \quad .$$

Equations (11) and (12) are valid until G_2 fires, after which the response is of no interest beyond the fact that V_o collapses very rapidly, i.e., is truly "chopped".

The response of the circuit of Fig. 8 is shown in Fig. 9 for V = 8.5 kV. This calculation is useful in ascertaining appropriate component values to be used in the initial design of the circuit. However, at these speeds stray capacitances and inductances play very important roles in determining the shape of the final wave. These stray parameters are never well known. Furthermore, their inclusion in the basic circuit creates an intolerably complicated and tedious analytical situation. Therefore, after the analytical first cut, design of the circuit was primarily experimental, consisting of varying the physical size, location and orientation of the circuit parameters, and observing

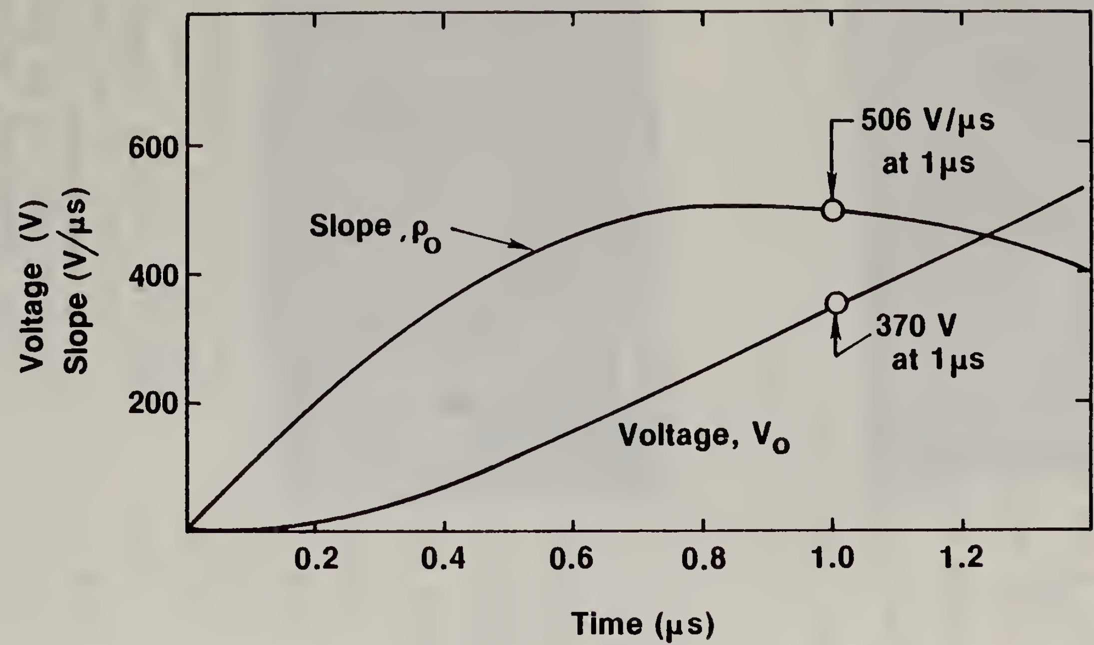


Fig. 9 Calculated response of ramp generator circuit.

the effects of these changes on the waveform. It may be noted in passing that the waveshape is much more sensitive to the size and orientation of the inductor than to any of the other parameters.

The efficiency of this design procedure is demonstrated by comparing Figs. 10a and 10b. The former shows a typical V_o wave early in the design process, the latter the output wave of the final circuit. In Fig. 10b, with applied voltage $V_1 \cong$ 8.5 kV, peak $V_o \cong$ 525 volts, chop time $\cong$ 1.02 μs, and the slope near the peak $\cong$ 520 V/μs. The wave is clean and the chop is sharp ($\cong$ 150 volts in 30 ns). This is close to the design goals.

The final circuit layout is shown in Fig. 11. The open, "breadboarded" layout on a large ground plane was found to be the simplest means of controlling strays and pick-up in order to optimize the waveform. Component descriptions are as follows:

Component	Values	Description
R	5 M Ω	Rated 1 mA steady-state, > 20 kV flashover
C	0.75 μF	Two 1.5 μF, 5 kV capacitors in series
C_1	0.1 μF	Four 0.1 μF, 5 kV capacitors in series-parallel
L	$\cong$ 7 μH	35 turn air core solenoid, wound on 3.8 cm OD x 23 cm plastic form
R_1	3.0 Ω	6 turn, handwound, #24 resistance wire on 1.6 cm OD x 7.6 cm form
R_h	9.3 Ω	7 turn, handwound, #30 resistance wire on 1.6 cm OD x 7.6 cm form
R_L	1.1 Ω	1 turn, handwound, #30 resistance wire on 1.6 cm OD x 5 cm form
G_1	-----	2.5 cm brass spheres in hardwood frame, air gap screw-adjusted
G_2	-----	Similar to G_1, except sphere diameter = 1.90 cm
Gnd Plane	-----	30 x 45 x 0.16 cm aluminum sheet, mounted on plywood base.

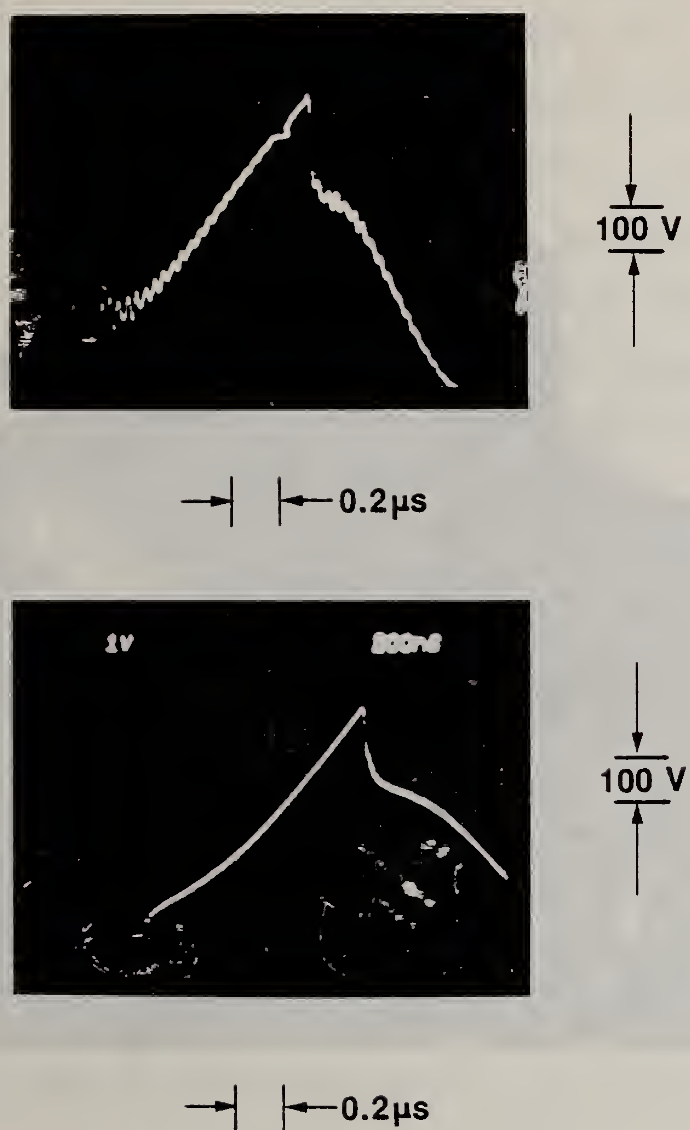


Fig. 10 Upper photo (a) shows output of generator as first constructed. Lower photo (b) shows output with component location and orientation optimized.

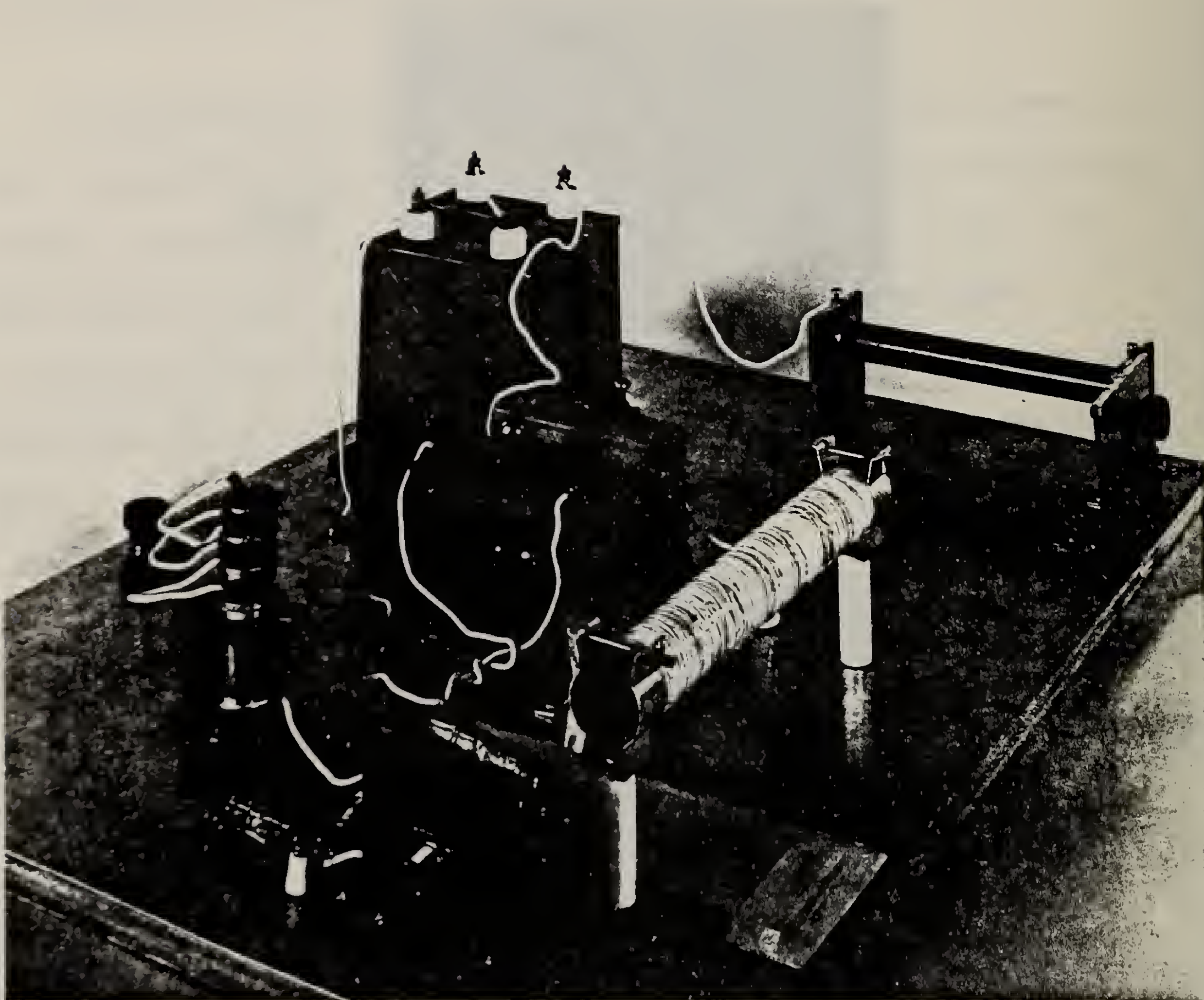


Fig. 11 Ramp generator.

II.3 Step Generator

The step generator is a conventional circuit based on a commercially-available mercury-wetted-contact relay (Fig. 12). A dc power supply provides a bias voltage through a current limiting resistor to a normally open contact of the relay. For the tests performed during this work, the dc voltage level is typically between 100 V and 150 V. A digital voltmeter is used to record accurately the voltage on the normally-open contact. When a pulse is applied to the coil of the relay, the normally-open contact is "instantaneously" shorted to the grounded contact. No attempt is made to determine accurately the actual risetime of the step. Using this generator, however, response times of measurement systems as short as 20-25 ns have been measured. This provides an upper bound on the risetime of the step.

Two operational constraints on this generator should be emphasized. One is the occasionally overlooked fact that for resistor dividers the magnitude of the voltage step must be determined at the relay side of the current-limiting resistor which is between the dc power supply and the relay. For capacitor or series RC dividers, however, the voltage at the power supply is the voltage step.

A second operational difficulty is the fact that the step generator, in order to simulate the high voltage measuring circuit, is usually at least the height of the divider away from the divider base. It is, however, necessary that the ground terminal of the relay remain at the same potential as the base of the divider. Because high voltage laboratory

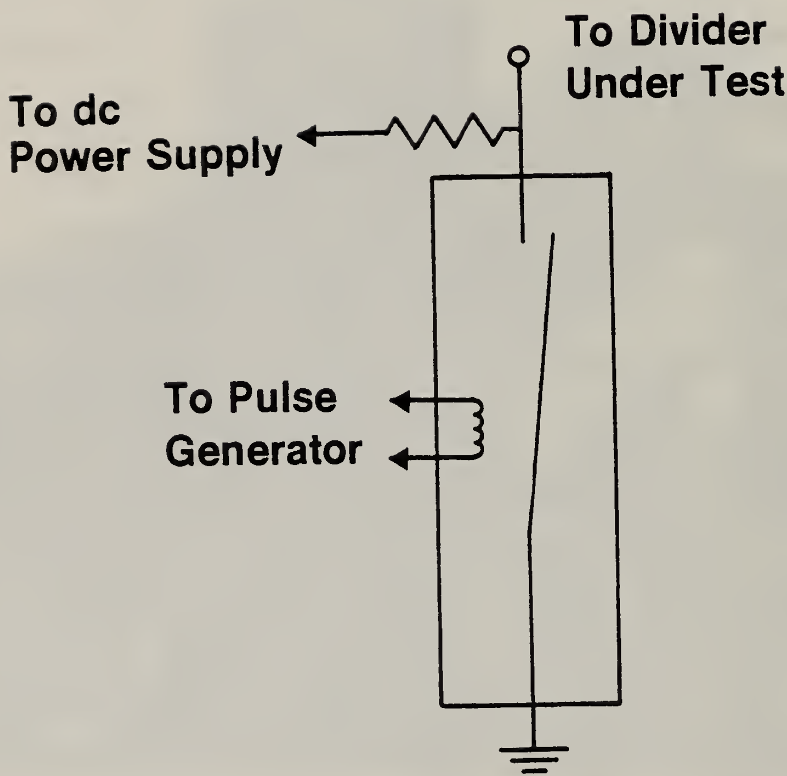


Fig. 12 Step generator circuit.

grounding systems are designed to accommodate high voltage, high current signals, it is sometimes necessary to make special provisions to insure accurate measurement of the response of the system to a low voltage, low current step.

III. COMPUTER ANALYSIS OUTLINE

III.1 Introduction

The coding required to perform the actual integration is a small fraction of the total program which is required.

First, data are converted to digital form for use by the computer. This is done in either of two ways:

1. Direct conversion using a transient recorder (very fast A/D converter with memory), or,
2. Indirect conversion using oscillographs for recording and subsequent digitizing by means of a graphics tablet with a computer interface.

Next, the digital image of the waveform is converted to a standard format for use by the software. Data from the transient recorder or graphic tablet is entered into computer memory via an interface link.

The data, once in memory, is converted from (X,Y) pairs of coordinates back into time-referred voltage values. After the various data conversion steps are performed, there are many options for dealing with the data sets in computer memory.

In addition to removing dc offsets and correcting algebraic signs of all waveforms, the step response of the divider under test must be normalized to a positive unit-step in order to perform the Duhamel's Integral computation.

To obtain accurate results, the data are smoothed, using a polynominal fitting subroutine called SMOOTH. After these adjustments, a calculation of the system output is performed through application of Duhamel's Integral to the measured input wave and step response.

After calculation of the theoretical output, the measured output is compared using CORRELATE, which calculates the average error and its standard deviation as well as instantaneous percent error. The waveforms involved may also be printed for plotting or further inspection.

The program is structured as a small main program handling filing, input/output, all operator functions, and subroutine control, with most of the numerical work handled by small subroutines. This configuration was found to be quite efficient as well as very easy to debug, maintain, and expand. All permanent data are stored as integers in the main-program in one of 12 columns. Each column has a capacity of 600 data points and a two-column work space is held in common. This limits access to main data storage while allowing free access to workspace.

To conserve limited minicomputer-core space, as well as execution time, all data are held in 1/2 word integer format rather than full-word floating-point despite the loss of accuracy. Thus, each column of data must have a scale-factor to reconstruct the real value of each data point. The sample interval and number of samples is read in at the beginning of a run, and remains constant. The operation of the control section is interactive, i.e., as each task is finished, control returns to the operator to select the next task. A string of control commands may also be prerecorded on a floppy disc for unattended "batch" processing.

III.2 Program Description

The program listing is given in the Appendix of this report. The purpose of this section is to provide a functional description of the various tasks performed by the software to clarify the considerations that went into the data analysis.

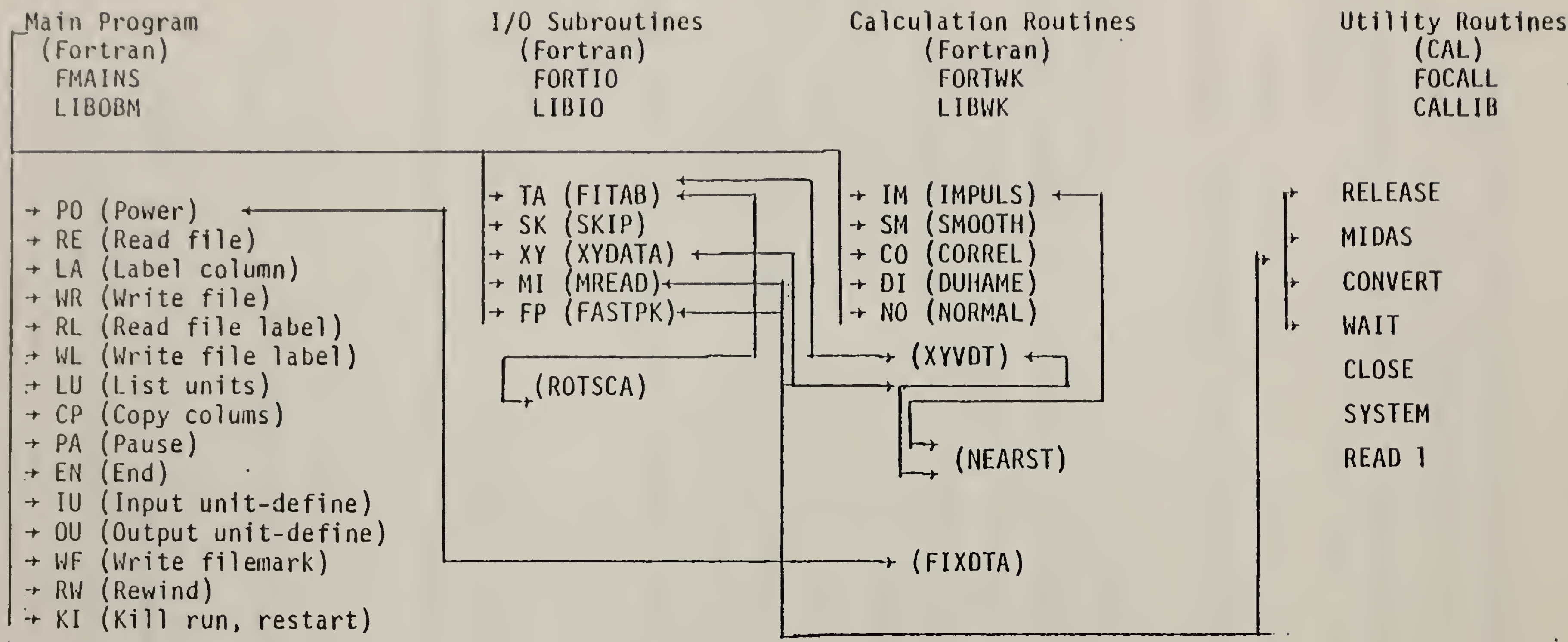
The main program and all essential subroutines are written in Fortran V. The code is specifically intended to be used on a 16-bit Interdata[8] minicomputer. It would require minor modifications to be used with different computers.

The subroutine organization is shown in Fig. 13. A brief functional description of each of the tasks follows listed by mnemonic and grouped by activity.

List of Tasks by Mnemonic and Function

Utility (Input/Output)

RE [a]	Read data directly from a mass storage file into memory by indicated operand column
WR [a]	Write data to a mass storage file, on logical unit OU, from column a


Main Program
(Fortran)
FMAINS
LIBOBM
PO (Power)
RE (Read file)
LA (Label column)
WR (Write file)
RL (Read file label)
WL (Write file label)
LU (List units)
CP (Copy colums)
PA (Pause)
EN (End)
IU (Input unit-define)
OU (Output unit-define)
WF (Write filemark)
RW (Rewind)
KI (Kill run, restart)
I/O Subroutines
(Fortran)
FORTIO
LIBIO
TA (FITAB)
SK (SKIP)
XY (XYDATA)
MI (MREAD)
FP (FASTPK)
(ROTSCA)
Calculation Routines
(Fortran)
FORTWK
LIBWK
IM (IMPULS)
SM (SMOOTH)
CO (CORREL)
DI (DUHAME)
NO (NORMAL)
(XYVDT)
(NEARST)
(FIXDTA)
Utility Routines
(CAL)
FOCALL
CALLIB
RELEASE
MIDAS
CONVERT
WAIT
CLOSE
SYSTEM
READ 1

RL Read file label from logical unit, IU

WL Write file label on logical unit, OU, after rewind

WR [a] Write filemark on logical unit a

RF [a] Rewind logical unit a

Control and Miscellaneous

LA [a] Label column a (using a 12 character alphanumeric label)

CP [ab] Copy data and labels from column a to column b

IU [a] Set input logical unit to a

OU [a] Set output logical unit to a

LU List units; display values of IU and OU and list all unit numbers assigned by the operating system

PA Pause into the operating system with easy return

KI Kill run - returns control to main program entry point; permits change in operating parameters without destroying data memory

EN End run - close all mass storage files, next logical unit assignments and return to the operating system

Data Input Routines

TA [a] Tablet data input; reads data in graphics table format, corrects (X,Y) pairs for rotation and scaling, generates a constant-sample-interval data set compatible with main program data array, and stores this in column a. Due to the nature of the input medium and the whole process, great care must be exercised in retracing the scope trace to provide data for this operation. For calibration of the graphic tablet output in terms of photograph divisions, a special procedure is followed: the corners of a 2 cm x 2 cm square from anywhere in the graticule is entered, along with six points along some "baseline", preferably a "ground-line" trace. This is done both before and after data are entered. Data are separated from calibration marks by a pair of points in the same location (before and after data).

This routine automatically scales and corrects the input data for minor trace (baseline) rotation with respect to the tablet axes, gives error messages for unusual conditions, allows for interactive "data-saving" patches during a run, e.g., if it cannot find the proper scaling numbers, or to correct minor errors made at the tablet, uses subroutine XYVDT to convert X,Y pairs to a compatible data set for the rest of the program, and it assumes no pulseshape for operation.

SK [a] Skip 'a' data sets (graphics tablet format) on logical unit IU

XY [a] Reads (X,Y) coordinate pairs from control terminal, converts to standard data set to store in column a. Generates a standard, compatible data set using time and voltage scaling, same as TA (tablet) routine but without leading and trailing automatic scaling, rotation numbers. Input time and voltage scales must be in units of seconds/nib or volts/nib, where 1 nib is the resolution of the table output. It provides a chance to correct errors after data are entered. It also allows observation of the data when the run is finished.

MI [a] Reads data from a Biomation[8] 8100 Transient Recorder via MIDAS[8] interface, stores data in column a

FP Reads data from a transient recorder until the first peak is observed. Prints out the true peak value and the position, virtual risetime and rate-of-rise of impulse.

Data Analysis Routine

PO [abc] If columns a,b represent the voltage and the current in a waveform, column c (output) will represent instantaneous power.

IM [a] Uses subroutine NEARST to locate peak (single maximum value).

Searches before and after an apparent peak to insure that the true peak has been located, calculates the value of the peak and its location in time.

Calculates the virtual risetime which is defined as 1.67 times the time interval between the points which are 30% and 90% of the peak value on the rise of a voltage pulse and as 1.25 times the time interval between the points which are 10% and 90% of the peak value on the rise of a current pulse.

Calculates the virtual rate of rise which is the ratio of the peak value and the virtual risetime.

Calculates the virtual origin which is a time defined as the time at which the voltage waveform reaches 30% of its peak value minus 0.3 times the virtual risetime for a voltage wave and, for a current wave, as the time at which the current waveform reaches 10% of its peak value minus 0.1 times the virtual risetime.

Calculates the virtual fall time which is defined as the time interval between the virtual origin and the time at which either the voltage or current waveform returns to a value of 50% of the peak after the peak has been reached.

SM [ab] Fits the data in column a to a third order polynominal, five points at a time, creating column b (non-destructive).

CO [abc] Calculates the average percent difference and standard deviation between data in columns a and b and stores instantaneous error in column c.

PI [abc] If an input waveform is in column a and a step response in column b, this subroutine uses Duhamel's integral to calculate an output waveform which is in column c.

NO [a] If column a contains a step response, it will be normalized to a positive unit step by altering the scale factor and assuming average of last five data points represents 1. This routine can be used to eliminate dc offsets from a waveform or to normalize the response of a Kerr system.

Auxiliary Subroutines

ROTSCA -- Corrects for rotation and scaling of (X,Y) coordinate data from graphics tablet (used by TA).

XYVDT -- Converts (X,Y) coordinate data set into constant-sample-interval data set for TA and XY routines.

NEARST -- Finds the nearest data point in a column of data to the specified value, returns its location and error.

FIXDTA -- Fits any floating-point data set into an integer column, finds best scale factor.

RELESE -- Releases interface driver for subsequent use.

MIDAS -- Interface driver, sends one line of commands, one line of data.

CONURT -- Converts interface ASCII output to 16-bit integer, reconstructs transient recorder output.

WAIT -- Interrupts operating system, waits for operator to press 'RUN' button on front panel of CPU.

CLOSE -- Closes all mass storage files.

SYSTEM -- Allows a FORTRAN program to execute operating system instructions by passing them through this routine as a character string.

READ 1 -- Reads one character from logical unit 5 and returns to program without carriage return.

IV. EXPERIMENTAL MEASUREMENTS

IV.1 Introduction

A series of measurements was performed in the high voltage laboratory of the Bonneville Power Administration (BPA), Vancouver, Washington. During these measurements, the primary measurement devices were three high voltage dividers. One was the resistor divider, rated at one million volts, which was described earlier. For convenience of notation, this divider is referred to as NBS-1.

The second divider was a resistor divider owned by the Bonneville Power Administration. This divider, which is referred to as BPA-R, is approximately 6.5 m tall and consists of counterwound resistor sections in a porcelain enclosure. Either one of two low-side resistances could be selected. Measured resistance values for this divider are presented in Table 3.

TABLE 3: MEASURED RESISTANCES DIVIDER BPA-R

	Value from earlier BPA data	Value measured using BPA bridge during test period
High Impedance Element	11630 Ω	11616 Ω
Low Impedance Element #1	43.88 Ω	44.05 Ω
Low Impedance Element #2	14.64 Ω	---

The third divider referred to as BPA-C, is a mixed (RC) divider approximately 15 m high and rated at 4.5 MV, shown schematically in Fig. 14. The high impedance element consists of a number of identical resistor-capacitor units in series, each unit consisting of a 2250 pF capacitor and a 50 Ω resistor (these values were provided by the manufacturer and not reverified as a part of this investigation). The series capacitance had been measured by the BPA staff to be 433.43 pF. The primary components of the low impedance element are a resistive and capacitive element bolted to the base of the divider, a cable -- with impedance matching series resistor R located at the divider -- to connect the divider to the oscilloscope, and the cable termination located at the input to the oscilloscope.

The capacitance at the base of the divider C_ℓ, has a value 0.9641 μF. The resistance R_ℓ is zero, a modification which was apparently performed after the original construction of the divider. The individual resistors which originally constituted this resistance were still in place but had been shunted by soldered pieces of wire. The cable-matching resistor had a value of 50.48 Ω.

The terminator is a series of switch-selectable circuits, three of which are shown in Fig. 14. Switch position (1) permits direct connection of the cable to the oscilloscope input. Position (2) applies a terminator as shown. The remaining switch positions select other terminator-attenuator combinations. All terminators were designed to have nominal equivalent single series RC elements of 0.95 μF and 50 Ω.

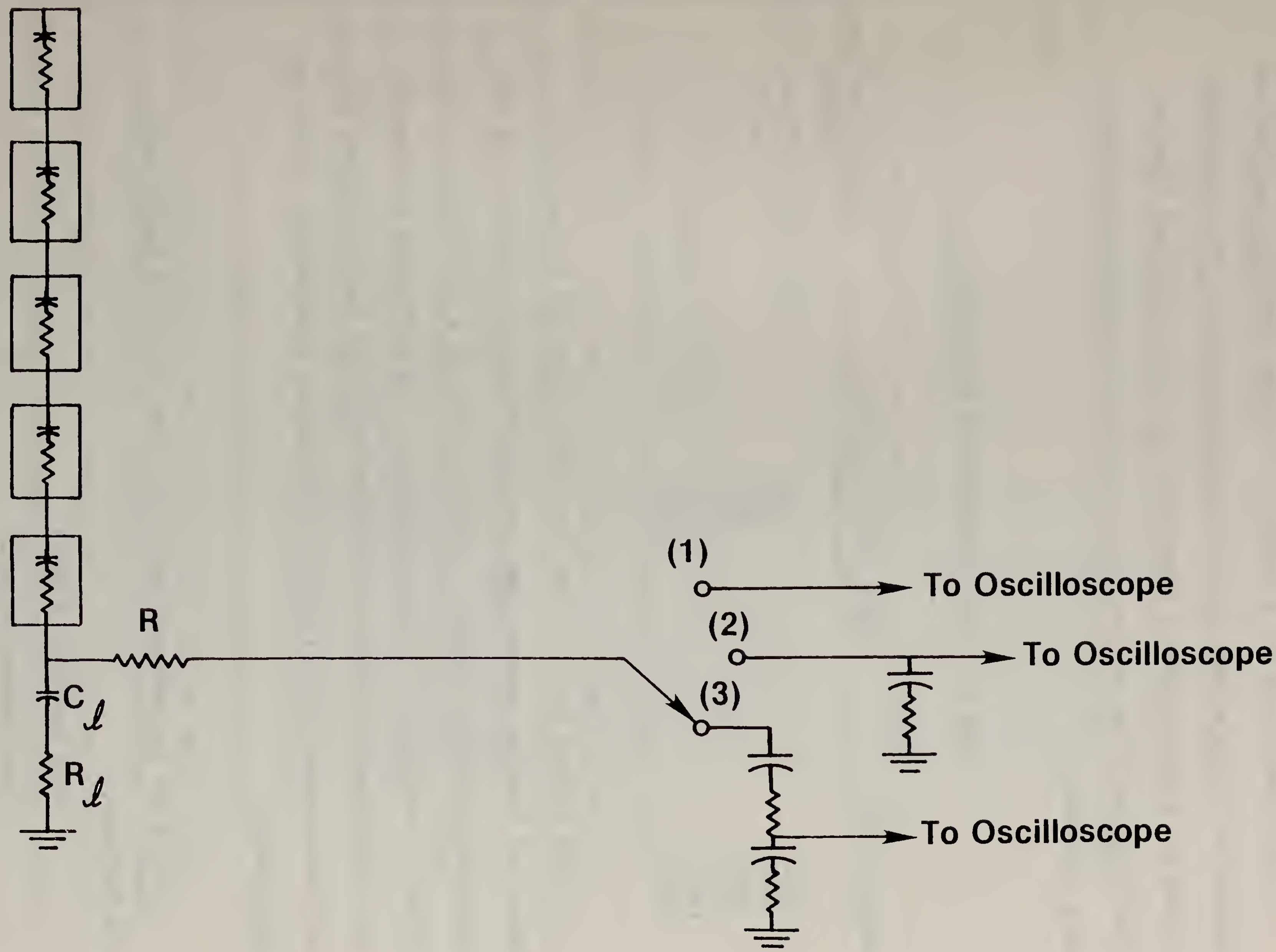


Fig. 14 Mixed divider (RC) with cable termination.

The divider ratio for a variety of divider terminator settings was determined at low voltage from the capacitance ratio. The calculated values are given in Table 4 along with the ratio determined from the step response at the one setting at which step response measurements were performed.

TABLE 4: BPA-C DIVIDER RATIO MEASUREMENTS

Nominal Ratio	Ratio from Capacitance Measurements	Ratio from Step-Response
2000	2334	--
4000	4636	4570
8000	9272	--
10000	11115	--
14000	16191	--
20000	23197	--

Table 4 shows that all the calculated ratios and the one ratio determined from the step-response are significantly different from the corresponding nominal ratios. This may be due to a modification of the divider's low-side after its manufacture. The difference between the ratio determined from capacitance measurements and that determined from the step-response (1.4%) is within the combined uncertainties of the two measurements.

During the two one-week test periods the following measurements were performed:

- step response of NBS-1
- step response of BPA-R
- step response of the combination of NBS-1 and BPA-R

- ramp response of the combination of NBS-1 and BPA-R
- step response of BPA-C
- step response of the combination of NBS-1 and BPA-C
- ramp response of the combination of NBS-1 and BPA-C.

Each of these measurements are described individually in the following sections.

IV.2 Step Response of NBS-1

The step-response of NBS-1 was measured in both BPA indoor high-voltage laboratories. The response time and divider ratio were consistent with those measured at NBS.

IV.3 Step Response of BPA-R

Step response measurements with various values of damping resistor are shown in Fig. 15. Note that for low values of the damping resistor two types of oscillation are apparent. One is a lower-frequency oscillation -- about 4 MHz -- attributable to a resonance between the lead inductance and divider capacitance which the damping resistor of higher value removes. The higher frequency oscillation -- about 30 MHz -- is apparently intrinsic to the divider.

In an effort to insure that the measured response was the true response to a voltage step and not due to an error in the design and/or construction of the test circuit, a variety of checks were made. A number of different configurations of the connections of the various devices to the ground mat were attempted. As a general observation, changes in the

$R_D = 0\,\Omega$
50 mV/Div Vertical
1 μs/Div Horizontal

$R_D = 184\,\Omega$
50 mV/Div Vertical
100 ns/Div Horizontal

$R_D = 576\,\Omega$
50 mV/Div Vertical
200 ns/Div Horizontal

Fig. 15 Typical step responses of BPA-R.

ground configuration produced slight changes in the high frequency oscillations, but no change yielded a substantive improvement. In addition, the following steps were taken:

- the stranded high voltage lead was replaced by a solid high voltage lead;

- tests were made in which the location of the cable connecting the divider to the oscilloscope was changed;

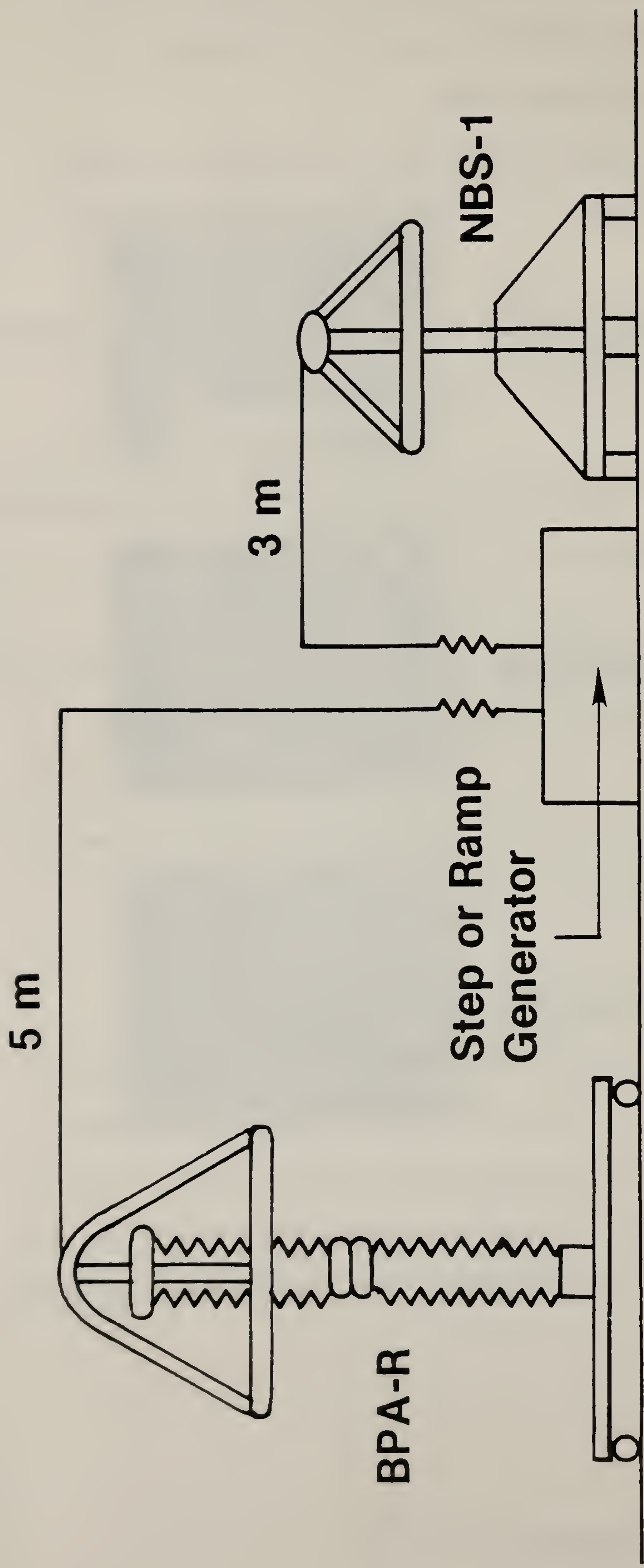
- an isolation transformer, provided by BPA, was used to separate the oscilloscope from the power system ground;

- an isolation transformer was used to separate the ground of the dc power supply from the power system ground.

None of these adjustments produced a significant modification of the high frequency oscillations.

IV.4 Step Response of the Combination of NBS-1 and BPA-R

One of the measurements performed was the simultaneous recording of the same waveform using the two different dividers. One purpose of these tests was to insure that the signal in one measuring circuit did not influence the response of the other measuring circuit. Using the circuit shown in Fig. 16, the following measurements were performed:


NBS-1
3 m
5 m
Step or Ramp
Generator
BPA-R

- the step response of NBS-1 with BPA-R disconnected from the step generator, i.e., the measurement circuit was open at the step generator, and the BPA-R measurement loop was grounded at the step generator;

- the step response of BPA-R with NBS-1 open and with NBS-1 grounded at the step generator;

- the simultaneous step responses with both measurement systems connected to the step generator.

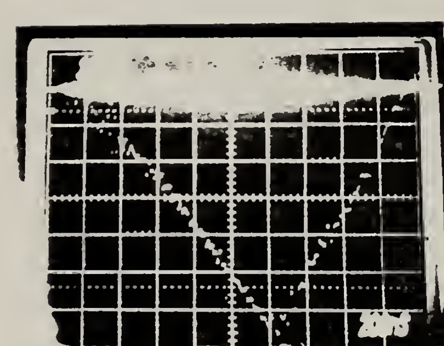
No difference in the step response was discernible in any of the configurations. This was the anticipated result.

IV.5 Ramp Response of the Combination of NBS-1 and BPA-R

The same sequence of measurements outlined above was performed with the step generator replaced by the low-voltage ramp generator. The significant result of these measurements is shown by the photographs in Fig. 17. These photographs show a simultaneous measurement of the same ramp using NBS-1 and BPA-R. Note the high frequency oscillations in the measurement using BPA-R. It is assumed that these are due to the same source as the high frequency oscillations in the step response. From

Simultaneous
Measurements

NBS-1
5 mV/Div Vertical
200 ns/Div Horizontal



BPA-R
100 mV/Div Vertical
200 ns/Div Horizontal

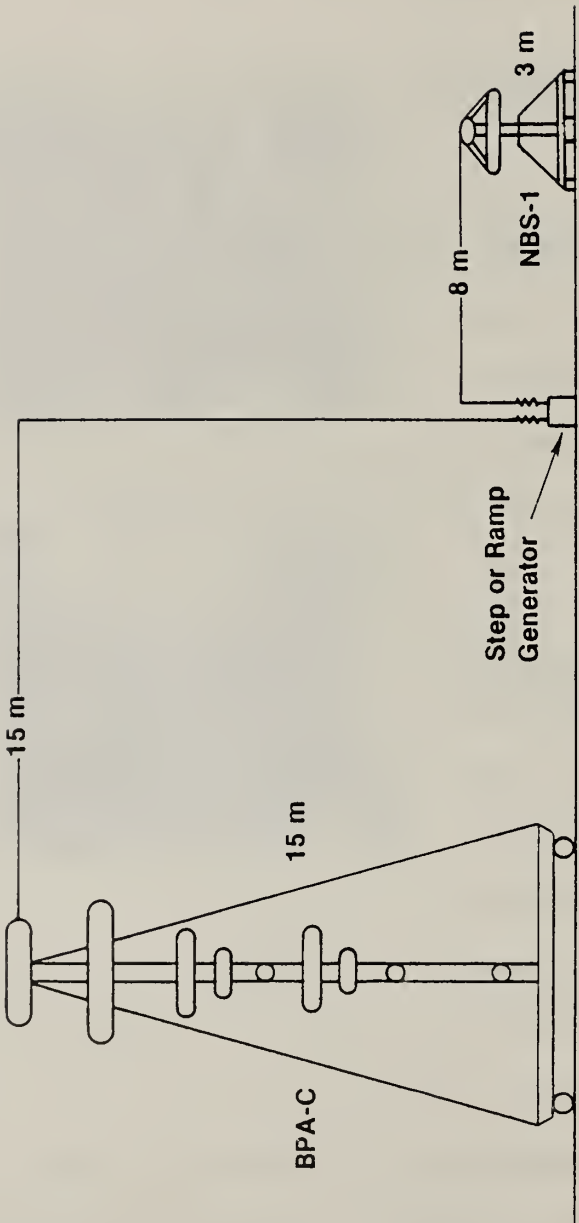
Fig. 17 Input ramp (upper photo) and response of BPA-R (lower photo).

the response of NBS-1, it can be seen that the ramp is chopped approximately 1.2 μs after the pulse is initiated. The oscillations in the BPA-R measurement system, therefore, persist into the time domain relevant for tests on power system apparatus. Information provided by the staff of BPA indicated that these oscillations are also apparent during high voltage tests using a standard lightning impulse and so are not merely an artifact of the low voltage calibration procedure.

Because the oscillations are apparently intrinsic to the BPA-R measurement system, and because they persist throughout the time domain of interest for these tests, it was concluded that this measurement system was inappropriate for the ±3% accuracy desired in these tests. For that reason the remainder of the experimentation and analysis was performed using BPA-C.

IV.6 Step Response of BPA-C

The step response of BPA-C was measured in the outdoor test area. The experimental arrangement is shown in Fig. 18. Measurements were made using damping resistors having values of 0, 61, 103, 141, 184, 269, and 451 Ω. A plot of the response time vs. damping resistance is shown in Fig. 19. The slope of the least-squares fit to the data points indicates that the input capacitance of the divider is 780 ± 40 pF. The input capacitance was also measured using a capacitance bridge. In the square loop arrangement -- the arrangement in which the step response was measured -- the input capacitance was 820 pF. If the high voltage lead is run along a


15 m
Step or Ramp Generator
8 m
NBS-1
3 m
BPA-C
15 m

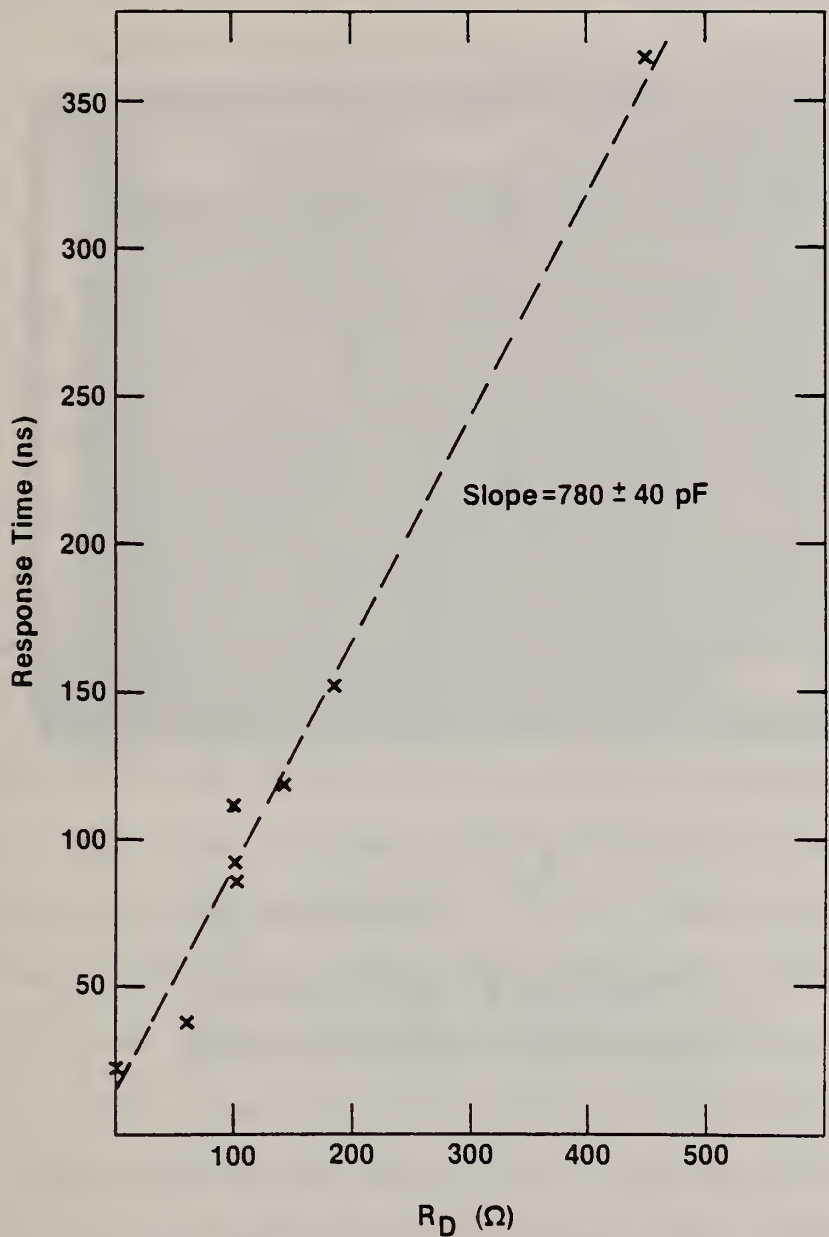
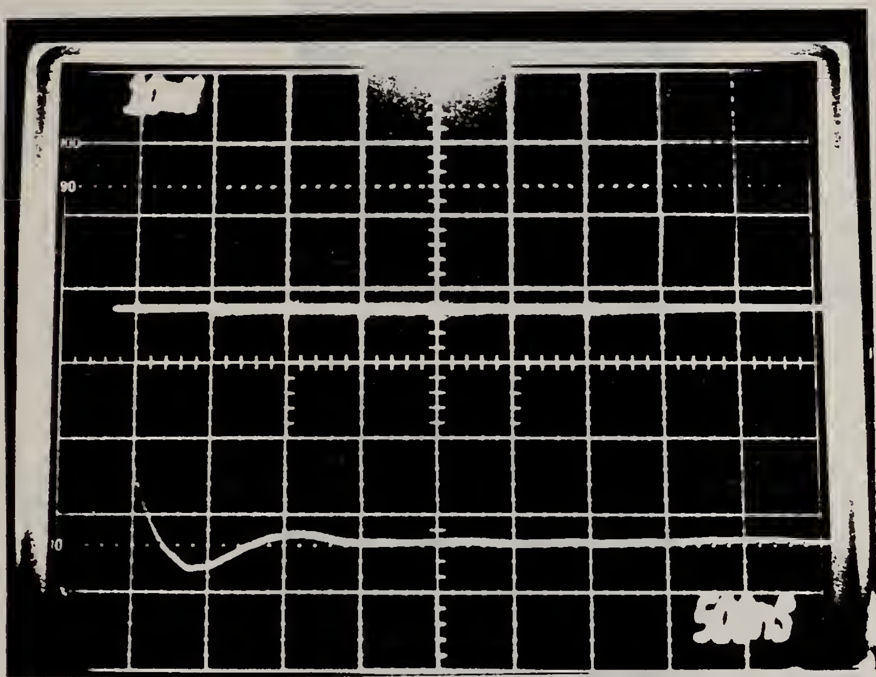


Fig. 19 Response time of BPA-C as a function of damping resistance.

diagonal of the original square loop, the input capacitance is 790 pF. Because the disagreement between the input capacitance as determined from the step response and as measured using bridge techniques is somewhat larger than anticipated, it was judged to be prudent to attempt to identify the source of the difference.

An examination of the step response data, Fig. 20, shows that there is a difference between the level at which the step was triggered and the position of the zero line as evidenced by a vertical gap of about 5 mV between the base line and the start of the step trace. An investigation of the circuit indicated that there is a 60 Hz signal with peak-to-peak amplitude of approximately 6 mV appearing on the oscilloscope screen with no input signal applied to the divider, Fig. 21a. If everything is left in the same physical location but the divider low-side is electrically disconnected from the divider high-side, the signal amplitude is reduced to about 3 mV peak-to-peak, Fig. 21b. If the low-side is reconnected to the divider, but the ground connection is broken, the peak-to-peak amplitude of the 60-Hz signals is 3 mV, Fig. 21c. From these data, it is inferred that approximately equal signals are coming from the divider and from pick-up in the low-side and connecting cables. There are a variety of 60-Hz sources in the vicinity of the outdoor laboratory including a non-interruptable 13.8 kV supply line about 18-20 m from the divider.

As a result of this investigation, it was concluded that it was not feasible to perform a low-voltage calibration of the divider in the outdoor test area, so the divider was moved inside the high voltage laboratory.



$R_D = 184\,\Omega$
10 mV/Div Vertical
500 ns/Div Horizontal

Fig. 20 Typical step response of BPA-C during outdoor tests.

(a) 10 mV/Div Vertical
5 ms/Div Horizontal

(b) 10 mV/Div Vertical
5 ms/Div Horizontal

(c) 10 mV/Div Vertical
5 ms/Div Horizontal

Fig. 21 Output of divider with no input (a); output with only the divider low-side and cable connected to the oscilloscope (b); output with shield of cable open-circuited at divider.

The physical arrangement of the divider in the laboratory is shown in Fig. 22. In this configuration, the measured input capacitance was 790 pF. In the indoor laboratory, the 60-Hz signal was negligible and to within experimental uncertainty the response time of the measuring circuit was the product of the input capacitance of the divider, as measured by the capacitance bridge -- and the value of the damping resistor. This result indicates that the low-voltage measuring system is behaving in a manner consistent with the theoretical model used for system calibration.

IV.7 Step Response of the Combination of NBS-1 and BPA-C

Before BPA-C was moved into the indoor laboratory, step responses were recorded in the outdoor test area using the measurement circuit shown in Fig. 18. Again the following measurements were performed:

- step response of BPA-C with NBS-1 grounded and "open" at the step generator;

- step response of NBS-1 with BPA-C grounded and "open" at the step generator;

- simultaneous responses of both NBS-1 and BPA-C to the same voltage step.

As before, no interaction between the two circuits was observed. As described in the previous section, the induced 60-Hz signal in the system made this data unsuitable for quantitative analysis. Because both

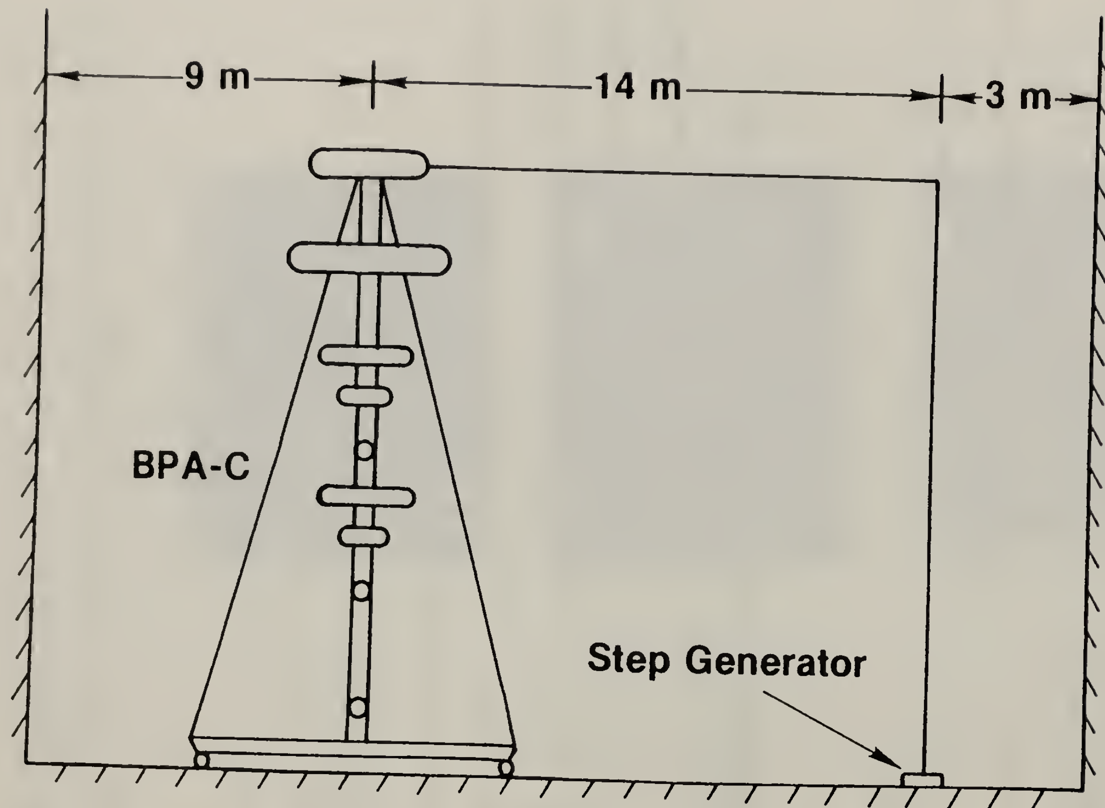


Fig. 22 Experimental arrangement for indoor step-response measurements of BPA-C.

these data and the measurements taken using NBS-1 and BPA-R indicated no interaction between the circuits, this set of measurements was not repeated in the subsequent indoor tests. Step responses of the dividers in the high voltage laboratory were, of course, measured and are shown in Fig. 23.

IV. 8 Ramp Response of the Combination of NBS-1 and BPA-C

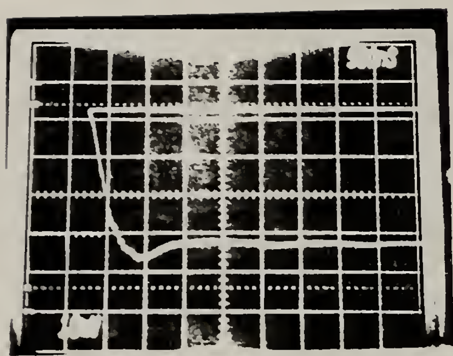
Ramp responses were obtained using both high and low voltage ramps. These responses were used to perform the calculations described in the next section of this report.

The low voltage ramp measurements were identical to those performed using NBS-1 and BPA-R, described above. Typical data showing the ramp measured with NBS-1, BPA-C and directly measured using a low-voltage attenuator are shown in Fig. 24.

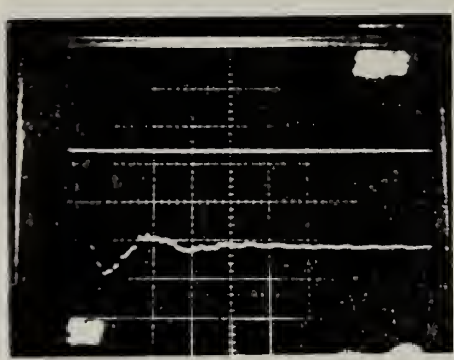
The circuit for the measurement with the high voltage ramp is shown in Fig. 25. A conventional Marx generator applied a high voltage pulse to a sphere gap. The voltage across the sphere gap was measured using both NBS-1 and BPA-C. High voltage damping resistors were constructed and were used in each measuring circuit. The high voltage ramp responses of the two measuring systems in the high voltage configuration using the high voltage damping resistors are shown in Fig. 26.

V. DUHAMEL'S INTEGRAL CALCULATIONS

To verify that the measuring system is well characterized, it is necessary to insure that Duhamel's Integral computation of the output waveform predicts the measured waveform.



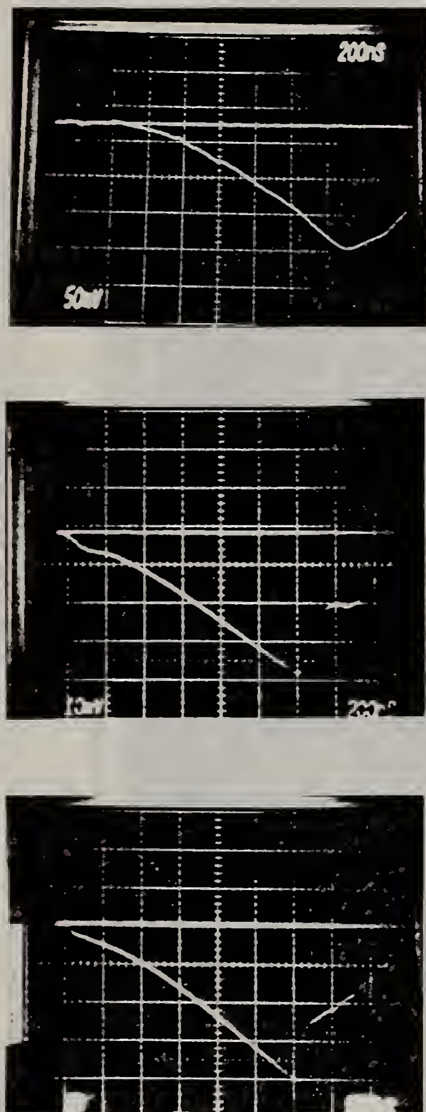
Step Response
BPA-C
Vertical: 10 mV/Div
Horizontal: 500 ns/Div



Step Response
NBS-1
Vertical: 10 mV/Div
Horizontal: 200 ns/Div

Fig. 23 Step responses of BPA-C and NBS-1 inside high voltage laboratory.

Low Voltage Ramp Measurements

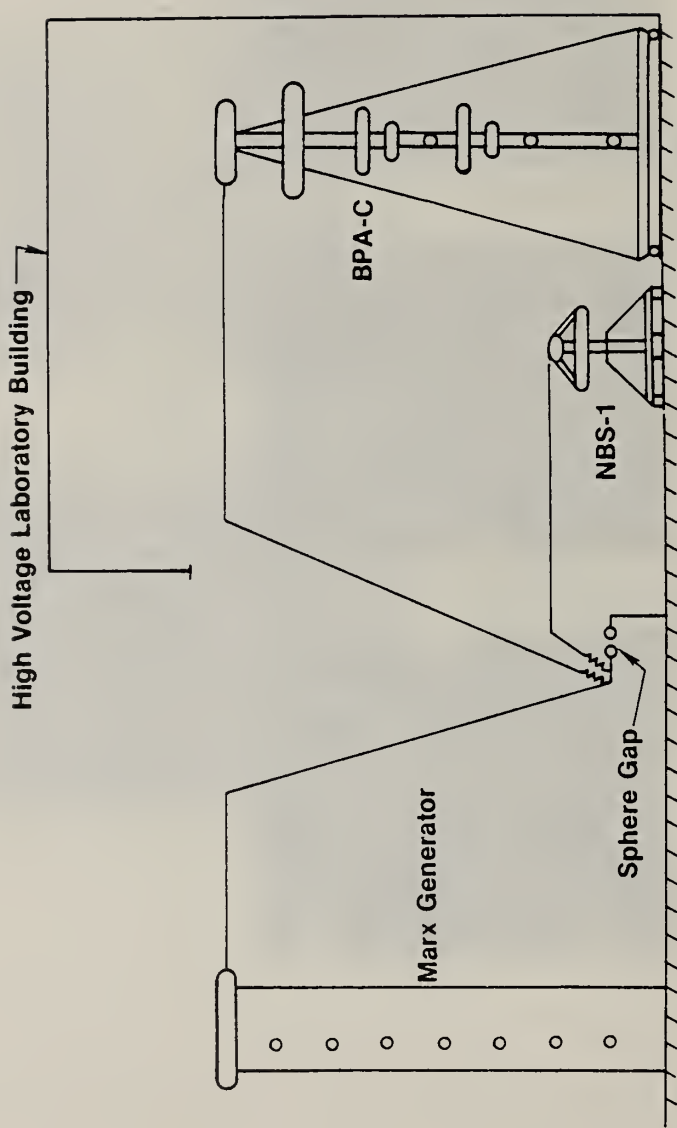


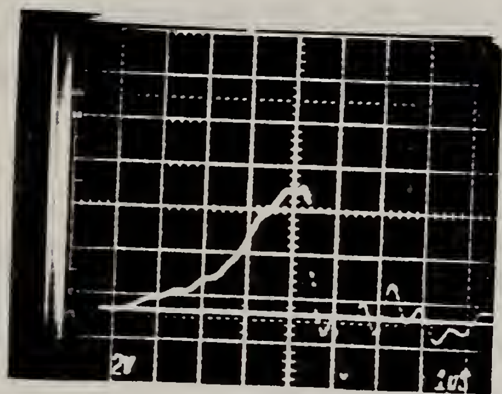
BPA-C

NBS-1

Direct

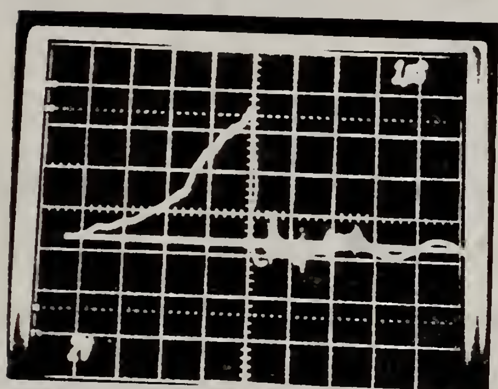
Fig. 24 Ramp measured with BPA-C, NBS-1, and directly from generator (simultaneous measurements).


High Voltage Laboratory Building
BPA-C
NBS-1
Marx Generator
Sphere Gap



Ramp Response

BPA-H
Vertical: 20 kV/Div
Horizontal: 1 μs/Div



NBS-1
Vertical: 20kV/Div
Horizontal: 1 μs/Div

Fig. 26 Typical ramp responses of BPA-C and NBS-1 (simultaneous measurements).

Data from three different experimental set-ups are summarized in Table 5. The first set of data was taken with a low voltage ramp measured simultaneously using the divider BPA-C and a low-voltage attenuator. The Duhamel's Integral calculation used the step response of BPA-C, measured in the experimental configuration, and the directly measured waveform to calculate the output waveform from BPA-C. Measured and calculated outputs are compared in columns 2-4.

The second set of data presented is the result of a simultaneous measurement of a low-voltage ramp using NBS-1 and BPA-C. In this case it is assumed that the waveform as measured by NBS-1 is the input to BPA-C. The comparison between the calculated and measured outputs is shown in columns 5-7.

The final set of data is the result of a simultaneous measurement of a high-voltage ramp using NBS-1 and BPA-C. Again it is necessary to assume that the output waveform from NBS-1 is the input waveform to BPA-C. These results are presented in columns 8-10.

The magnitude of the average difference obtained is within expected experimental uncertainty. Each calculation required four measurements -- the step response of each divider and the ramp response of each divider. The step response was needed both to determine the divider ratios and to perform the integration. The ramp was recorded and digitized for the integration and transcription of results. The accuracy of recording and transcription is estimated to be of order 1%, so an average difference of less than about 2% is probably coincidental.

TABLE 5: DUHAMEL'S INTEGRAL CALCULATIONS

Time (μs)	Calculated Output (V)	Measured Output (V)	Difference % of Peak	Calculated Output (V)	Measured Output (V)	Difference % of Peak	Calculated Output (kV)	Measured Output (kV)	Difference % of Peak
	Input: Direct; Output: BPA-C; Low Voltage Ramp			Input: NBS-1; Output: BPA-C; Low Voltage Ramp			Input: NBS-1; Output: BPA-C; High Voltage Ramp		
0.2	20.7	23.7	-1.0	9.6	15.8	-2.0	25.0	19.5	+1.8
0.3	40.1	40.7	-0.2	27.1	36.4	-3.0	46.4	41.3	+1.7
0.4	61.8	63.0	-0.4	46.9	58.9	-3.8	93.1	88.2	+1.6
0.5	88.0	87.1	+0.3	68.1	85.6	-5.6	124.0	121.0	+1.0
0.6	118.0	115.0	+1.0	94.4	106.0	-3.7	154.0	154.0	---
0.7	153.0	148.0	+1.6	126.0	137.0	-3.5	176.0	181.0	-1.7
0.8	190.0	184.0	+2.0	160.0	166.0	-1.9	210.0	207.0	+1.0
0.9	230.0	220.0	+3.2	197.0	195.0	+0.6	233.0	233.0	---
1.0	271.0	260.0	+3.0	234.0	232.0	+0.6	254.0	257.0	-1.0
1.1	311.0	399.0	+4.0	273.0	272.0	+0.3	278.0	278.0	---
1.2	---	---	---	312.0	313.0	+0.3	300.0	301.0	-0.3
	Average Difference		1.7%	Average Difference		2.3%	Average Difference		0.9%

VI. CONCLUSIONS

The data presented indicate that, under the conditions of this test, a Duhamel's Integral calculation is valid for a 4.5 MV divider. From this it can be inferred that the measured response of this divider to a low voltage step provides sufficient information about the transfer function of the measurement system to predict the response to the specific pulses used in this test.

Although this is a significant first step, more work remains to completely characterize the measuring system. Specific individual investigations which would be desirable include:

- measurements of higher voltage, faster ramps where the higher time rate of change of the current may provide more significant coupling between the voltage generating circuit and either of the two measuring circuits;

- development of methods to evaluate the transfer functions of the measurement systems outdoors in situations where the 60-Hz signals make low voltage measurements unfeasible;

- development of more convenient calibration methods which will permit rapid recalibration of the measurement system in each configuration used in an industrial laboratory.

The necessity to develop fast, convenient, accurate methods to evaluate measurement system behavior cannot be overemphasized. A change in divider location or in lead configuration significantly changes the divider ratio. For large dividers, such as the one tested here, variations of the ratio of several percent can occur for the measurement of the peak value of a standard lightning impulse. For faster pulses, even very small changes in the circuit configuration may have significant impact on the divider ratio. It is, therefore, necessary to verify the magnitude of the ratio in each configuration of the measurement circuit.

The low-voltage step response method used here (presented in the standard IEEE-4), although proven to be correct in this application, requires very accurate low voltage measurements under adverse circumstances. Routine application of the technique, therefore, requires experienced, highly trained measurement specialists. Until improved calibration methods are proven to be accurate, industrial high voltage laboratories will be forced to develop specific training programs for laboratory staff or tolerate unspecified, but probably significant, measurement errors.

VII. REFERENCES

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2. R. Malewski, D. Train and A. De Champlain, "Cavity Resonance Effect in Large HV Laboratories Equipped with Electromagnetic Shield," IEEE Trans. Power App. Sys., Vol. PAS-77, pp 1863-1871, 1977.

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5. See, for example, F.C. Creed and M.M.C. Collins, "The Measurement of Short-Duration Impulse Voltages," AIEE Trans., pp 621-630, 1963.

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7. R.E. Hebner, R. Malewski, E.C. Cassidy, "Optical Methods of Electrical Measurement at High Voltage Levels," Proc. IEEE, Vol. 65, pp 1524-1548, 1977.

8. Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

APPENDIX 1

LISTING OF SOFTWARE USED FOR

DATA ANALYSIS

```
      INTEGER*2 NA(600,12)
      REAL DV(12),DATE(5),XNAME(5),COLABL(12,3)
      COMMON /SCRAT/WORK(600)
      IMPLICIT INTEGER*2 (I-N)
1001  LOU=2
      LIU=1
      WRITE(6,101)
101   FORMAT('ENTER DATE, TIME, N, DT')
      READ(5,102)DATE,N,DT
102   FORMAT(5A3,I4,E10.3)
      IF(N.GT.600)WRITE(6,114)N
114   FORMAT('N GREATER THAN 600 =',I4,' OVERLAP WILL OCCUR ****')
      WRITE(6,102)DATE,N,DT
1000  WRITE(6,103)
103   FORMAT('>')
      READ(5,104)I2,K1,K2,K3
104   FORMAT(A2,1X,3Z1)
      WRITE(6,104)I2,K1,K2,K3
      IF(K1.GT.12.OR.K2.GT.12.OR.K3.GT.12)GOTO 21
      IF(I2.NE.'SM'.OR.K1.EQ.K2)GOTO 1
      DV(K2)=DV(K1)
      CALL SMOOTH(NA(1,K1),NA(1,K2),N)
      GOTO 1000
1     IF(I2.NE.'CO')GOTO 2
      CALL CORREL(NA(1,K1),NA(1,K2),DV(K1),DV(K2),N)
      DO 116 I=1,N
      NA(1,K3)=IFIX(WORK(I)*1000.)
116   CONTINUE
      DV(K3)=1.
      GOTO 1000
2     IF(I2.NE.'DI'.OR.K3.EQ.0)GOTO 3
      D3=DV(K1)*DV(K2)
      CALL DUHAME(NA(1,K1),NA(1,K2),N,D3)
      CALL FIXDTA(NA(1,K3),DV(K3),N)
      GOTO 1000
3     IF(I2.NE.'IM')GOTO 4
      CALL IMPULS(NA(1,K1),N,DV(K1),DT)
      GOTO 1000
4     IF(I2.NE.'NO')GOTO 45
      CALL NORMAL(NA(1,K1),N,DV(K1))
      GOTO 1000
45    IF(I2.NE.'PO')GOTO 5
      D3=DV(K1)*DV(K2)
      DO 46 I=1,N
      WORK(I)=D3*NA(I,K1)*NA(I,K2)
46    CONTINUE
      CALL FIXDTA(NA(1,K3),DV(K3),N)
      GOTO 1000
5     IF(I2.NE.'MI')GOTO 6
      CALL MREAD(NA(1,K1),N,DV(K1))
      GOTO 1000
```

```
      GOTO 1000
6     IF(I2.NE.'FP')GOTO 7
      CALL FASTPK
      GOTO 1000
7     IF(I2.NE.'TA')GOTO 8
      CALL FITAB(LIU,NA(1,K1),N,DV(K1),DT)
      GOTO 1000
8     IF(I2.NE.'SK')GOTO 85
      CALL SKIP(LIU,K1)
      GOTO 1000
85    IF(I2.NE.'XY')GOTO 9
      CALL XYDATA(NA(1,K1),N,DV(K1),DT)
      GOTO 1000
9     IF(I2.NE.'RE')GOTO 95
      READ(LIU,109)(COLABL(K1,J),J=1,3),DV(K1)
109   FORMAT(3A4,' DATA, SCALE-FACTOR=',E12.5)
      READ(LIU,110)(NA(I,K1),I=1,N)
110   FORMAT(11I6)
      GOTO 1000
95    IF(I2.NE.'LA')GOTO 10
      WRITE(6,106)
106   FORMAT('ENTER LABEL (12 CHARS.)')
      READ(5,115)(COLABL(K1,J),J=1,3)
115   FORMAT(3A4)
      GOTO 1000
10    IF(I2.NE.'WR')GOTO 11
      WRITE(LOU,109)(COLABL(K1,J),J=1,3),DV(K1)
      WRITE(LOU,110)(NA(I,K1),I=1,N)
      GOTO 1000
11    IF(I2.NE.'RL')GOTO 12
      READ(LIU,111)DATE,XNAME,NC,N1,DT1
111   FORMAT(5A3,5A4,I2,I4,E12.5)
      WRITE(6,111)DATE,XNAME,NC,N1,DT1
      GOTO 1000
12    IF(I2.NE.'WL')GOTO 13
      REWIND LOU
      WRITE(6,112)
112   FORMAT('ENTER NUMBER OF DATA SETS(I2), FILENAME(20)')
      READ(5,113)NC,XNAME
113   FORMAT(I2,5A4)
      WRITE(LOU,111)DATE,XNAME,NC,N,DT
      GOTO 1000
13    IF(I2.NE.'LU')GOTO 14
      CALL SYSTEM('LU',2)
      WRITE(6,105)LIU,LOU
105   FORMAT('INPUT UNIT=',Z1,' OUTPUT UNIT=',Z1)
      GOTO 1000
14    IF(I2.NE.'CP')GOTO 15
      DV(K2)=DV(K1)
      DO 141 I=1,N
```

```
      NA(I,K2)=NA(I,K1)
 141  CONTINUE
      GOTO 1000
 15   IF(I2.NE.'PA')GOTO 16
      PAUSE
      GOTO 1000
 16   IF(I2.NE.'EN')GOTO 17
      WRITE(6,107)
 107  FORMAT('END RUN--FILES CLOSED AND ZAPPED')
      CALL CLOSE
      CALL SYSTEM('ZU',2)
      STOP
 17   IF(I2.NE.'IU')GOTO 18
      LIU=K1
      GOTO 1000
 18   IF(I2.NE.'OU')GOTO 19
      LOU=K1
      GOTO 1000
 19   IF(I2.NE.'WF')GOTO 20
      ENDFILE K1
      GOTO 1000
 20   IF(I2.NE.'RW')GOTO 21
      REWIND K1
      GOTO 1000
 21   IF(I2.EQ.'KI')GOTO 1001
      WRITE(6,108)
 108  FORMAT(' WHAT?')
      GOTO 1000
      END
.U       EXT FUNC
NA       INT2 VAR
DV       REAL VAR
DATE     REAL VAR
XNAME    REAL VAR
COLABL   REAL VAR
SCRAT    COMMON     X'0960'
WORK     REAL VAR
1001     LABEL
LOU      INT2 VAR
LIU      INT2 VAR
101      LABEL
@H       EXT FUNC
102      LABEL
N        INT2 VAR
DT       REAL VAR
114      LABEL
1000     LABEL
103      LABEL
104      LABEL
```

```
K1      INT2 VAR
K2      INT2 VAR
K3      INT2 VAR
21      LABEL
1       LABEL
SMOOTH  EXT FUNC
2       LABEL
CORREL  EXT FUNC
116     LABEL
I       INT2 VAR
IFIX    EXT FUNC
3       LABEL
D3      REAL VAR
DUHAME  EXT FUNC
FIXDTA  EXT FUNC
4       LABEL
IMPULS  EXT FUNC
45      LABEL
NORMAL  EXT FUNC
5       LABEL
46      LABEL
.W      EXT FUNC
6       LABEL
MREAD   EXT FUNC
7       LABEL
FASTPK  EXT FUNC
8       LABEL
FITAB   EXT FUNC
85      LABEL
SKIP    EXT FUNC
9       LABEL
XYDATA  EXT FUNC
95      LABEL
109     LABEL
J       INT2 VAR
110     LABEL
10      LABEL
106     LABEL
115     LABEL
11      LABEL
12      LABEL
111     LABEL
NC      INT2 VAR
N1      INT2 VAR
DT1     REAL VAR
13      LABEL
@R      EXT FUNC
112     LABEL
113     LABEL
14      LABEL
```

```
SYSTEM  EXT FUNC
105     LABEL
15      LABEL
141     LABEL
16      LABEL
.H      EXT FUNC
17      LABEL
107     LABEL
CLOSE   EXT FUNC
.S      EXT FUNC
18      LABEL
19      LABEL
20      LABEL
@Z      EXT FUNC
108     LABEL
.V      EXT FUNC
```

```
$BATCH
      SUBROUTINE FITAB(LU,NA,N,DV,DT)
C **** READ AND CONVERT DATA FROM GRAPHICS TABLET ****
      INTEGER*2 NA(600),N,LU
      LOGICAL K
      IMPLICIT INTEGER*2 (I-N)
      COMMON /SCRAT/NBX(600),NBY(600)
      DO 1 I=1,600,4
      I1=I+3
      READ(LU,401)NEOD,(NBX(J),NBY(J),J=I,I1)
      IF(NEOD.NE.'.')GOTO 2
 401  FORMAT(A1,I6,7(1X,I6))
 1    CONTINUE
 2    READ(LU,402)N1,XSCALE,YSCALE
 402  FORMAT(I4,2E10.3)
      N2=I-1
      IF(N1.NE.N2)WRITE(6,403)N2,N1,N1
      IF(N1.GT.600)N1=600
 403  FORMAT('READ',I4,' YOU SAID',I4,' USE',I4)
      DT1=DT
      CALL ROTSCA(N1,XSCALE,YSCALE,DT1,K)
      IF(.NOT.K)RETURN
      DV=YSCALE
      CALL XYVDT(NA,N,N1,DT1)
      RETURN
      END
FITAB   FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
LU      FORM PAR
NA      FORM PAR
N       FORM PAR
DV      FORM PAR
DT      FORM PAR
K       LOG. VAR
SCRAT   COMMON    X'0960'
NBX     INT2 VAR
NBY     INT2 VAR
1       LABEL
I       INT2 VAR
I1      INT2 VAR
401     LABEL
@H      EXT FUNC
NEOD    INT2 VAR
J       INT2 VAR
2       LABEL
402     LABEL
N1      INT2 VAR
XSCALE  REAL VAR
YSCALE  REAL VAR
```

```
N2       INT2 VAR
403      LABEL
DT1      REAL VAR
ROTSCA   EXT FUNC
XYVDT    EXT FUNC
```

```
      SUBROUTINE SKIP(LU,I1)
C **** SKIP I1 DATA SETS ON TABLET FILE ****
      INTEGER*2 LU,I1,NX
      DO 2 I=1,I1
 1    READ(LU,401)NEOD,NX,NX,NX,NX,NX,NX,NX,NX
 401  FORMAT(A1,I6,7(1X,I6))
      IF(NEOD.EQ.'.')GOTO 1
      READ(LU,402)N,XSCALE,YSCALE
 402  FORMAT(I4,2E10.3)
      WRITE(6,402)N,XSCALE,YSCALE
 2    CONTINUE
      RETURN
      END
SKIP    FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
LU      FORM PAR
I1      FORM PAR
NX      INT2 VAR
2       LABEL
I       INT4 VAR
1       LABEL
401     LABEL
@H      EXT FUNC
NEOD    INT4 VAR
402     LABEL
N       INT4 VAR
XSCALE  REAL VAR
YSCALE  REAL VAR
```

```
      SUBROUTINE XYDATA(NA,N,DV,DT)
C **** GENERATE (X,Y) DATA SET, CONVERT TO (V,DT) ****
      INTEGER*2 NA(600),N
      REAL DV,DT
      IMPLICIT INTEGER*2 (I-N)
      COMMON /SCRAT/NBX(600),NBY(600)
      WRITE(6,101)
 101  FORMAT('ENTER NO. OF POINTS, TIME AND VOLTAGE SCALES, DATA')
      READ(5,102)N1,DT1,DV
 102  FORMAT(I3,2E10.3)
      DT1=DT/DT1
      READ(5,103)(NBX(I),NBY(I),I=1,N1)
 103  FORMAT(1X,I5,1X,I5)
      WRITE(6,104)(NBX(I),NBY(I),I=1,N1)
 104  FORMAT(4('.',2I5,3X))
 1    WRITE(6,105)
 105  FORMAT('CHANGE A PAIR?')
      CALL READ1(NY)
      IF(NY.EQ.'N')GOTO 2
      IF(NY.EQ.'Y')GOTO 3
      WRITE(6,104)(NBX(I),NBY(I),I=1,N1)
 3    WRITE(6,106)
 106  FORMAT('ENTER I,X,Y')
      READ(5,107)I,NX,NY
 107  FORMAT(I3,1X,I5,1X,I5)
      NBX(I)=NX
      NBY(I)=NY
      GOTO 1
 2    CALL XYVDT(NA,N,N1,DT1)
      RETURN
      END
XYDATA  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NA      FORM PAR
N       FORM PAR
DV      FORM PAR
DT      FORM PAR
SCRAT   COMMON     X'0960'
NBX     INT2 VAR
NBY     INT2 VAR
101     LABEL
@H      EXT FUNC
102     LABEL
N1      INT2 VAR
DT1     REAL VAR
103     LABEL
I       INT2 VAR
104     LABEL
```

```
105      LABEL
READ1    EXT FUNC
NY       INT2 VAR
2        LABEL
3        LABEL
106      LABEL
107      LABEL
NX       INT2 VAR
XYVDT    EXT FUNC
```

```
      SUBROUTINE MREAD(NA,N,DV)
C **** MIDAS-READING ROUTINE ****
      INTEGER*2 NA(600),NOCMD(8),N
      IMPLICIT INTEGER*2 (I-N)
      WRITE(6,503)
 503  FORMAT('ENTER D.R., V. SCALE')
      READ(5,505)DR,DV
 505  FORMAT(2E10.3)
      DV=DV*DR/128.
      WRITE(6,504)
 504  FORMAT(' PUSH ''RUN'' BUTTON WHEN READY')
 53   CALL WAIT
      DO 51 I=1,N
      CALL MIDAS(34,NOCMD,NA(I),2,NSTAT)
      DATA NOCMD/X'2343','T1','T2','R:','S0','T3','B1','0 '/
      CALL CONVRT(NA(I),2)
      IF(NSTAT.EQ.0)GOTO 51
      WRITE(6,501)NSTAT,I
 501  FORMAT('MIDAS ERROR ',I3,' AT ',I4)
      GOTO 53
 51   CONTINUE
      CALL RELESE(34)
      RETURN
      END
MREAD   FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NA      FORM PAR
N       FORM PAR
DV      FORM PAR
NOCMD   INT2 VAR
503     LABEL
@H      EXT FUNC
505     LABEL
DR      REAL VAR
504     LABEL
53      LABEL
WAIT    EXT FUNC
51      LABEL
I       INT2 VAR
MIDAS   EXT FUNC
NSTAT   INT2 VAR
CONVRT  EXT FUNC
501     LABEL
RELESE  EXT FUNC
```

```
      SUBROUTINE FASTPK
C **** FAST PEAK-FINDING ROUTINE ****
      INTEGER*2 NOCMD(8)
      IMPLICIT INTEGER*2 (I-N)
      COMMON /SCRAT/NA(1200)
      WRITE(6,503)
503   FORMAT('ENTER D.R., V. SCALE, T. SCALE')
      READ(5,505)DR,DV,DT
505   FORMAT(3E10.3)
      DV=DV*DR/128.
      WRITE(6,504)
504   FORMAT(' PUSH ''RUN'' BUTTON WHEN READY')
41    CALL WAIT
      DO 42 I=1,1200
      CALL MIDAS(34,NOCMD,NA(I),2,NSTAT)
      DATA NOCMD/X'2343','T1','T2','R;','S0','T3','B1','0 '/
      CALL CONVRT(NA(I),2)
      IF(NSTAT.EQ.0)GOTO 43
      WRITE(6,501)NSTAT,I
501   FORMAT(' MIDAS ERROR =',I3,' AT ',I4)
      GOTO 41
43    DO 42 J=1,10
      J1=I-J
      IF(J1.LT.0.OR.NA(I).GT.NA(J1))GOTO 42
      GOTO 44
42    CONTINUE
      WRITE(3,507)I,NA(I)
507   FORMAT(' NO PEAK FOUND--',I4,I6)
44    ND3=I
      ND5=I/2
      DO 45 I=ND5,ND3
      DO 46 J=1,ND5
      J1=I-J
      ND2=MIN02(I+J,ND3)
      IF(NA(I).LE.NA(J1).OR.NA(I).LT.NA(ND2))GOTO 45
46    CONTINUE
      DO 47 J=1,10
      J1=I-J
      IF(NA(I).NE.NA(J1))GOTO 48
47    CONTINUE
45    CONTINUE
48    V=DV*NA(I)
      TIME=DT*ND3
      NDATA=IFIX(0.3*ND3)
      CALL NEARST(NA,NDATA,NEAR,1,ND3,LOC1)
      WRITE(6,506)NEAR,LOC1,NA(LOC1)
      NDATA=IFIX(0.9*ND3)
      CALL NEARST(NA,NDATA,NEAR,1,ND3,LOC2)
      WRITE(6,506)NEAR,LOC2,NA(LOC2)
506   FORMAT(1X,I6,1X,I4,1X,I6)
```

```
      TRISE=1.67*(LOC2-LOC1)*DT
      RATE=DV*ND3/TRISE
      CALL RELESE(34)
      WRITE(6,502)V,TIME,TRISE,RATE
  502 FORMAT('PEAK=',E12.5,' AT ',E12.5,/'RISE-TIME=',E12.5,/'RATE
     1-OF-RISE=',E12.5)
      RETURN
      END
FASTPK  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NOCMD   INT2 VAR
SCRAT   COMMON    X'0960'
NA      INT2 VAR
503     LABEL
@H      EXT FUNC
505     LABEL
DR      REAL VAR
DV      REAL VAR
DT      REAL VAR
504     LABEL
41      LABEL
WAIT    EXT FUNC
42      LABEL
I       INT2 VAR
MIDAS   EXT FUNC
NSTAT   INT2 VAR
CONVRT  EXT FUNC
43      LABEL
501     LABEL
J       INT2 VAR
J1      INT2 VAR
44      LABEL
507     LABEL
ND3     INT2 VAR
ND5     INT2 VAR
45      LABEL
46      LABEL
ND2     INT2 VAR
MIN02   EXT FUNC
47      LABEL
48      LABEL
V       REAL VAR
.W      EXT FUNC
TIME    REAL VAR
NDATA   INT2 VAR
IFIX    EXT FUNC
NEARST  EXT FUNC
NEAR    INT2 VAR
506     LABEL
LOC2    INT2 VAR
TRISE   REAL VAR
```

```
506       LABEL
LOC2      INT2 VAR
TRISE     REAL VAR
RATE      REAL VAR
RELESE    EXT FUNC
502       LABEL
```

```
      SUBROUTINE ROTSCA(N,XSCALE,YSCALE,DT,K)
C **** CALCULATE ROTATION, SCALING FOR DATA FROM TABLET ****
      INTEGER*2 N
      LOGICAL K
      IMPLICIT INTEGER*2 (I-N)
      COMMON /SCRAT/NBX(600),NBY(600)
      IROUND(A)=(IFIX(2.*A)+1)/2
      K=.FALSE.
      N=N-24
      N2=13
      IF(IABS(NBX(11)-NBX(12)).LE.1.AND.IABS(NBY(N+13)-NBY(N+14))
     1.LE.1)GOTO 1
      J1=N+9
      J2=N+24
      WRITE(6,101)(NBX(J),NBY(J),J=1,20),(NBX(J),NBY(J),J=J1,J2)
101   FORMAT(8(1X,I6))
      WRITE(6,102)N,N2
102   FORMAT(I4,' PAIRS START AT',I3,' ENTER NEW LIMITS')
      READ(5,103)N,N2
103   FORMAT(2I4)
1     X1=XSCALE*8./(NBX(3)-NBX(2)+NBX(4)-NBX(1))
      Y1=YSCALE*8./(NBY(2)-NBY(1)+NBY(3)-NBY(4))
      J1=N+N2+2
      X2=XSCALE*8./(NBX(J1+2)-NBX(J1+1)+NBX(J1+3)-NBX(J1))
      Y2=YSCALE*8./(NBY(J1+1)-NBY(J1)+NBY(J1+2)-NBY(J1+3))
      J1=J1+4
      X3=0.
      Y3=0.
      DO 2 J=1,5
      J2=J1+J
      Y3=Y3+FLOAT(NBY(J2)-NBY(J1))/(NBX(J2)-NBX(J1))
      J2=J+5
      X3=X3+FLOAT(NBY(J2)-NBY(5))/(NBX(J2)-NBX(5))
2     CONTINUE
      X3=X3/5.
      Y3=Y3/5.
      WRITE(6,104)X3,X1,Y1,Y3,X2,Y2
104   FORMAT('BEFORE, SLANT=',F5.3,' SCALE FACTORS=',2E10.3,/'AFT
     1ER, SLANT=',F5.3,' SCALE FACTORS=',2E10.3,' OK?')
      CALL READ1(NY)
      IF(NY.EQ.'R')RETURN
      IF(NY.EQ.'Y')GOTO 5
      IF(NY.NE.'B')GOTO 3
      X2=X1
      Y2=Y1
      Y3=X3
      GOTO 5
3     IF(NY.NE.'A')GOTO 4
      X1=X2
       GOTO 5
4
```

```
      GOTO 5
 4    WRITE(6,102)N,N2
      READ(5,103)N,N2
      GOTO 1
 5    DT=DT*2./ABS(X1+X2)
      YSCALE=(Y1+Y2)/2.
      X3=ATAN((X3+Y3)/2.)
      IF(NY.NE.'2')GOTO 6
      DT=DT*2.
      YSCALE=YSCALE/2.
 6    X4=COS(X3)
      Y4=SIN(X3)
      X5=X4*NBX(N2)+Y4*NBY(N2)
      Y5=X4*NBY(N2)-Y4*NBX(N2)
      N2=N2-1
      DO 7 I=1,N
      J1=N2+I
      NBX(I)=IROUND(X4*NBX(J1)+Y4*NBY(J1)-X5)
      NBY(I)=IROUND(X4*NBY(J1)-Y4*NBX(J1)-Y5)
 7    CONTINUE
      K=.TRUE.
      RETURN
      END
ROTSCA  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
N       FORM PAR
XSCALE  FORM PAR
YSCALE  FORM PAR
DT      FORM PAR
K       FORM PAR
SCRAT   COMMON     X'0960'
NBX     INT2 VAR
NBY     INT2 VAR
IROUND  STATE FN
A       FORM PAR
IFIX    EXT FUNC
N2      INT2 VAR
IABS    EXT FUNC
IABS2   EXT FUNC
1       LABEL
J1      INT2 VAR
J2      INT2 VAR
101     LABEL
@H      EXT FUNC
J       INT2 VAR
102     LABEL
103     LABEL
X1      REAL VAR
```

```
.W       EXT FUNC
Y1       REAL VAR
X2       REAL VAR
Y2       REAL VAR
X3       REAL VAR
Y3       REAL VAR
2        LABEL
FLOAT    EXT FUNC
FLOAT2   EXT FUNC
104      LABEL
READ1    EXT FUNC
NY       INT2 VAR
5        LABEL
3        LABEL
4        LABEL
ABS      EXT FUNC
ATAN     EXT FUNC
6        LABEL
X4       REAL VAR
COS      EXT FUNC
Y4       REAL VAR
SIN      EXT FUNC
X5       REAL VAR
Y5       REAL VAR
7        LABEL
I        INT2 VAR
```

```
$BATCH
      SUBROUTINE IMPULS(NA,N,DV,DT)
C **** IMPULSE PARAMETER ROUTINE ****      MOD 04 AUG 78
      INTEGER*2 NA(600),N
      IMPLICIT INTEGER*2 (I-N)
      IROUND(A)=(IFIX(2.*A)+1)/2
      CALL NEARST(NA,32767,NEAR,1,N,LOC1)
      LOCPK=LOC1/2
      DO 34 I=LOCPK,N
      DO 32 J=1,LOCPK
      ISRCH=I-J
      JSRCH=MIN02(I+J,N)
      IF(NA(I).LE.NA(ISRCH).OR.NA(I).LT.NA(JSRCH))GOTO 34
 32   CONTINUE
      DO 33 J=1,10
      ISRCH=I-J
      IF(NA(I).NE.NA(ISRCH))GOTO 35
 33   CONTINUE
 34   CONTINUE
      WRITE(3,307)I,J,NA(LOC1),LOC1
 307  FORMAT(' NO PEAK FOUND--',2I4,I6,I4)
      IF(LOC1.EQ.N)GOTO 39
      I=LOC1
 35   LOCPK=I
      IPEAK=NA(I)
      WRITE(6,310)
 310  FORMAT('VOLTAGE OR CURRENT WAVE? (V OR I)')
      CALL READ1(NWAVE)
      IF(NWAVE.NE.'V'.AND.NWAVE.NE.'I')GOTO 35
      WRITE(6,308)LOC1,LOCPK,IPEAK
 308  FORMAT(1X,I4,1X,I4,' PEAK =',I6/' ERROR LOC. VALUE ')
      JSRCH=IROUND(0.3*IPEAK)
      IF(NWAVE.EQ.'I')JSRCH=IROUND(0.1*IPEAK)
      CALL NEARST(NA,JSRCH,NEAR,1,LOCPK,LOC1)
      WRITE(6,309)NEAR,LOC1,NA(LOC1)
 309  FORMAT(1X,I6,1X,I4,1X,I6)
      JSRCH=IROUND(0.9*IPEAK)
      CALL NEARST(NA,JSRCH,NEAR,1,LOCPK,LOC2)
      WRITE(6,309)NEAR,LOC2,NA(LOC2)
      TRISE=1.67*(LOC2-LOC1)*DT
      IF(NWAVE.EQ.'I')TRISE=1.25*(LOC2-LOC1)*DT
      RATE=DV*IPEAK/TRISE
      TORIG=DT*LOC1-0.3*TRISE
      IF(NWAVE.EQ.'I')TORIG=DT*LOC1-0.1*TRISE
      JSRCH=IROUND(0.5*IPEAK)
      CALL NEARST(NA,JSRCH,NEAR,LOCPK,N,LOC1)
      WRITE(6,309)NEAR,LOC1,NA(LOC1)
      THALF=DT*LOC1-TORIG
      VPEAK=DV*IPEAK
      ENERGY=ENERGY+(NA(I)*NA(I)*D)
 36   CONTINUE
```

```
      ENERGY=ENERGY+(NA(I)*NA(I)*D)
 36   CONTINUE
      WRITE(6,312)VPEAK,TRISE,RATE,TORIG,THALF,ENERGY
 312  FORMAT('PEAK VALUE=',E12.5/'VIRTUAL FRONT TIME=',E12.5/'RATE-
     1OF-RISE=',E12.5/'VIRTUAL ORIGIN=',E12.5/'V. FALL TIME=',E12.5/
     2'ONE-OHM ENERGY=',E12.5,' JOULES')
 39   RETURN
      END
IMPULS   FUNC/SUB
.Q       EXT FUNC
.P       EXT FUNC
NA       FORM PAR
N        FORM PAR
DV       FORM PAR
DT       FORM PAR
IROUND   STATE FN
A        FORM PAR
IFIX     EXT FUNC
NEARST   EXT FUNC
NEAR     INT2 VAR
LOC1     INT2 VAR
LOCPK    INT2 VAR
34       LABEL
I        INT2 VAR
32       LABEL
J        INT2 VAR
ISRCH    INT2 VAR
JSRCH    INT2 VAR
MIN02    EXT FUNC
33       LABEL
35       LABEL
307      LABEL
@H       EXT FUNC
39       LABEL
IPEAK    INT2 VAR
310      LABEL
READ1    EXT FUNC
NWAVE    INT2 VAR
308      LABEL
.W       EXT FUNC
309      LABEL
LOC2     INT2 VAR
TRISE    REAL VAR
RATE     REAL VAR
TORIG    REAL VAR
THALF    REAL VAR
VPEAK    REAL VAR
D        REAL VAR
36       LABEL
```

ENERGY REAL VAR
312 LABEL

```
      SUBROUTINE SMOOTH(NA1,NA2,N)
C **** SMOOTH TO 5TH DEGREE POLYNOMIAL ****     MOD 24 JUL 78
      INTEGER*2 NA1(600),NA2(600),N
      IMPLICIT INTEGER*2 (I-N)
      IROUND(A)=(IFIX(2.*A)+1)/2
      ND2=NA1(1)
      ND3=NA1(2)
      DO 1 I=5,N
      ND1=ND2
      ND2=ND3
      ND3=NA1(I-2)
      ND4=ND3-ND2-NA1(I-1)
      ND4=ND4+ND4+ND3
      ND4=ND4+ND4+ND1+NA1(I)
      NA2(I-2)=ND3-IROUND(0.857143E-1*ND4)
      IF(I.GT.5)GOTO 1
      NA2(1)=ND1-IROUND(0.142857E-1*ND4)
      NA2(2)=ND2+IROUND(0.571428E-1*ND4)
 1    CONTINUE
      NA2(N-1)=NA1(N-1)+IROUND(0.571428E-1*ND4)
      NA2(N)=NA1(N)-IROUND(0.142857E-1*ND4)
      RETURN
      END
SMOOTH  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NA1     FORM PAR
NA2     FORM PAR
N       FORM PAR
IROUND  STATE FN
A       FORM PAR
IFIX    EXT FUNC
ND2     INT2 VAR
ND3     INT2 VAR
1       LABEL
I       INT2 VAR
ND1     INT2 VAR
ND4     INT2 VAR
.W      EXT FUNC
```

```
      SUBROUTINE CORREL(NA1,NA2,DV1,DV2,N)
C **** CORRELATION OF TWO COLUMNS OF DATA ****     MOD 01 AUG 78
      INTEGER*2 NA1(600),NA2(600),N
      COMMON /SCRAT/WORK(600)
      IMPLICIT INTEGER*2 (I-N)
      SIG2=0.
      ERROR=0.
      D1=NA2(N)*DV2
      DO 21 I=1,N
      ERR=(DV1*NA1(I)-DV2*NA2(I))/D1
      WORK(I)=ERR
      ERROR=ERROR+ERR
      SIG2=SIG2+ERR**2
 21   CONTINUE
      ERROR=ERROR/N
      SIG2=ABS(SIG2/N-ERROR**2)
      STDDEV=SQRT(SIG2)
      WRITE(6,202)ERROR,STDDEV
 202  FORMAT(' AVG. ERROR =',E12.5,' STD DEV =',E12.5)
      RETURN
      END
CORREL  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NA1     FORM PAR
NA2     FORM PAR
DV1     FORM PAR
DV2     FORM PAR
N       FORM PAR
SCRAT   COMMON     X'0960'
WORK    REAL VAR
SIG2    REAL VAR
ERROR   REAL VAR
D1      REAL VAR
.W      EXT FUNC
21      LABEL
I       INT2 VAR
ERR     REAL VAR
.R      EXT FUNC
ABS     EXT FUNC
STDDEV  REAL VAR
SQRT    EXT FUNC
202     LABEL
@H      EXT FUNC
```

```
      SUBROUTINE DUHAME(NA1,NA2,N,DV)
C **** PERFORM DUHAMEL'S INTEGRAL CALCULATION ****  MOD 01 AUG 78
      INTEGER*2 NA1(600),NA2(600),N
      COMMON /SCRAT/WORK(600)
      IMPLICIT INTEGER*2 (I-N)
      A1=DV*NA1(1)
      DO 33 J=1,N
      WORK(J)=A1*NA2(J)
 33   CONTINUE
      DO 35 I=2,N
      A1=DV*(NA1(I)-NA1(I-1))
      DO 34 J=I,N
      J1=J-I+1
      WORK(J)=WORK(J)+A1*NA2(J1)
 34   CONTINUE
 35   CONTINUE
      RETURN
      END
DUHAME  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NA1     FORM PAR
NA2     FORM PAR
N       FORM PAR
DV      FORM PAR
SCRAT   COMMON     X'0960'
WORK    REAL VAR
A1      REAL VAR
.W      EXT FUNC
33      LABEL
J       INT2 VAR
35      LABEL
I       INT2 VAR
34      LABEL
J1      INT2 VAR
```

```
      SUBROUTINE NORMAL(NA,N,DV)
C **** NORMALIZE DATA ****    MOD 08 AUG 78
      INTEGER*2 NA(600),NSET,N
      REAL DV,PLACE(4)
      IMPLICIT INTEGER*2 (I-N)
      IROUND(A)=(IFIX(2.*A)+1)/2
 1    WRITE(6,101)
 101  FORMAT('WHAT TYPE DATA SET? (S,K,P)')
      CALL READ1(NSET)
      NZERO=NA(1)
C KERR='K';PULSE='P';STEP='S'.
      IF(NSET.NE.'S')GOTO 2
      DV=5./(NA(N-4)+NA(N-3)+NA(N-2)+NA(N-1)+NA(N)-5*NZERO)
 2    DO 3 I=1,N
      NA(I)=NA(I)-NZERO
 3    CONTINUE
      RETURN
C UNTESTED--MAKES SCALE FACTOR A POWER OF 10. :
      XLOG=ALOG10(DV)
      DV=10.**(INT(XLOG)-1)
      SCALE=10.**(XLOG-INT(XLOG))
      DO 4 I=1,N
      NA(I)=IROUND(NA(I)*SCALE)
 4    CONTINUE
      RETURN
      END
NORMAL  FUNC/SUB
.O      EXT FUNC
.P      EXT FUNC
NA      FORM PAR
N       FORM PAR
DV      FORM PAR
NSET    INT2 VAR
PLACE   REAL VAR
IROUND  STATE FN
A       FORM PAR
IFIX    EXT FUNC
1       LABEL
101     LABEL
@H      EXT FUNC
READ1   EXT FUNC
NZERO   INT2 VAR
2       LABEL
.W      EXT FUNC
3       LABEL
I       INT2 VAR
XLOG    REAL VAR
ALOG10  EXT FUNC
INT     EXT FUNC
```

INT EXT FUNC
SCALE REAL VAR
.A EXT FUNC
4 LABEL

```
      SUBROUTINE XYVDT(NA,N,N1,DT)
C *** CONVERT X,Y PAIRS TO CONSTANT-INTERVAL SET *** MOD 24 JUL 78
      INTEGER*2 NA(600),N,N1
      IMPLICIT INTEGER*2 (I-N)
      COMMON /SCRAT/NBX(600),NBY(600)
      IROUND(A)=(IFIX(2.*A)+1)/2
      IWIDTH=1+N1/20
      LOC=1
      DO 1 I=1,N
      IMIN=MAX02(LOC-IWIDTH,1)
      IMAX=MIN02(IMIN+IWIDTH*5,N1-1)
      ISERCH=IROUND(DT*I)
      CALL NEARST(NBX,ISERCH,NEAR,IMIN,IMAX,LOC)
      IMIN=MAX02(LOC-IWIDTH,1)
      IMAX=MIN02(LOC+IWIDTH,N1-1)
      DYDX=0.
      IRUN=IMAX-IMIN+1
      DO 2 J=IMIN,IMAX
      IF(NBX(J).NE.NBX(J+1))GOTO 3
      NBY(J+1)=(NBY(J)+NBY(J+1))/2
      IRUN=IRUN-1
      J=MIN02(J+1,IMAX)
 3    DYDX=DYDX+FLOAT(NBY(J+1)-NBY(J))/(NBX(J+1)-NBX(J))
 2    CONTINUE
      DYDX=DYDX/IRUN
      NA(I)=NBY(LOC)+IROUND(DYDX*(DT*I-NBX(LOC)))
 1    CONTINUE
      RETURN
      END
XYVDT   FUNC/SUB
.O      EXT FUNC
.P      EXT FUNC
NA      FORM PAR
N       FORM PAR
N1      FORM PAR
DT      FORM PAR
SCRAT   COMMON    X'0960'
NBX     INT2 VAR
NBY     INT2 VAR
IROUND  STATE FN
A       FORM PAR
IFIX    EXT FUNC
IWIDTH  INT2 VAR
LOC     INT2 VAR
1       LABEL
I       INT2 VAR
IMIN    INT2 VAR
MAX02   EXT FUNC
```

```
.W       EXT FUNC
NEARST   EXT FUNC
NEAR     INT2 VAR
DYDX     REAL VAR
IRUN     INT2 VAR
2        LABEL
J        INT2 VAR
3        LABEL
FLOAT    EXT FUNC
FLOAT2   EXT FUNC
```

```
      SUBROUTINE NEARST(NA,NDATA,NEAR,IMIN,IMAX,LOC)
C **** FIND POINT IN SET NEAREST TO NDATA ****     MOD 24 JUL 78
      INTEGER*2 NA(600),NDATA,NEAR,IMIN,IMAX,LOC
      IMPLICIT INTEGER*2 (I-N)
      NEAR=32767
      DO 1 I=IMIN,IMAX
      ND1=IABS(NA(I)-NDATA)
      NEAR=MIN02(NEAR,ND1)
      IF(NEAR.EQ.ND1)LOC=I
 1    CONTINUE
      RETURN
      END
NEARST  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NA      FORM PAR
NDATA   FORM PAR
NEAR    FORM PAR
IMIN    FORM PAR
IMAX    FORM PAR
LOC     FORM PAR
1       LABEL
I       INT2 VAR
ND1     INT2 VAR
IABS    EXT FUNC
IABS2   EXT FUNC
MIN02   EXT FUNC
```

```
      SUBROUTINE FIXDTA(NA,DV,N)
C **** STORE F.P. WORKSPACE IN INTEGER COLUMN ****   MOD 01 AUG 78
      INTEGER*2 NA(600),N
      REAL DV,PLACE(4)
      COMMON /SCRAT/WORK(600)
      IMPLICIT INTEGER*2 (I-N)
      IROUND(A)=(IFIX(2.*A)+1)/2
      XMAX=0.
      DO 1 I=1,N
      XMAX=AMAX1(XMAX,ABS(WORK(I)))
 1    CONTINUE
      DV=XMAX/1000
      DO 2 I=1,N
      NA(I)=IROUND(WORK(I)/DV)
 2    CONTINUE
      RETURN
      END
FIXDTA  FUNC/SUB
.Q      EXT FUNC
.P      EXT FUNC
NA      FORM PAR
DV      FORM PAR
N       FORM PAR
PLACE   REAL VAR
SCRAT   COMMON     X'0960'
WORK    REAL VAR
IROUND  STATE FN
A       FORM PAR
IFIX    EXT FUNC
XMAX    REAL VAR
1       LABEL
I       INT2 VAR
AMAX1   EXT FUNC
ABS     EXT FUNC
.W      EXT FUNC
2       LABEL
```

```
REL PROGS:
  ACB0 MIDAS    B14E ATAN    B230 COS     B250 SIN
  B316 .R       B352 .A      B3F0 SQRT    B500 ALOG10
  B550 ALOG     B65E EXP     B764 MIN02   B77A MAX02
  B790 AMAX1    B7A4 .1      B7B6 AMOD    B7E0 AINT
  B85B INT      B85E INT2    B864 .2      B876 $1
  B8BE $22      B8C2 $3      B8EE FLOAT2  B926 IFIX
  B92C IFIX2    B94A .Y2     B9CA ABS     B9E0 IABS2
  BA1A .W       BA6B .COMP   BA94 .RRARG  BAD2 $6
  BB1C .RARG    BB4B $B      BB72 .5      BB7A .ZERO
  BBB2 .H       BBD4 .S      BC0A .P      BCBC .Q
  BD3C .O       BD84 .MES    BDFA .U      BE2A .V
  BE3B @R       BE5E @Z      BEB4 @H      D0CE

ABS PROGS:
NONE

ENTRY-POINTS:
  7BF6 FITAB    7E42 SKIP    7FB8 XYDATA  B32C MREAD
  B544 FASTPK   BB4C ROTSCA  94CE IMPULS  9D40 SMOOTH
  A01E CORREL   A230 DUHAME  A3AC NORMAL  A6AE XYVDT
  AA3B NEARST   AB1C FIXDTA  ADA0 RELESE  ADEA MIDAS
  AFDE CONVRT   B04C CLOSE   B05A SYSTEM  B0EC WAIT
  B11E READ1    B150 ATAN    B232 COS     B252 SIN
  B31B .R       B354 .A      B3FA SQRT    B502 ALOG10
  B552 ALOG     B660 EXP     B766 MIN02   B77C MAX02
  B792 AMAX1    B7A6 .1      B7BB AMOD    B7E2 AINT
  B85A INT      B860 INT2    B866 .2      B87B $1
  B890 $22      B8C4 $3      B8F0 FLOAT2  B92B IFIX
  B92E IFIX2    B94C .Y2     B9CC ABS     B9E2 IABS2
  BA1C .W       BA6A .COMP   BA96 .RRARG  BAD4 $6
  BB1E .RARG    BB4A $8      BB76 .5      BB7E .ZERO
  BB84 .H       BBD6 .S      BC0C .P      BCBE .Q
  BD3E .O       BDB6 .MES    BE0B .U      BE30 .V
  BE3A @R       BE60 @Z      BED2 @H

COMMON-BLOCKS:
  F69E SCRAT.

UNDEFINED:
NONE
```

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

The calibration of a 4.5 MV impulse divider was evaluated by measuring both the input and output waveforms and the response of the divider to a low voltage step. The measured output was compared to an output calculated from the step response and the measured input waveform using Duhamel's Integral. The validity of the approach for this large measurement system was demonstrated for the specific waveforms studied.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Divider; Duhamel's integral; high voltage; impulse; pulse measurements; response time; step response; transients

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