NBSIR 87-3549

A Survey of Electronic Measurement Needs Below 10 MHz

John R. Sorrells

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Gaithersburg, MD 20899

February 1987

Issued June 1987

U.S. DEPARTMENT OF COMMERCE
[N]ATIONAL [B]UREAU OF STANDARDS

NBSIR 87-3549

A SURVEY OF ELECTRONIC MEASUREMENT NEEDS BELOW 10 MHz

John R. Sorrells

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Electrosystems Division
Gaithersburg, MD 20899

February 1987

Issued June 1987

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

EXECUTIVE SUMMARY

This report presents the results of a survey conducted by the Center for Electronics and Electrical Engineering to assess the measurement needs of the electronics industry at frequencies from dc to 10 MHz. The purpose of the survey was to obtain information that can be used in planning and implementing NBS programs to develop new or improved calibration services or measurement methods to support industry needs.

In conducting the survey, the Center received cooperation and assistance from the following organizations: the IEEE Instrumentation and Measurements Society, the Electronic Industries Association, the National Conference of Standards Laboratories, the American Physical Society, and the Instrument Society of America. These organizations provided comments and suggestions on the survey questionnaire, and/or provided membership mailing lists for use in soliciting survey participation.

The survey vehicle was a seven-part questionnaire that elicited information regarding (1) the respondent's type of organization or business, (2) the principal reasons for needing NBS measurement support, (3) the measurement needs for critical electrical quantities, (4) the usage and support of measuring instruments or devices, (5) needs related to automatic test equipment or complex measurement systems, (6) concerns with conducted electromagnetic interference, and (7) the effectiveness of mechanisms for communicating or interacting with NBS. Space was also provided for the respondents to enter "other" responses or provide additional comments if desired.

Questionnaires were returned by a total of 527 respondents, representing most segments of the electronics industry. The largest number of responses came from organizations involved with test equipment or instruments, followed by aerospace organizations, and independent test, repair, or calibration service organizations.

The largest percentage of respondents indicated that their organizations need NBS measurement support to meet government requirements. However, there was a strong expression of need for NBS assistance to support R&D and other production-related activities.

The responses to Section C of the questionnaire indicated that the measurement of many of the more basic quantities such as voltage, current, resistance, capacitance, frequency, etc., were of critical importance and that new/improved measurement methods or NBS calibration services are needed for many quantities already supported by NBS measurement services. Further study is planned to determine the implications of these responses.

Also in Section C, 33% of the respondents indicated that they were familiar with the NBS calibration services described in NBS Special Publication 250 and 51% indicated that their organizations use such services.

The responses to Section D of the questionnaire regarding the usage and need for support of measuring instruments or devices correlates well with those regarding electrical quantities. Those instruments or devices involved in the measurement of basic quantities ranked high on the usage list. Also, many of the instruments were perceived to require new or improved characterization methods or NBS calibration services.

Responses to the questions regarding the respondents' involvement with automatic test equipment or complex measurement systems and with conducted electromagnetic interference indicate that these are important technical areas needing NBS support. In particular, there is a strong expression of needs for practical support such as calibration and test guides, documented measurement methods, definitions and terminology, and characterization/measurement techniques in these areas.

The four communication means used most by the respondents to obtain information on NBS programs and services were indicated to be NBS reports/special publications, journal publications, conferences/workshops/seminars, and specific requests. Others such as staff interactions, media releases, and technical committees were ranked somewhat less important. For each of the listed communication means, some percentage of the respondents indicated a need for improvement.

A final question of the survey asked if NBS has provided the necessary support when requested by the respondent's organization. There were 259 responses to this question, with 92% affirmative answers.

Twenty-seven percent of the respondents provided additional comments regarding specific measurement needs or general metrology-related issues. A common theme in these comments was the need to learn more about NBS services, programs, and activities.

The appendices of this report include a copy of the survey questionnaire, a listing of the responding organizations, lists of various "other" responses, and histograms of the responses regarding measurement requirements (accuracy vs. frequency or time) for the electrical quantities listed in the questionnaire. Essentially all of the data derived from the survey are tabulated and presented either in the body of the report or in the appendices.

The results of this survey will be provided to all participants and made available to other interested parties. Internally, the results will be used to plan NBS programs and establish priorities for responding to the measurement needs of the electronics industry.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	iii
TABLE OF CONTENTS	v
LIST OF FIGURES	vi
LIST OF TABLES	vi
ABSTRACT	1
1. INTRODUCTION	1
2. THE QUESTIONNAIRE	2
3. SUMMARY OF RESPONSES	3
Section A. Organization/Business	3
Section B. Organizational Needs	4
Section C. Basic Electrical Quantities	6
Section D. Precision Instruments/Devices	14
Section E. ATE/Complex Measurement Systems	20
Section F. Conducted Electromagnetic Interference (CEMI)	22
Section G. Communications/Interactions	23
Section H. Additional Comments	27
4. CONCLUSIONS	28
5. ACKNOWLEDGMENTS	30
APPENDIX A	31
APPENDIX B	39
APPENDIX C	47
APPENDIX D	81
APPENDIX E	82
APPENDIX E.2	83

Page

LIST OF FIGURES

Figure 1. Requirements from survey and NBS capabilities for voltage 10

LIST OF TABLES

Table 1. Distribution of responses by type of organization/business. 3

Table 2. Overall ranking of reasons for needing NBS measurement support. 4

Table 3. Reasons for needing NBS measurement support as ranked by each type of organization/business. 5

Table 4. Overall ranking of electrical quantities, based on the number of Section C responses 6

Table 5. Section C responses indicating the need for a new/improved measurement method or an NBS calibration service. 8

Table 6. Top eleven quantities based on the number of responses indicating the need for an NBS calibration service. 9

Table 7. Top eleven quantities based on the number of responses indicating the need for a new/improved measurement method. 11

Table 8. Percentage of respondents familiar with NBS calibration services--classified by type of organization 12

Table 9. Percentage of respondents using NBS calibration services--classified by type of organization 13

Table 10. Ranking of instruments/devices, based on number of users (Section D responses). Usage data for each instrument/device is also shown 15

Table 11. Top eleven instruments or devices based on the number of responses indicating their use as a standard 16

Table 12. Number of responses indicating the need for a new/improved characterization method or NBS calibration service for the instrument/devices. Ranking is the same as in Table 11 17

Page

LIST OF TABLES (contd.)

Table 13. Top eleven instruments or devices based on the number of responses indicating the need for an NBS calibration service 18

Table 14. Top eleven instruments or devices based on the number of responses indicating the need for new/improved characterization methods. 19

Table 15. Summary of responses regarding respondents' involvement with ATE or complex measurement systems. 20

Table 16. Summary of responses regarding types of ATE or complex measurement systems with which respondents are involved 20

Table 17. Summary of responses regarding the usefulness of possible NBS outputs related to ATE or complex measurement systems. 21

Table 18. Summary of responses regarding the manufacture or use of CEMI-related equipment 22

Table 19. Summary of responses regarding the usefulness of possible NBS outputs related to CEMI. 23

Table 20. Summary of responses regarding the communication means used by respondents to obtain information on NBS programs and services 24

Table 21. Ranking of communication means by type of organization/business. 25

Table 22. Summary of responses indicating the need to improve the given communication means. 26

A SURVEY OF ELECTRONIC MEASUREMENT NEEDS BELOW 10 MHz

John R. Sorrells

Abstract

The results of a survey to assess the measurement needs of the electronics industry over the frequency range from dc to 10 MHz are presented. The questionnaire used in the survey covered three broad areas of measurement needs: (1) basic electrical quantities and related precision instruments, (2) automatic test equipment and other complex measurement systems, and (3) conducted electromagnetic interference. The data provided by 527 respondents are summarized, and the results of various analyses are described. Several conclusions, suggested by the analyses, are also discussed.

Key words: automatic test equipment; ATE; complex measurement systems; electrical quantities; electronic measurement needs; precision instruments; questionnaire; survey

1. Introduction

In 1985 the NBS Center for Electronics and Electrical Engineering (CEEE) began plans for conducting an electronic measurement needs survey, and, in August of that year, received formal approval from the Office of Management and Budget to proceed with the endeavor. The objective of the survey was to elicit information from the electronics industry pertaining to current and future measurement needs that might require NBS measurement support, particularly from the Electrosystems Division. Thus, the survey questionnaire focused primarily on the assessment of measurement needs over the frequency range from dc to 10 MHz.

The first step in conducting the survey was the development of a suitable questionnaire — one that covered both general and specific areas of concern. Several versions were prepared, revised, and subjected to internal review before a final draft was produced. By prior arrangements, copies of this draft were sent to representatives of the IEEE Instrumentation and Measurements Society, the National Conference of Standards Laboratories (NCSL), and the Electronic Industries Association for their review and comments. Copies were also provided to individuals within NBS who were aware of the proposed survey and interested in the results. In response, we received thoughtful comments and constructive suggestions on the draft questionnaire from thirteen representatives in these organizations. All comments and suggestions were given careful consideration, and, where feasible, incorporated into the final version of the questionnaire.

With the approval and cooperation of the appropriate authorities, more than 11,500 advance letters were mailed to members of the IEEE Instrumentation and Measurement Society, the Electronic Industries Association, the National Conference of Standards Laboratories, the Instrument and Measurement Science Group of the American Physical Society, and three divisions of the Instrument

Society of America. The advance letters gave a brief description of the planned survey, and asked the recipient to return a pre-addressed post card if he or she were interested in participating. Twelve percent (1418) of the letter recipients requested and received a copy of the survey questionnaire. Of these, 527 (37%) were completed and returned to NBS.

The following sections of this report summarize the results of the survey. Section 2 discusses the format and structure of the questionnaire and the purpose of each set of questions; Section 3 gives a summary of the responses and presents tabulations of some of the data and cross-correlation results; and Section 4 presents a discussion of conclusions that are based on our interpretation of the data.

2. The Questionnaire

A copy of the questionnaire and its cover letter are included in Appendix A. The questionnaire is composed of seven major sections. Section A requests information on the respondent's organization or business. Section B asks the respondent to identify the principal reasons why his or her organization needs measurement support from NBS. Section C seeks to identify and quantify the respondent's specific measurement needs. In this section, the respondent is asked to identify electrical quantities whose measurement is critical in his or her operation and to indicate the required accuracy and frequency ranges. The respondent is also asked to indicate if a new or improved measurement method or calibration service is needed for the listed quantities. Similar information is requested for several time-domain quantities. Two final questions in this section pertain to the respondent's awareness of existing NBS calibration services and the use of those services by his or her organization. Section D contains a list of instruments or devices that are commonly used for measuring electronic or electrical quantities and requests information on how they are used by the respondent's organization. The respondent was also asked to indicate if a characterization method or calibration service is needed for any of the listed instruments.

The questions in sections E and F are more general in scope than in the preceding sections and are aimed at assessing the measurement needs of organizations involved with automatic test equipment or complex measurement systems and with conducted electromagnetic interference. In both of these sections, the respondent is asked to identify the nature of his or her organization's involvement, and to estimate the usefulness of possible NBS outputs in each area. The questions in Section G are aimed at determining the primary mechanisms by which the respondent's organization communicates or interacts with NBS and the effectiveness of those mechanisms and of NBS support on prior measurement problems. Finally, Section H provides space for additional comments and for optional information regarding the respondent's name and affiliation.

For most questions, space was provided for the respondent to enter an "other" response or specific comments.

3. Summary of Responses

This section contains summaries of the responses to each part of the questionnaire, as well as the results of several analyses to determine cross-correlations between certain responses.

The following data presentations are arranged according to the sections of the questionnaire. Where percentages are used to report the data, it is indicated whether the figure is based on the total number of questionnaires returned, or on the number of responses to that particular question. In some instances, the total number of responses to a given question is also reported.

Section A. Organization/Business

As stated above, 527 questionnaires were completed and returned during the survey. Of these, 84 were submitted anonymously. The organizations represented by the remaining respondents are listed in Appendix B. A breakdown of these according to the categories listed in Section A is shown below. Since many respondents checked more than one category, the sum of the percentages is greater than 100 percent.

Table 1. Distribution of responses by type of organization/business

Organization/Business	Section A Responses	Percent of Questionnaires Returned (527)
Test Equipment/Instruments	132	25
Aerospace	79	15
Independent test, repair, calibration service	45	9
Military	43	8
Electronic Components	42	8
University	42	8
Electric Power	36	7
Other Government	30	6
National Laboratory	26	5
Computer Equipment	25	5
Medical Electronics	24	5
Consumer Electronics	20	4
Telecommunication	19	4
Automotive	17	3
Other	99	19

Excluding the "Other" category, the largest percentage of responses came from organizations involved in Test Equipment/Instruments and Aerospace. The most common businesses listed in the "Other" category were R&D and consulting. The remainder of the "Other" list includes a wide variety of organizations involved in such business as pharmaceuticals, machinery, nuclear power, chemicals, oil, gas, and the manufacture of various products.

Section B. Organizational Needs

In this section, the respondent was asked to indicate the principal reasons why his or her organization needs measurement support from NBS. All respondents (527) answered this section of the questionnaire, and generally checked more than one category.

Table 2. Overall ranking of reasons for needing NBS measurement support.

Reason for Needing NBS Support	Section B Responses	Percent of Questionnaires Returned (527)
1. To meet government requirements, e.g., for traceability	384	73
2. To support R&D	250	47
3. To improve quality control in production	209	40
4. To improve product reliability	172	33
5. To assist in development of product specifications	166	31
6. To support development of voluntary standards	147	28
7. To improve product compatibility	129	24
8. To meet requirements of foreign governments/buyers	92	17
9. To ensure market equity	88	17
10. To increase productivity	82	16
11. To reduce the cost of reaching buyer/seller agreement	51	10
12. Other	33	6

A large percentage of the respondents indicated that their organizations need NBS measurement support to meet government requirements. However, 47 percent of the respondents indicated they need NBS support to support R&D, and more than 30 percent indicated a need for support in production-related activities. This suggests that NBS measurement support is considered important and necessary by many organizations in helping to solve some of the practical problems involved in developing and producing reliable products.

Although 33 respondents listed "other" reasons for needing NBS support, most of these were variations or restatements of those given in the above list. Some of the new reasons cited were "to improve personnel safety," "to develop standards in new areas of technology," and "to increase reliability in the nuclear power area."

To obtain further insight into the question of organizational needs, the responses for this section were tabulated and ranked according to type of organization/business.

In the table below, the needs ranked first, second, and third by each type of organization are shown. In each column, the numbers 1 through 11 refer to the overall ranking of the eleven listed needs; the numbers in parenthesis indicate the percentage of organizations in each category that ranked the need either first, second, or third in importance.

Table 3. Reasons for needing NBS measurement support as ranked by each type of organization/business

Type of Organization	Needs Ranking		
	1st	2nd	3rd
Aerospace	1 (90)	2 (56)	3 (42)
Automotive	1 (94)	3 (41)	2,4,6 (29)
Computer Equipment	1 (68)	3 (60)	7 (56)
Consumer Electronics	1 (85)	3 (65)	9 (55)
Electric Power	1 (83)	3 (42)	4 (39)
Electronic Components	1 (83)	3 (60)	6 (48)
Independent test, repair, calib. service	1 (89)	3 (44)	6 (36)
Medical Electronics	1 (67)	3 (54)	2,4 (38)
National Laboratory	2 (77)	1 (46)	6 (27)
Military	1 (86)	2 (44)	4 (28)
Other Government	1 (80)	2 (47)	4 (43)
Telecommunications	1 (63)	6 (59)	3 (53)
Test Equipment/Instruments	1 (77)	3,5 (46)	2 (38)
University	2 (79)	1 (33)	6 (21)

With only two exceptions, all types of organizations ranked the need to meet government requirements as their top concern; the exceptions were National Laboratories and Universities, both of which ranked the support of R&D as their principal need for NBS support. The need to improve quality control in production was ranked second in importance by eight of the fourteen organization types, and the support of R&D was ranked second by Aerospace, Military, and Other Government organizations. Third place rankings included six of the eleven needs categories.

Section C. Basic Electrical Quantities

This section of the questionnaire collected the largest body of data and undoubtedly required the greatest investment of time by the respondents. From a list of 33 quantities, each respondent was asked to identify those of critical importance to his or her organization, and, for those so identified, to indicate the required measurement accuracy, the frequency or time range of concern, and the type of NBS support needed (measurement method or calibration service). As shown, the number of responses varied by an order of magnitude, depending upon the electrical quantity.

In the following table, the electrical quantities are ranked in descending order, based on the number of respondents who indicated that the quantity is critical to his or her operation by indicating their accuracy vs. frequency (or time) requirements. As can be seen, the quantities receiving the highest percentage of responses are many of the more basic ones.

Table 4. Overall ranking of electrical quantities, based on the number of Section C responses.

Electrical Quantity	Section C Responses	Percent of Questionnaires Returned (527)
1. Voltage	404	77
2. Resistance	332	63
3. Current	323	61
4. Capacitance	250	47
5. Frequency	237	45
6. Voltage, transient	235	45
7. Rise/fall time	224	43
8. Power	172	33
9. Current, transient	167	32
10. Inductance	164	31
11. Delay time	149	28
12. Phase	132	25
13. Impedance	125	24
14. Magnetic Field Strength	121	23
15. Settling Time	118	22
16. Harmonic Distortion	100	19
17. Acquisition Time	96	18
18. Leakage Current	87	17
19. Conductance	85	16
20. Noise Amplitude	85	16
21. Electric Field Strength	81	15
22. Power Factor	78	15
23. Quality Factor	74	14
24. Dissipation Factor	71	13
25. Reactive Power	64	12
26. Linearity, Differential	62	12
27. Linearity, Integral	61	12
28. Energy	60	11
29. Percent Modulation, AM	58	11
30. Percent Modulation, FM	56	11
31. Phase Noise	42	8
32. Admittance	42	8
33. Effective Bits	36	7

Thirty-three respondents listed "other" quantities whose measurement they considered important to their operations. This list contained few repeats and included both physical and electrical quantities such as charge, pressure, optical power, wavelength, force, permittivity, duty cycle, baseline offset, delay time jitter, and transient resistance.

Quantities receiving the highest percentage of responses were also the quantities that appeared near the top of the two lists in Section C of the questionnaire, and, thus, might be expected to receive a greater number of responses. However, this does not appear to be the case since many of the more derived quantities such as rise/fall time, phase, harmonic distortion, etc. were also considered to be of critical importance, and they appeared later in the list.

The responses regarding required measurement accuracies and frequencies also varied considerably, depending upon the quantity to be measured. For example, for some of the more basic quantities such as voltage, current, and resistance, many respondents indicated the need for high accuracy measurements (0.001% and 0.0001%) over the full range of frequencies, but with the greatest need being for dc measurements. For other quantities such as power, reactive power, and power factor, the highest measurement accuracy required was 0.001% and the frequency ranges of most concern were those encompassing the standard power frequencies (60 and 400 Hz). For frequency measurements, the respondents indicated the greatest need for the most accurate (0.0001%) measurements at the highest frequency (1 MHz - 10 MHz) range addressed by the survey.

For the interested reader, a complete summary of the accuracy vs. frequency data for all of the listed quantities is presented in Appendix C.

The responses regarding the need for new or improved measurement methods or calibration services for the electrical quantities are tabulated in the following table. Here the quantities are again ranked by the number of responses received, and the number of responses indicating the need for a measurement method or calibration service are listed. Many respondents indicated a need for both. Quantities that are followed by an asterisk are those for which a routine NBS calibration service or special test is available for certain levels of accuracy and certain ranges of frequency or time.

Table 5. Section C responses indicating the need for a new/improved measurement method or an NBS calibration service.

Quantity	Section C Responses	Number Needing Meas. Method	Number Needing NBS Calib. Service
1. Voltage*	404	88	148
2. Resistance*	332	51	110
3. Current*	323	71	87
4. Capacitance*	250	49	85
5. Frequency*	237	33	65
6. Voltage, transient	235	82	47
7. Rise, fall time*	224	72	48
8. Power*	172	28	45
9. Current, transient	167	56	24
10. Inductance*	164	30	49
11. Delay Time*	149	41	28
12. Phase*	132	32	35
13. Impedance	125	28	32
14. Magnetic Field Strength*	121	47	32
15. Settling Time	118	41	24
16. Harmonic Distortion	100	27	22
17. Acquisition Time	96	32	17
18. Leakage Current	87	23	20
19. Conductance	85	15	20
20. Noise Amplitude	85	40	28
21. Electric Field Strength	81	34	17
22. Power Factor	78	16	17
23. Quality Factor	74	25	25
24. Dissipation Factor	71	22	24
25. Reactive Power	64	9	15
26. Linearity, differential	62	20	18
27. Linearity, integral	61	20	15
28. Energy*	60	8	10
29. Percent Modulation, AM	58	15	12
30. Percent Modulation, FM	56	13	10
31. Phase Noise	42	15	10
32. Admittance	42	7	9
33. Effective Bits	36	14	10

Although the numbers vary from quantity to quantity, on the average, approximately half of those responding to Section C indicated the need for a new or improved measurement method or an NBS calibration service for the listed quantities. These results imply that approximately half of the respondents who consider the measurement of a given quantity critical to their operation, also believe existing measurement methods and NBS calibration services need improvement. Since NBS already provides calibration services or special tests for more than a third of the quantities, the data could also be interpreted as an indication that NBS should do more to make the user community aware of available services. The responses to some of the other survey questions tend to support this interpretation.

To explore the significance of these results further, the quantities were ranked according to the number of responses indicating a need for an NBS calibration service. Listed below are the eleven quantities that comprise the upper third of that rank. Quantities that are followed by an asterisk are those for which a routine NBS calibration service or special test is available.

Table 6. Top eleven quantities based on the number of responses indicating the need for an NBS calibration service.

Quantity	Section C Responses	Number Needing NBS Calibration Service
1. Voltage*	404	148
2. Resistance*	332	110
3. Current*	323	87
4. Capacitance*	250	85
5. Frequency*	237	65
6. Inductance*	164	49
7. Rise/fall time*	224	48
8. Voltage/transient	235	47
9. Power*	172	45
10. Phase*	132	35
11. Impedance	125	32

There are two points worth noting about the above list. First, nine of the eleven quantities (all but phase and impedance) also appear in the upper third of table 4, where the quantities are ranked according to the percentage of total respondents who indicated that the quantity is critically important to his or her organization. Second, except for transient voltage and impedance, all of these quantities are ones for which an NBS calibration service or special test is available.

To determine if NBS is already providing services at the accuracies and frequencies of interest indicated by the survey, NBS is conducting further analyses. In these analyses, the measurement needs indicated by the survey data will be compared with the measurement services currently offered by NBS to determine where differences or similarities exist. As an example, the results of such an analysis for voltage are discussed below.

An example of how the survey data can be utilized for NBS planning purposes is illustrated by the requirements/capability charts for voltage, given in figure 1. As a starting point, Appendix C provides a histogram of the number of responses regarding measurement requirements (accuracy vs. frequency or time) for all of the quantities listed in the questionnaire. For voltage, the 404 responses are seen to be distributed, with the higher accuracy requirements at dc and the lower frequency ranges. Tables 5 and 6 above indicate that 148 of the respondents indicated the need for an NBS calibration service for voltage. The first chart in figure 1 shows the voltage measurement requirements of these respondents, where the heavy border encloses the areas where the number of responses were at least 20 percent of the

REQUIREMENTS/CAPABILITIES - VOLTAGE

ACCURACY LIMITS

	DC	DC-100Hz	100Hz-1kHz	1kHz-10kHz	10kHz-100kHz	100kHz-1MHz	1MHz-10MHz
1%	3	2	3	3	4	8	7
0.1%	8	15	12	13	14	18	25
0.01%	18	36	31	29	34	25	18
0.001%	32	39	35	30	19	10	6
0.0001%	63	8	4	4	2	3	2

Voltage requirements of 148 respondents needing an NBS calibration service for voltage.

	DC	DC-100Hz	100Hz-1kHz	1kHz-10kHz	10kHz-100kHz	100kHz-1MHz	1MHz-10MHz
1%							
0.1%		✓				✓	✓
0.01%		✓	✓	✓	✓	✓	
0.001%	✓	✓	✓	✓	✓		
0.0001%	✓						
0.00001%	O						

DC voltage measurements and indirect AC voltage measurements Via AC-DC difference of TVCs (existing NBS calibration services).

Note:

- ✓ – Routine and special tests *
- ● – Best uncertainty available using NBS Voltage Calibration System. *
- O – Best uncertainty available at 1 V by direct comparison to the National Standard of voltage.

	DC	DC-100Hz	100Hz-1kHz	1kHz-10kHz	10kHz-100kHz	100kHz-1MHz	1MHz-10MHz
1%						✓	✓
0.1%		✓	✓	✓	✓	✓	●
0.01%	✓	✓	✓	✓	✓	●	
0.001%	✓	●	●	●	●		
0.0001%	✓						
0.00001%	O						

Voltage measurements directly via best available calibrators and DVMs (proposed NBS calibration services).

* Best uncertainty available within (but not necessarily over) the entire frequency range.

Figure 1. Requirements from survey and NBS capabilities for voltage.

maximum value of 63 (i.e., 12 or higher). As can be seen, the requirements are generally focused at the 0.1% through 0.001% accuracy limits, with 0.0001% (1 ppm) needed at dc. In the 1 - 10 MHz frequency band, 0.1% to 0.01% accuracy is required.

The second chart in figure 1 gives an approximate description of the existing NBS calibration service capabilities for dc voltage measurements, as well as ac voltage measurements. The latter are supported indirectly by means of ac-dc difference measurements of thermal voltage converters. The 0.1 ppm (0.00001%) accuracy limit at dc is achieved by a special test that requires the use of precision dc transfer standards which have the requisite stability, low temperature coefficient, and mechanical ruggedness. The 10 ppm (0.001%) accuracy limit shown from dc through 100 kHz is achievable only as a special ac-dc difference test for voltages from 5V to 100V, 100 Hz to 20 Hz, provided that the performance of the instrument under test is adequate. A 200 ppm (0.02%) accuracy limit occurs above 100 kHz to 500 kHz, and 300 ppm (0.03%) is the accuracy limit from 500 kHz to 1 MHz. From 1 MHz to 10 MHz, the accuracy limit varies between 300-500 ppm (0.03-0.05%).

The third chart in figure 1 describes the NBS capabilities now planned for providing a proposed new NBS calibration service for measuring voltage directly. Consequently, this proposed new NBS service would be responsive to the needs expressed in Section D of the questionnaire for the calibration of voltmeters and calibrators. In general, the limit to the accuracy available will depend upon the uncertainty (indicated by the black dots) of the NBS Voltage Calibration System (VCS), and the stability of the calibrator or voltmeter standard under test. The VCS is capable of high accuracy over a voltage range from several millivolts to one kilovolt, at frequencies ranging from near dc to 10 MHz, with measurement uncertainties estimated to be 10-20 ppm (0.001-0.002%) in the midrange of voltage amplitudes and frequencies. Thus, it appears that the proposed new NBS calibration service would meet most of the voltage requirements expressed by the survey respondents.

In another analysis of the data provided in Section C, the quantities were ranked according to the number of responses indicating a need for a new or improved measurement method. Again, the eleven quantities comprising the upper third of that rank are listed in the table below, where asterisks identify those for which an NBS calibration service or special test is available.

Table 7. Top eleven quantities based on the number of responses indicating the need for a new/improved measurement method.

Quantity	Section C Responses	Number Needing Measurement Method
1. Voltage*	404	88
2. Voltage, transient	235	82
3. Rise/fall time*	224	72
4. Current*	323	71
5. Current, transient	167	56
6. Resistance*	332	51
7. Capacitance*	250	49
8. Magnetic Field Strength*	121	47
9. Delay Time*	149	41
10. Settling Time	118	41
11. Noise Amplitude	85	40

As shown in table 7, when the quantities are ranked by this means, a different set of eleven from that shown in table 6 appears at the top. Since two of these (rise/fall time and delay time) are supported by NBS for frequencies above 10 MHz, these results appear to indicate a need for new/improved measurement methods for these two quantitites in the low frequency regimes. The transient voltage, transient current, noise amplitude and settling time quantities are dynamic, derived quantities for which new/improved measurement methods could be developed under present and future NBS research programs.

Question C11 of this section asks the respondent if he or she is familiar with the calibration services currently offered by NBS and described in Special Publication 250. Of the 527 respondents, only 33% answered "yes" to this question. These responses were broken down by type of organization and are shown in the table below.

Table 8. Percentage of respondents familiar with NBS calibration services — classified by type of organization.

Organization Type	Total Responses	"Yes" Responses	Percentage of "Yes" Responses
1. Aerospace	74	27	36
2. Automotive	14	7	50
3. Computer Equipment	21	9	43
4. Consumer Electronics	18	4	22
5. Electric Power	31	9	29
6. Electronic Components	39	10	26
7. Independent Test, Repair, Calibration Service	42	23	55
8. Medical Electronics	20	8	40
9. National Laboratory	24	5	21
10. Military	40	15	38
11. Other Government	27	9	33
12. Telecommunication	19	7	37
13. Test equipment/instruments	120	29	24
14. University	39	5	13
15. Other	92	28	30

Seventy-nine percent of the respondents who said they are familiar with NBS calibration services described in SP250 also said that their organization uses those services (question C12) or normally seeks NBS assistance on measurement problems (question G3). Conversely, only 44% of the respondents who were not familiar with NBS calibration services said their organizations use NBS calibration services or seek NBS measurement assistance.

These results suggest rather strongly that efforts are needed to increase public awareness of available NBS calibration services.

Question C12 asks the respondent if his or her organization uses any of the NBS calibration services. Of the 527 respondents, 51 percent answered "yes" to this question. These responses were also broken down by type of organization and are tabulated below.

Table 9. Percentage of respondents using NBS calibration services — classified by type of organization.

Organization Type	Total Responses	"Yes" Responses	Percentage of "Yes" Responses
1. Aerospace	71	42	59
2. Automotive	16	12	75
3. Computer Equipment	20	9	45
4. Consumer Electronics	18	8	44
5. Electric Power	30	17	57
6. Electronic Components	37	14	38
7. Independent Test, Repair, Calibration Service	44	29	66
8. Medical Electronics	19	11	58
9. National Laboratory	20	14	70
10. Military	41	29	71
11. Other Government	26	15	58
12. Telecommunication	17	10	59
13. Test equipment/instruments	122	67	55
14. University	40	8	20
15. Other	89	32	36

It is interesting to note that more respondents answered "yes" to this question than to C11. We assume this to mean that some respondents knew that their organizations use one or more of NBS calibration services but were not necessarily aware of or familiar with the full range of calibration services offered by NBS and described in Special Publication 250.

Section D. Precision Instruments/Devices

This section of the survey is closely related to the previous section on electrical quantities since it requests information on instruments or devices that are commonly used to measure those quantities. The questions in this section focus on how the instruments or devices are used by the respondent's organization and the need for new/improved characterization methods or NBS calibration services for the instruments.

The data regarding the use of the instruments or devices is tabulated in the following table, where the instruments are ranked in descending order, according to the number of responses received indicating that the instrument is used either in general purpose applications or as a standard by the respondent's organization. Here, the number of responses was generally somewhat higher than those received for the basic electrical quantities themselves. It is noteworthy that function generators, signal generators, pulse generators, counter-timers, frequency meters, oscillators, and spectrum analyzers were considered to be of critical importance. Since these instruments did not appear near the top of the list in the questionnaire, this ranking shows that the number of responses received is not related to the order in which the instruments/devices were listed in the questionnaire.

Seventy respondents also listed "other" instruments or devices which they considered important to their measurement operations. This list is given in Appendix D and includes a wide variety of items.

The figures in the two columns to the right of the table indicate the number of respondents that use the instrument/device as a general purpose instrument, or as a standard. While NBS does not generally offer calibration services for general purpose equipment, it does calibrate many types of precision instruments or devices that are used as standards. Furthermore, using NBS calibrations, industrial laboratories calibrate other instruments that are themselves used as lower echelon standards. Thus, those on the list that are reported to be used most heavily as standards are of greater importance to NBS plans for measurement support.

Table 10. Ranking of instruments/devices, based on number of users (Section D responses). Usage data for each instrument/device is also shown.

Instrument/Device	Number of Users	Number Using as General Purpose	Number Using as Standard
1. Voltmeters	446	395	240
2. Multimeters	445	415	130
3. Function Generators	339	315	65
4. Calibrators	338	129	274
5. Counter-timers	333	295	122
6. Signal Generators	332	305	95
7. Frequency Meters	319	275	136
8. Oscillators	303	281	82
9. Pulse Generators	299	275	57
10. Spectrum Analyzers	288	266	60
11. Oscilloscopes, real time/analog	283	268	60
12. A/D Converters	278	262	50
13. Instrumentation Amplifiers	272	258	51
14. Current Shunts	259	180	158
15. Oscilloscopes, digitizing	248	234	27
16. D/A Converters	245	229	47
17. Impedance Meters	237	201	61
18. Wattmeters	209	179	77
19. Waveform Recorders	203	196	28
20. Distortion Analyzers	180	148	58
21. Phase Angle Meters	168	147	54
22. Instrument Transformers	164	128	71
23. Sample/hold amplifiers	149	145	19
24. Q Meters	133	116	28
25. Noise Analyzers	119	110	22
26. Power Factor Meters	95	82	25
27. CEMI Meters/recorders	94	90	13
28. Watthour Meters	84	69	36
29. CEMI High Voltage Generators	80	72	15
30. Watt Converters	71	59	23
31. Var/Varhour Meters	51	44	17

Several additional analyses were performed on the data submitted in this section. For the following analysis, the instrument/devices were ranked according to the number of respondents (for a given instrument or device) who indicated their usage as a standard. The instruments in the upper third of the rank are listed in the table below. Those followed by an asterisk are ones for which an NBS calibration service or special test is available.

Table 11. Top eleven instruments or devices based on the number of responses indicating their use as a standard.

Instrument/Device	Section D Responses	Number Using as a Standard
1. Calibrators	338	274
2. Voltmeters	446	240
3. Current Shunts*	259	158
4. Frequency Meters	319	136
5. Multimeters	445	130
6. Counter-timers	333	122
7. Signal Generators	332	95
8. Oscillators*	303	82
9. Wattmeters*	209	77
10. Instrument Transformers*	164	71
11. Function Generators	339	65

It is interesting to note that four of the instruments/devices on this list are supported by an NBS calibration service or special test. Models of current shunts, instrument transformers, wattmeters, and oscillators having sufficient precision and stability are used by NBS as standards in performing special tests or calibration services for the quantities of resistance, ratio, power and frequency. Calibrators, which strongly appear at the top of the list, are also used extensively now as standards for supporting voltage, current, and resistance measurements. However, voltmeters and multimeters are also emerging as instruments capable of serving as standards for these basic quantities. Frequency meters and counter-timers are used, of course, as standards for measuring frequency and time intervals (such as delay time and settling time), both of which quantities were shown to be of critical interest in the discussion on quantitites (Section C of the survey). The fact that signal generators and function generators appear on this list indicates that these instruments are apparently being used as standards for supporting various frequency and time-domain analysis quantities.

The responses regarding the need for new/improved characterization methods or NBS calibration services for instruments/devices are summarized in the following table, where again, the instruments are ranked according to the number of responses received in Section D regarding the use of these instruments. The figures in the two right-most columns of the table show the number of respondents that indicated a need for a new/improved characterization method or NBS calibration service. As shown, the indicated needs vary significantly, depending upon the type of instrument/device.

Table 12. Number of responses indicating the need for a new/improved characterization method or NBS calibration service for the instruments/devices. Ranking is the same as in Table 11.

		Number Needing	
Instrument/Device	Section D Responses	Char. Method	NBS Calib. Service
1. Voltmeters	446	41	67
2. Multimeters	445	36	42
3. Function Generators	339	24	16
4. Calibrators	338	38	59
5. Counter-timers	333	25	30
6. Signal Generators	332	23	20
7. Frequency Meters	319	25	33
8. Oscillators	303	18	13
9. Pulse Generators	299	21	19
10. Spectrum Analyzers	288	34	25
11. Oscilloscopes, real time/analog	283	23	21
12. A/D Converters	278	48	21
13. Instrumentation Amplifiers	272	31	12
14. Current Shunts	259	28	31
15. Oscilloscopes, digitizing	248	29	17
16. D/A Converters	245	38	13
17. Impedance Meters	237	24	19
18. Wattmeters	209	24	32
19. Waveform Recorders	203	18	16
20. Distortion Analyzers	180	22	9
21. Phase Angle Meters	168	21	22
22. Instrument Transformers	164	17	26
23. Sample/hold amplifiers	149	15	2
24. Q Meters	133	17	12
25. Noise Analyzers	119	17	9
26. Power Factor Meters	95	13	15
27. CEMI Meters/recorders	94	13	8
28. Watthour Meters	84	13	18
29. CEMI High Voltage Generators	80	14	9
30. Watt Converters	71	10	6
31. Var/Varhous Meters	51	8	8

To explore these results further, the instruments and devices were reranked according to the number of respondents for a given type who indicated the need for NBS calibration services. The instruments/devices comprising the upper third of that rank are listed below, in descending order. Those followed by an asterisk are ones for which an NBS calibration service is available.

Table 13. Top eleven instruments or devices based on the number of responses indicating the need for an NBS calibration service.

Instrument/Device	Section D Responses	Number Needing NBS Calib. Service
1. Voltmeters	446	67
2. Calibrators	338	59
3. Multimeters	445	42
4. Frequency Meters	319	33
5. Wattmeters*	209	32
6. Current Shunts*	259	31
7. Counter-timers	333	30
8. Instrument transformers*	164	26
9. Spectrum Analyzers	288	25
10. Phase Angle Meters*	168	22
11. A/D Converters*	278	21

Once again voltmeters, calibrators, and multimeters appear at the top of the list. This correlates well with the results of Section C where voltage, resistance, and current ranked at the top of the list of quantities in need of NBS measurement support. As discussed in Section C, a proposed new NBS calibration service would make use of the best available high accuracy voltmeters and calibrators to provide a capability for measuring voltage directly. The fact that wattmeters and current shunts are high on the list is also in agreement with Section C results where the need for measuring current and power received relatively high ranking. As indicated earlier in Table 11, frequency meters and counter-timers are used by many respondents as standards, which suggests that there is considerable interest in having an NBS calibration service for these instruments as well. It is also interesting to note that this list is quite similar to that in table 11, except for spectrum analyzers, phase angle meters, and A/D converters. This suggests that there is interest in having these instruments and devices traceable to NBS standards.

The fact that several instruments or devices on this list are presently supported by NBS calibration services or special tests suggests that further analysis is required to determine specific user needs relative to the NBS services.

In another analysis of the results from Section D, the instrument/devices were ranked according to the number of respondents for a given item who indicated the need for a new/improved characterization method. The instruments or devices comprising the upper third of that rank are listed in the following table, and those for which an NBS calibration service or special test is available are followed by an asterisk.

Table 14. Top eleven instruments or devices based on the number of responses indicated the need for new/improved characterization methods.

Instrument/Device	Section D Responses	Number Needing Improved Char. Method
1. A/D Converters*	278	48
2. Voltmeters	446	41
3. Calibrators	338	38
4. D/A Converters*	245	38
5. Multimeters	445	36
6. Spectrum Analyzers	288	34
7. Instrumentation Amplifiers	272	31
8. Oscilloscopes, digitizing	248	29
9. Current Shunts*	259	28
10. Counter-timers	333	25
11. Frequency Meters	319	25

For those instruments/devices marked by an asterisk in the above list, NBS is presently working on better characterization methods for use in the calibration services now offered. These results would seem to indicate a need for better dissemination of NBS methodology for those items. Most of the other instruments/devices have also appeared on the earlier tables analyzing their usage as standards and the need for NBS calibration services. The appearance of instrumentation amplifiers and digitizing oscilloscopes in this table would seem to imply that these items are more general purpose in usage, and mostly in need of better characterization methods.

Section E. ATE/Complex Measurement System

In this section, the respondent was asked to provide information regarding his or her organization's involvement, if any, with automatic test equipment (ATE) or complex measurement systems. The responses to the first question are tabulated below, where the number of responses are given together with the percentage with respect to the total number of respondents (527).

Table 15. Summary of responses regarding respondents' involvement with ATE or complex measurement systems.

Involvement Capacity	Responses to Question 1	Percent of Questionnaires Returned (527)
Equipment User	304	58
Instrument Manufacturer	90	17
Systems Manufacturer	88	17
Software Designer	88	17
ATE Manufacturer	68	13
Standards Developer	50	9
Other	51	10

As shown above, the largest majority of the respondents are users of ATE or complex measurement systems, but there is also a fair degree of involvement in the remaining categories. A listing of the 51 responses entered under "Other" is given in Appendix E.

The second question of this section asked the respondent to identify the types of ATE or complex measurement systems with which his or her organization is involved. The responses are summarized below, using the same notation as the previous table.

Table 16. Summary of responses regarding types of ATE or complex measurement systems with which respondents are involved.

Equipment Type	Responses to Question 2	Percent of Questionnaires Returned (527)
General Purpose Testers	189	36
Automatic Calibration Systems	182	35
Passive Component Testers	124	24
Functional Board Testers	112	21
Active Component Testers (incl. VLSI)	89	17
In-circuit Board Testers	70	13
Computer Systems Testers	69	13
Other	46	9

The entries under "Other" included a variety of equipment types — some general purpose in nature and some for making specific measurements. These are also given in Appendix E.In the final part of this section, several possible NBS outputs pertaining to ATE or complex measurement systems are listed and the respondent is asked to rate the usefulness to his or her organization as "extremely valuable," "useful," or "not useful." These responses are summarized in the following table where the figures in each column represent the percentage of total respondents (527) who gave the indicated rating.

Table 17. Summary of responses regarding the usefulness of possible NBS outputs related to ATE or complex measurement systems.

	Percent of Questionnaires Returned (527)			
Possible NBS Outputs	Extremely Valuable	Useful	Both*	Not Useful
Practical calibration/test guides	39	30	69	2
Documented measurement methods, definitions, terminology	38	29	67	2
Development of new standards for ATE	20	29	49	9
Theoretical calibration/test strategies	19	33	52	6
Technical contributions to voluntary standards organizations	19	31	50	6
Calibration services for ATE standards	17	32	49	10

*Sum of "extremely valuable" and "useful" responses.

Here, the usefulness of two of the listed outputs were rated well above the others; namely, "practical calibration/test guides" and "documented measurement methods, definitions, terminology." This appears to be a strong expression of need for documented outputs and assistance that offer straightforward solutions to practical problems. Furthermore, the generally high level of response to this entire section of the questionnaire suggests the need for NBS research and support in this area.

Section F. Conducted Electromagnetic Interference (CEMI)

As in the previous section, the questions in this section focus on a specific area of electronic technology. The first question asks for information on how the respondent's organization is involved, if at all, with problems associated with CEMI. More specifically, the respondent is asked to indicate if his or her organization is a manufacturer and/or user of certain types of equipment or participates in developing voluntary standards for CEMI. In the following table, the responses to this question are presented in terms of the percentage of total respondents (527) answering a given query.

Table 18. Summary of responses regarding the manufacture or use of CEMI-related equipment.

	Percent of Questionnaires Returned (527)		
Equipment Type	Manufacturer	User	Both
Protective Devices	3	39	4
Detection/Measurement Instruments	4	40	4
Potentially Susceptible Equipment	14	31	9
Potentially Interfering Equipment	13	26	9

Five percent of the respondents indicated their involvement in voluntary standards development, and 11 respondents (2%) listed "other" types of involvement. The latter included such activities as "effects on living organisms," "evaluation of EMC," "effects of education," and "evaluation of tests."

In the final part of this section, the respondents again were asked to evaluate the usefulness of several possible NBS outputs, relative to CEMI. Those responses are tablulated below.

Table 19. Summary of responses regarding the usefulness of possible NBS outputs related to CEMI.

Possible NBS Output	Percent of Questionnaires Returned (527) Extremely Valuable	Useful	Both*	Not Useful
Documented measurement methods, definitions, terminology	32	29	61	2
Techniques for measuring CEMI signals	26	34	60	2
Techniques for characterizing CEMI sources	18	32	50	5
Test methods for protective devices	17	31	48	4
Calibration services for CEMI standards	13	25	38	8
Technical contributions to voluntary standards organizations	11	25	36	6

*Sum of "extremely valuable" and "useful" responses.

As in Section F, the strongest need appears to be for practical measurement methods and techniques. The level of response to questions in this section suggests an awareness of and concern for CEMI-related problems, as well as a need for NBS support.

Section G. Communications/Interactions

The questions in this section are aimed at assessing the effectiveness of communications and interactions between the respondent's organization and NBS. In question one, several communication mechanisms are listed and the respondent is asked to indicate those that are used to obtain information about NBS programs and services. Eighty-nine percent (470) of the respondents answered this question, and generally checked more than one category. Their responses are summarized in the following table, where the communication means are ranked according to the number of responses to question 1.

Table 20. Summary of responses regarding the communication means used by respondents to obtain information on NBS programs and services.

Communication Means	Question 1 Responses	Percentage of Total Responses (470)
1. NBS reports/special publications	271	58
2. Journal publications	268	57
3. Conferences/workshops/seminars	210	45
4. Specific requests	207	44
5. Staff interactions	137	29
6. Media releases	108	23
7. Technical committees	78	17
8. Other	44	9

As shown above, the four communication means that were ranked most important overall by the respondents are NBS reports/special publications, journal publications, conferences/workshops/seminars, and specific requests. The top three and others on the list are ones which obviously can be influenced by internal policies and actions at NBS. These results suggest that the dissemination of research results and other NBS outputs via NBS reports, special publications, journal publications, and technical conferences, workshops, or seminars should continue to receive special emphasis.

Under "Other," 20 respondents listed the National Conference of Standards Laboratories (NCSL) as their source of information about NBS, and five respondents entered "none." Additional means listed under "Other" included manufacturers, vendors, and organizations such as IEEE, the Aerospace Guidance and Metrology Center (AGMC) and the Calibration Coordination Group (CCG).

To explore the results from this question further, the responses were broken down by type of organization. These results are shown in the following table where the numbers in each column refer to the overall ranking of the eight listed communication means.

Table 21. Ranking of communication means by type of organization/business.

Organization/Business	Rank Based on Usage 1st	2nd	3rd	4th	5th	6th	7th	8th
Aerospace	1	2	4	3	5	6	7	8
Automotive	1	4	2	3	6	7	5	8
Computer Equipment	2	3	1	4	6	7	5	8
Consumer Electronics	2	4	3	5	1	6	7	8
Electric Power	1	2	4	3	5	7	6	8
Electronic Components	1	2	3	4	6	5	7	8
Independent Test/Repair Calibration Service	3	1	2	4	5	7	6	8
Medical Electronics	1	2	4	3	6	5	7	8
National Laboratory	1	5	4	3	2	7	6	8
Military	1	3	2	4	5	6	7	8
Other Government	2	1	3	4	5	6	7	8
Telecommunication	2	3	4	1	5	7	6	8
Test Equipment/Instruments	1	2	3	4	5	6	7	8
University	2	1	4	5	3	6	7	8
Other	2	1	4	3	6	5	7	8

This table shows some interesting variations in the relative importance of the given communication means to different types of organizations. For example, for all but three types of organizations, the four most-used communication means are NBS reports/special publications, journal publications, conferences/workshops/ seminars, and specific requests. The three exceptions are consumer electronics, national laboratories, and universities, all of which ranked staff interactions as one of their four most used communication means.

The second question in Section G asked the respondent to indicate whether or not the listed communication means are effective in keeping his or her organization informed about NBS, and to identify those that should be improved. There were 470 responses to the first part of the question of which 54% were "yes" answers. A total of 217 respondents answered "no" to the question and indicated a need for greater emphasis on, or improvement in, the communication means. These latter responses are tabulated below where the percentage of the 217 respondents who indicated the need for improvement is given for each communication means.

Eighty-six percent of the respondents who said the listed communication means are not effective also said their organizations do not use NBS calibration services (question C12) and do not normally seek NBS assistance on measurement problems (question G3).

Table 22. Summary of responses indicating the need to improve the given communication means.

Communication Means	Percentage of Respondents (217) indicating improvements needed
NBS reports/special publications	70
Journal publications	35
Media releases	29
Conferences/workshops/seminars	25
Technical committees	8
Specific requests	7
Staff interactions	6
Other	3

It is interesting to note that the two communication means that were reported to be used the most (NBS reports/special publications and journal publications) are the same ones that were perceived by the most respondents to need improvement or greater emphasis. This may be an indication that many of the responding organizations would like to receive more of these publications.

Most of the respondents (471) answered question 3 which asked if his or her organization normally seeks NBS assistance on calibration or measurement problems. Of these, 34% answered "yes." This figure agrees almost exactly with the response to an earlier question (C. 11) where 33% of the respondents said they were familiar with NBS calibration services. One could conclude from these results that more organizations would probably make use of NBS services if they were aware of the available services.

The final question in this section asks if NBS has provided the necessary support when requested by the respondent's organization. There were 259 responses to this question, with 92% (239) of the respondents giving a "yes" answer.

Section H. Additional Comments

In this section, space was provided for additional general comments, and the respondent was encouraged to elaborate on key measurement needs that NBS should meet and to provide estimates of any economic benefits that would result. Twenty seven percent (143) of the respondents took the time to provide comments that ranged in length from a few words to several paragraphs. NBS has considered all comments carefully and appreciates the time invested by respondents in providing them.

These comments varied greatly from respondent to respondent and included discussions of very specific measurement needs (for both electrical and physical quantities) as well as general metrology-related issues. By far the most common theme was the expression of needs to learn more about NBS services, programs, and activities. Some 17% of the comments addressed this subject. One respondent stated that the discontinuation of the NBS publication DIMENSIONS has been a severe loss to his organization.

Eleven respondents expressed their satisfaction with NBS services and support, while three respondents voiced complaints about the services. Two of the latter complained about long turnaround times for NBS calibrations, and the third said that the calibration fees are too high.

Other measurement quantities or technology areas that received multiple comments are listed below in alphabetical order.

Measurement Concern	Number of Comments
Automatic Test Equipment	6
AC Current	4
AC/DC Voltage	7
Capacitance	4
Conducted Electromagnetic Interference	3
Optical Power	3
Quality Factor (Q)	3
Resistance	5
Time domain quantities	3

4. Conclusions

In this summary report, tabulations of essentially all of the raw data are presented, along with the results of several cross-correlation analyses and listings of such items as responding organizations and items entered under "Other" categories. Further analyses of the data are needed and will be performed to extract additional information or meaning. However, at this point we believe the results lead to and support the following conclusions:

1. A majority of the respondents cited the need to meet government requirements for traceability as their principal reason for needing NBS measurement support. In addition, there was a strong expression of need for NBS measurement support by organizations involved in research and in the development, production, and quality control of products. This is borne out by the responses received in Section B of the questionnaire which suggest that the measurement services offered by NBS should address and be applicable to the practical problems encountered by this segment of industry.

2. Additional analysis of the data from Section C is required in order to further assess its significance and its impact upon NBS calibration services and research programs. For each of the 33 listed electrical quantities, some number of the respondents considered its measurement critical to their operations, and indicated the need for new/improved measurement methods and calibration services. Since the measurement needs of all respondents for all of the quantities cannot be addressed simultaneously, some order of priority must be assumed. Thus, we believe it is appropriate to focus on those quantities that are included in Tables 6 and 7, which are the top eleven identified by the most respondents as needing improved measurement methods or NBS calibration services. By providing an analysis on these quantities of interest, similar to that given for voltage in Section C of this report, the desired guidance for planning NBS measurement programs can be developed. In addition to voltage, the quantities that should receive further analysis include resistance, current, capacitance, frequency, inductance, rise/fall time, transient voltage, power, phase, impedance, delay time, and settling time. Many of these are quantities for which NBS already offers calibration services or special tests. Some of these services may need improvements to achieve higher accuracies and/or broader frequency ranges. Some may be adequate but need to be publicized better. Other quantities on the list are ones for which NBS calibration services or improved measurement methods could be developed under existing or future research programs.

3. The responses received for Section D of the questionnaire show that all of the instruments and devices that are listed are used by some organizations as general purpose equipment, as standards, or as both. Also, in all cases, some of these users indicated the need for a new/improved characterization method or an NBS calibration service. Those instruments or devices that are most widely used as standards and for which there is the greatest need for improved characterization methods or calibration services are the ones that should be given primary consideration in NBS plans. Instruments or devices that meet these criteria are listed in Tables 11, 13, and 14 and include calibrators, voltmeters, multimeters, current shunts, frequency meters, counter-timers, signal generators, oscillators, wattmeters, instrument transformers, function generators, phase meters, spectrum anmalyzers, A/D converters, D/A converters, instrument amplifiers, and digitizing oscilloscopes. Six of these instruments/devices are supported by existing NBS calibration services or special tests, namely, current shunts, wattmeters, instrument transformers, phase meters, A/D converters, and D/A converters. Also, many of the others are calibrated by industrial or commercial laboratories using standards that are traceable to NBS. We believe these results indicate the need for a thorough review of the measurement capabilities of the instruments listed above, compared to the characterization methods and calibration services that are presently available. Those instruments whose capabilities exceed the capabilities of existing characterization methods or calibration services would be candidates for NBS to address in its technical programs. In those cases where existing documented characterization methods or calibration services appear to be adequate, better methods to disseminate and publicize these methods and services should be considered.

4. We believe that the level of response to the questions on ATE/ Complex Measurement Systems and on Conducted Electromagnetic Interference indicate a need for NBS programs in these areas. Fifty-eight percent of the responding organizations indicated that they are now using ATE or complex measurement systems, and many others indicated their involvement with various aspects of such systems. Likewise, a relatively high percentage of responding organizations reported their involvement with CEMI technology as users or manufacturers of instruments and equipment. The responses on both subjects indicate that the respondents want NBS programs that place special emphasis on the development and dissemination of practical guides, techniques, and test/calibration methods. These results also support anecdotal information received from various conferences, inquiries, informal suggestions from calibration clients, etc.

5. A large number of organizations that apparently need and could use NBS measurement support are not aware of, or are only vaguely familiar with, existing NBS programs and services. Furthermore, from some of the comments received in Section H, this situation does not appear to be peculiar to CEEE, but to apply to NBS in general. These results suggest that existing programs and mechanisms for publicizing NBS activities and services need improvement.

The above conclusions are those that are most apparent from our analysis of the results thus far. Further analyses, aimed at resolving questions about the implications of certain responses, are planned. In addition, we can foresee a continuing need to review and study the data to extract specific information in certain areas. Thus, the usefulness of the survey results will continue into the future.

5. Acknowledgments

Our special thanks go to Thomas Leedy, Ann Lovett, and Dawna Whitworth for their diligent and patient efforts in developing and debugging the software programs for extracting, processing, and analyzing the survey data. We also appreciate the extensive support provided by Jennifer Muse and Betty Meiselman in data entry, mail preparation, and preparing this report. The contributions of these individuals were essential to the timely completion of this project.

Many other people also provided valuable assistance and suggestions. Internally, J. French, R. Powell, B. Bell, and O. Petersons were very helpful in drafting and revising the survey questionnaire. Barry Bell provided additional assistance in analyzing and interpreting the survey data. Also, G. Tassey, B. Belanger, and J. Mayo-Wells provided constructive comments and suggestions.

Without the cooperation and help provided by representatives of several external organizations, it is doubtful that the survey could have been carried out. Mr. Fred Ligouri of the IEEE Instrumentation and Measurement Society, Mr. R. B. England of NCSL, Mr. Jack Kinn of the Electronic Industries Association, and Mr. Lawrence Rubin of the American Physical Society all endorsed the program and lent their support by providing mailing labels for their members and participating in the review and critique of the questionnaire. Mr. Ted Plum of the Instrument Society of Anerica provided valuable support by coordinating our first mailing to 5000 members of his Society.

APPENDIX A - QUESTIONNAIRE

OMB Approval No.: 0652-0022
Expiration Date: September, 1986

SURVEY OF ELECTRONIC MEASUREMENT NEEDS BELOW 10 MHz

by the

National Bureau of Standards
Center for Electronics and Electrical Engineering
Metrology Building, Room B-162
Gaithersburg, MD 20899

Thank you for returning the postcard indicating that you wish to participate in this survey.

The purpose of the survey is to determine how the National Bureau of Standards can best support the current and future measurement requirements of your organization. You can help by completing the parts of the survey that apply to your measurement needs.

The survey seeks information in the low frequency domain from DC to 10 MHz for three broad areas of measurement need: (1) basic electrical quantities and related precision instruments, (2) automatic test equipment and other complex measurement systems, and (3) conducted electromagnetic interference.

Measurement needs at frequencies above 10 MHz, including those in the microwave and millimeter-wave domains, are the subject of a separate study.

The survey findings will help NBS plan research programs that provide documented measurement methods and calibration services for industry and Government. These services support quality control, productivity, marketplace equity, international competitiveness, and other goals important to the U.S. economy. NBS seeks to support, rather than compete with, the private sector. NBS is not a regulatory agency.

Other important sources of information will also be considered in NBS planning, including the 1982 National Measurement Requirements Survey of the National Conference of Standards Laboratories.

If you find that the questions in the survey do not adequately cover your measurement needs, please describe those needs in the comments section at the end of the survey.

Your response to this survey is entirely voluntary and may be submitted anonymously, if you wish. Please call John Sorrells if you have any questions (301-921-2727). Thank you for your assistance.

Judson C. French, Director
Center for Electronics and
Electrical Engineering

U.S. Department of Commerce
National Bureau of Standards
NBS-1215
(1-86)

A. Your Organization/Business

1. ☐ Aerospace
2. ☐ Automotive
3. ☐ Computer Equipment
4. ☐ Consumer Electronics
5. ☐ Electric Power
6. ☐ Electronic Components
7. ☐ Independent test, repair, calibration service
8. ☐ Medical Electronics
9. ☐ National Laboratory
10. ☐ Military
11. ☐ Other government
12. ☐ Telecommunication
13. ☐ Test Equipment/Instruments
14. ☐ University
15. ☐ Other: ____________________

B. Organizational Needs

Please indicate the principal reasons why your organization needs measurement support from NBS. Check all categories that apply.

1. ☐ To reduce the cost of reaching buyer/seller agreement.
2. ☐ To ensure market equity.
3. ☐ To meet government requirements, e.g., for traceability.
4. ☐ To meet requirements of foreign governments/buyers.
5. ☐ To assist in development of product specifications.
6. ☐ To support development of voluntary standards.
7. ☐ To support R&D.
8. ☐ To improve quality control in production.
9. ☐ To increase productivity.
10. ☐ To improve product reliability.
11. ☐ To improve product compatibility.
12. ☐ Other: ____

C. Basic Electrical Quantities

If the measurement of one or more quantities in the following list is critically important in your operations, indicate the frequency and accuracy ranges of most concern by entering an accuracy code letter in the appropriate frequency column. If a new/improved measurement method* or NBS calibration service** is needed, place a check in the appropriate "NEEDS" column. For example, if you were concerned with measuring ac voltage to an accuracy of 0.1% at a frequency of 5 MHz and need a calibration service for your reference standards, you would enter the letter "b" in the "1 MHz-10 MHz" frequency column and place a check in the "Cal. Service" column for "Voltage." Further comments can be entered, if desired.

Accuracy Code Letters

a - 1%
b - 0.1%
c - 0.01%
d - 0.001%
e - 0.0001%

QUANTITY	Frequency							Needs		Comments
	dc	dc - 100 Hz	100 Hz - 1 kHz	1 kHz - 10 kHz	10 kHz - 100 kHz	100 kHz - 1 MHz	1 MHz - 10 MHz	Meas. Method	Cal. Service	
1. Voltage										
2. Current										
3. Resistance										
4. Capacitance										
5. Conductance										
6. Dissipation Factor										
7. Inductance										
8. Impedance										
9. Admittance										
10. Quality Factor (Q)										
11. Power										
12. Reactive Power										
13. Power Factor										
14. Energy										
15. Phase										
16. Linearity, Integral										
17. Linearity, Differential										
18. Effective Bits										
19. Frequency										
20. Phase Noise										
21. Harmonic Distortion										
22. Percent Modulation, AM										
23. Percent Modulation, FM										
24. Noise Amplitude										
25. Electric Field Strength										
26. Magnetic Field Strength										
27. Leakage Current										
28. Others:										
29.										
30.										
31.										

*In the context of this survey, a measurement method is defined as a published technique for the measurement of a given quantity, employing appropriate standards.

**In the context of this survey, a calibration service is defined as a service for determining the errors of instrument or device standards submitted to NBS.

C. Basic Electrical Quantities (Cont'd.)

For the following time-domain quantities, note that the frequency ranges have been replaced by time ranges. Otherwise, the procedure for entering your response is unchanged.

Accuracy Code Letters

a - 1%
b - 0.1%
c - 0.01%
d - 0.001%
e - 0.0001%

QUANTITY	Time: ≤1 ns	Time: 1 ns - 10 ns	Time: 10 ns - 100 ns	Time: 100 ns - 1 μs	Time: 1 μs - 10 μs	Time: 10 μs - 100 μs	Time: 100 μs - 1 ms	Time: 1 ms - 1 s	Needs: Meas. Method	Needs: Cal. Service	Comments
1. Voltage, transient											
2. Current, transient											
3. Rise/Fall Time											
4. Settling Time											
5. Delay Time											
6. Acquisition Time											
7. Others:											
8.											
9.											
10.											

11. Are you familiar with the calibration services currently offered by NBS and described in Special Publication 250? ☐ Y ☐ N

12. Does your organization use any of the NBS calibration services? ☐ Y ☐ N

D. Precision Instruments/Devices

If an instrument or device in the following list is important to your measurement operations, indicate how it is used by placing a check in the appropriate "USE" column(s). If a new/improved characterization method* or NBS calibration service is needed, place a check in the appropriate "NEEDS" column.

	Use		Needs		
INSTRUMENT/DEVICE	Gen'l. Purpose	Standard	Char. Method	Cal. Service	Comments
1. Voltmeters					
2. Multimeters					
3. Calibrators					
4. Impedance Meters					
5. Q Meters					
6. Wattmeters					
7. Watt Converters					
8. Var/Varhour meters					
9. Power factor meters					
10. Watthour meters					
11. Phase angle meters					
12. Current shunts					
13. Instrument transformers					
14. A/D Converters					
15. D/A Converters					
16. Sample/hold amplifiers					
17. Instrumentation amplifiers					
18. Waveform recorders					
19. Oscilloscopes					
a. real time/analog storage					
b. digitizing					
20. Frequency meters					
21. Function generators					
22. Oscillators					
23. Pulse generators					
24. Counter-timers					
25. Signal generators					
26. Distortion analyzers					
27. Spectrum analyzers					
28. Noise analyzers					
29. Conducted EMI instruments					
a. high voltage generators					
b. meters/recorders					
30. Others:					
31.					
32.					

*In the context of this survey, a characterization method is defined as a published procedure for evaluating the performance of an instrument or device, employing appropriate standards.

E. ATE/Complex Measurement Systems

In what capacity is your organization involved with automatic test equipment (ATE) or complex measurement systems? Please check all categories that apply.

1. ☐ Systems Manufacturer
2. ☐ Software Designer
3. ☐ Standards Developer
4. ☐ Instrument Manufacturer
5. ☐ ATE Manufacturer
6. ☐ Equipment User
7. ☐ Other: ____________________

____

With what types of ATE/Complex Measurement Systems is your organization involved?

8. ☐ Passive component testers
9. ☐ Functional board testers
10. ☐ General purpose testers (for instruments, avionics, etc.)
11. ☐ Automatic calibration systems
12. ☐ Active component testers (including VLSI)
13. ☐ In-circuit board testers
14. ☐ Computer systems testers
15. ☐ Other: ____________________

Indicate the usefulness to your organization of the following possible NBS outputs for ATE/Complex Measurement Systems. Circle E for extremely valuable, U for useful, X for not useful, or leave blank if you have insufficient information to judge.

16. Theoretical calibration/test strategies	E	U	X
17. Practical calibration/test guides	E	U	X
18. Calibration services for ATE standards*	E	U	X
19. Development of new standards* for ATE	E	U	X
20. Documented measurement methods, definitions, terminology	E	U	X
21. Technical contributions to voluntary standards organizations	E	U	X
22. Other:			
____________________	E	U	X
____________________	E	U	X
____________________	E	U	X

*As used here, an ATE standard is defined as an instrument or device used for the accurate generation/measurement of electrical quantities and especially adapted for ATE.

F. Conducted Electromagnetic Interference (CEMI)*

In what capacity is your organization involved with the problems associated with CEMI? Please check all categories that apply.

1. Protective Devices — a. ☐ Manufacturer — b. ☐ User
2. Detection/Measurement Instruments — a. ☐ Manufacturer — b. ☐ User
3. Potentially Susceptible Equipment — a. ☐ Manufacturer — b. ☐ User
4. Potentially Interfering Equipment — a. ☐ Manufacturer — b. ☐ User
5. Voluntary Standards Development ☐
6. Other: ____________________

Indicate the usefulness to your organization of the following possible outputs from NBS. Circle E for extremely useful, circle U for useful, circle X for not useful, or leave blank if you have insufficient information to judge.

7. Test methods for protective devices	E	U	X
8. Techniques for characterizing CEMI sources, e.g., source impedance	E	U	X
9. Techniques for measuring CEMI signals	E	U	X
10. Calibration services for CEMI standards**	E	U	X
11. Documented measurement methods, definitions, terminology	E	U	X
12. Technical contributions to voluntary standards organizations	E	U	X
13. Other:			
____________________	E	U	X
____________________	E	U	X
____________________	E	U	X

*In the context of this survey, CEMI is defined as any unwanted signal that enters a system by means of power lines, signal lines, or other conducting paths.

**As used here, a CEMI standard is defined as an instrument or device used for the accurate generation/measurement of electrical quantities involved in CEMI testing.

G. Communications/Interactions

1. By what means does your organization obtain/receive information regarding NBS electronic measurement programs and services? Please check all categories that apply.

   a. ☐ Staff interactions
   b. ☐ Conferences/workshops/seminars
   c. ☐ NBS reports/special publications
   d. ☐ Journal publications
   e. ☐ Technical committees
   f. ☐ Specific requests
   g. ☐ Media releases
   h. ☐ Other: ________________

2. Are the above mechanisms effective in keeping your organization informed about NBS activities, services, and results? ☐ Y ☐ N

   If not, which ones should be improved or receive greater emphasis? Please circle the appropriate letter designations: a. b. c. d. e. f. g. h.

3. If your organization has a calibration or measurement problem does it normally seek assistance from NBS? ☐ Y ☐ N

4. In those cases where your organization has requested NBS help in solving a calibration or measurement problem, has NBS provided the necessary support? ☐ Y ☐ N

H. Additional Comments

Please elaborate on key measurement needs you want NBS to meet; as an aid in establishing work priorities, provide, if possible, an estimate of economic benefit to your organization or the nation if NBS meets those needs. Use the back of this form if you need additional space.

Optional Information:

Name of person responding: ________________________________ Tel.: ____________

Organizaton: ____

Address (for mailing survey findings): ____

____

Are you willing to be contacted by NBS for further information? ☐ Y ☐ N

Note: Survey responses should be returned in the enclosed envelope. Anonymous respondents can receive a summation of survey findings by sending a separate request to NBS at the address on the cover page.

APPENDIX B - PARTICIPATING ORGANIZATIONS

A SQUARE D COMPANY
AAI CORP.
ABBOTT LABORATORIES
ACME ELECTRIC CORP.
ADC TELECOMMUNICATIONS
ADVANCED PERIPHALS INC.
AIR FORCE WEAPONS LAB
AIRESEARCH
AIRESEARCH MFG. CO.
ALLISON GAS TURBINE DIV. GM
ALLIS. CHALMERS HYDRO, INC.
ALPHA INDUSTRIES
AMADOR CORP.
AMERICAN CRITICAL CARE
AMERICAN EDWARDS LABS
AMERICAN TECHNICAL CERAMICS CORP.
AMTRAK
AMXTM-CW-WS
ANADRILL/SCHLUMBERGER
ANALOG DEVICES
ANALOG DEVICES SEMICONDUCTOR
ANALOGIC-INDUSTRIAL TECH. GROUP
ANR STORAGE CO.
APPLIED SENSORS INTERNATIONAL
ARCO OIL & GAS CO. MEASUREMENT DEPT.
ARGONNE NATIONAL LAB
ARLO ALASKA INC.
ARVIN/CALSPAN ATC.
ASTRA CORP.
ATEAM CORP.
ATKINS TECHNICAL INC.
AUSTRON INC.
AVCO SYSTEMS DIVISION
AXIOM TECHNOLOGY, INC.
BAILEY CONTROLS CO.
BALLANTINE LABORATORIES
BARNANT/COLE-PARMER
BARRIOS TECHNOLOGY INC.
BATTELLE MEMORIAL INSTITUTE
BATTELLE NORTHWEST LABORATORIES
BDM CORP.
BEAR MEDICAL SYSTEMS
BEARD ENGINEERING, INC.
BELL HELICOPTER TEXTRON CANADA
BENDIX FIELD ENGR. CORP. - DEPT. OF ENERGY
BERGAN MERCY HOSPITAL
BIOMAGNETIC TECHNOLOGIES, INC.
BIO-TEX INSTRUMENTS INC.
BKC CONSULTANTS
BLACKBURN - A DIV. OF FL INDUSTRIES, INC.

BOEING MILITARY AIRPLANE CO.
BONNEVILLE POWER ADMINISTRATION
BORG WARNER RESEARCH
BROOKHAVEN NATIONAL LABORATORIES
BRUNSWICK CORP.
BTI
CABLE SYSTEMS INC.
CALIFORNIA MICROWAVE INC.
CALVIN COLLEGE
CANADIAN GENERAL ELECTRIC
CAPINTEL INSTRUMENTS INC.
CATALYST RESEARCH, DIV. MSA
CATEC
CATERPILLAR, INC.
CENTURION INSTRUMENT CO.
CERTIFIED MEASUREMENTS, INC.
CHEMISTRY DEPT., JOHNS HOPKINS UNIVERSITY
CITY OF TACOMA, WA, DEPT. OF UTILITIES
CLARK COUNTY HEALTH DISTRICT
COILCRAFT INC.
COLORADO CRYSTAL CORP.
COLORADO STATE UNIVERSITY
COLUMBIA ENGINEERING
COMMERCIAL RADIO CO.
COMMONWEALTH EDISON CO.
COMPUTER INSTRUMENTS CORP.
COMSAT LABORATORIES
CONSULTANT
CORNING GLASS WORKS
CORPUS CHRISTI PETROCHEMICAL CO.
CUMMING ENGINE CO.
C.E.D.
DATRON INSTRUMENTS LTD.
DEPT. OF LABOR MINE SAFETY & HEALTH ADMIN.
DUQUENSE LIGHT CO.
DICKSON CO.
DICONIX, A KODAK COMPANY
DIGITAL EQUIPMENT CORP.
DODIG
DORIC SCIENTIFIC
DRAVO ADVANCED TECHNOLOGY
DUKE POWER CO.
DYNAMIC SCIENCES
EASTMAN KODAK APPARATUS DIVISION
EATON CORP. ENGR. & RES.
ECTRON CORP.
E G & G OCEAN PRODUCTS
E G & G/EM INC.
EIL INSTRUMENTS, INC.
EIP MICROWAVE
ELECTRO RENT CORP.
ELECTRO SCIENTIFIC INDUSTRIES, INC.
ELECTROMAGNETIC SCIENCES
ELECTRONIC CONTROLS DESIGN

ELECTRO-MECHANICS
ELERY F. BUCKLEY
ELI LILLY & CO.
ERFO
ESC ELECTRONICS CORP.
ETHICON, INC.
E-A-R DIV./CABOT CORP.
E-M INSTRUMENTS
E-SYSTEMS UNIT 4 84322
E. G. & G. IDAHO INC.
E. I. DU PONT DE NEMOURS & CO.
FAIRCHILD SEMICONDUCTOR
FLORIDA SOLAR ENERGY CENTER
FLOW SYSTEMS, INC.
FMC CORP.
FORD MOTOR CO.
FOTEC, INC.
FREQUENCY AND TIME SYSTEMS
FTS
GEC AVIONICS
GENERAL CABLE CO.
GENERAL DYNAMICS ELECTRONICS
GENERAL DYNAMICS/CONVAIR
GENERAL DYNAMICS/ELEC. BOAT DIV.
GENERAL DYNAMICS/FT. WORTH DIVISION
GENERAL ELECTRIC
GENERAL ELECTRIC NUCLEAR ENERGY BUS. ORG.
GENRAD INC.
GENRAD, SEMICONDUCTOR TEST DIV.
GIORDANO ASSOC. IND.
GOULD OSD
GUIDED WAVE, INC.
GUILDLINE INSTRUMENTS INC.
HARRIS SEMICONDUCTOR
HARRY DIAMOND LABORATORIES
HEKIMIAN LABORATORIES, INC.
HEWLETT PACKARD
HEWLETT PACKARD CO. - LOVELAND INSTR. DIV.
HEWLETT PACKARD MEMORY DIV.
HNB INTERSTATE
HONEYWELL INC.
HONEYWELL INFO. SYSTEMS
HONEYWELL OPTOELECTRONICS
HONEYWELL STANDARDS LAB.
HOTTINGER BALDWIN MEASUREMENTS, INC.
HUGHES AIRCRAFT
HUGHES OPTICAL
I & E MAINT. ENG. INC.
IBM
IBM CORP., GPD
IFR INC.
INCAL SERVICES
INSTRULAB, INC.
INSTRUMENTATION SERVICE, WYETH LABS

INTEL CORP.
INTERNATIONAL JENSEN, INC.
ITI CO.
ITT CORP.
ITT TELECOM
I.S.A.
JOHN FLUKE MFG. CO.
JOHN TYLER COMMUNITY COLLEGE
JOHNS HOPKINS APPLIED PHYSICS LABORATORY
JOHNS HOPKINS UNIVERSITY
JOHNS HOPKINS UNIVERSITY, DEPT. OF PHYSICS
JOMAR SYSTEMS
JOY MANUFACTURING
J. A. JONES APPLIED RESEARCH
KAMAN SCIENCES CORP.
KAMAN TEMPO
KEITHLEY INSTRUMENTS INC.
KISTLER INSTRUMENT CORP.
KNOPP, INC.
KOLLMORGEN CORP. PHOTO RESEARCH DIV.
KOLLSMAN INSTRUMENT CO.
LAWRENCE LIVERMORE NATIONAL LABORATORY
LEDFORD MACHINE & GAGE LAB
LEWIS ELECTRONIC INSTRUMENTATION
LFE CORP. INSTRUMENTS DIV.
LITTON ELECTRON DEVICES
LMSC RES. LAB
LOCKHEED GEORGIA CO.
LOCKHEED MISSILES AND SPACE COMPANY
LOCKHEED SPACE OPERATIONS CO.
LOCKHEED-CALIFORNIA CO.
LOCKHEED/EMSCO, JOHNSON SPACE CENTER
LORD CORP. R&D CENTER
LOS ALAMOS NATIONAL LABORATORY
LOS ANGELES PIERCE COLLEGE
LOTUS DEVELOPMENT CORP.
LTX CORP.
MACK TRUCKS INC.
MAGNAVOX CO.
MAGNAVOX GOV. & INDUST. ELEC. CO.
MAGNETIC MEASUREMENTS ENGINEERING
MARATHON OIL GULF COAST REGION ELECTRONICS
MAROTTA SCIENTIFIC
MATSUSHITA/PANASONIC
MAXWELL LABORATORIES
MCDONNELL DOUGLAS
MEDTRONIC INC.
METROLOGY-AIRESEARCH MANUFACTURING
MIAMI HEART INSTITUTE
MICRO SWITCH
MICROMANIPULATION CO.
MICROSEM CORP.
MILES LABS-AMES DIVISION
MILES LABS, INC.
MINE SAFETY APPLIANCES CO.

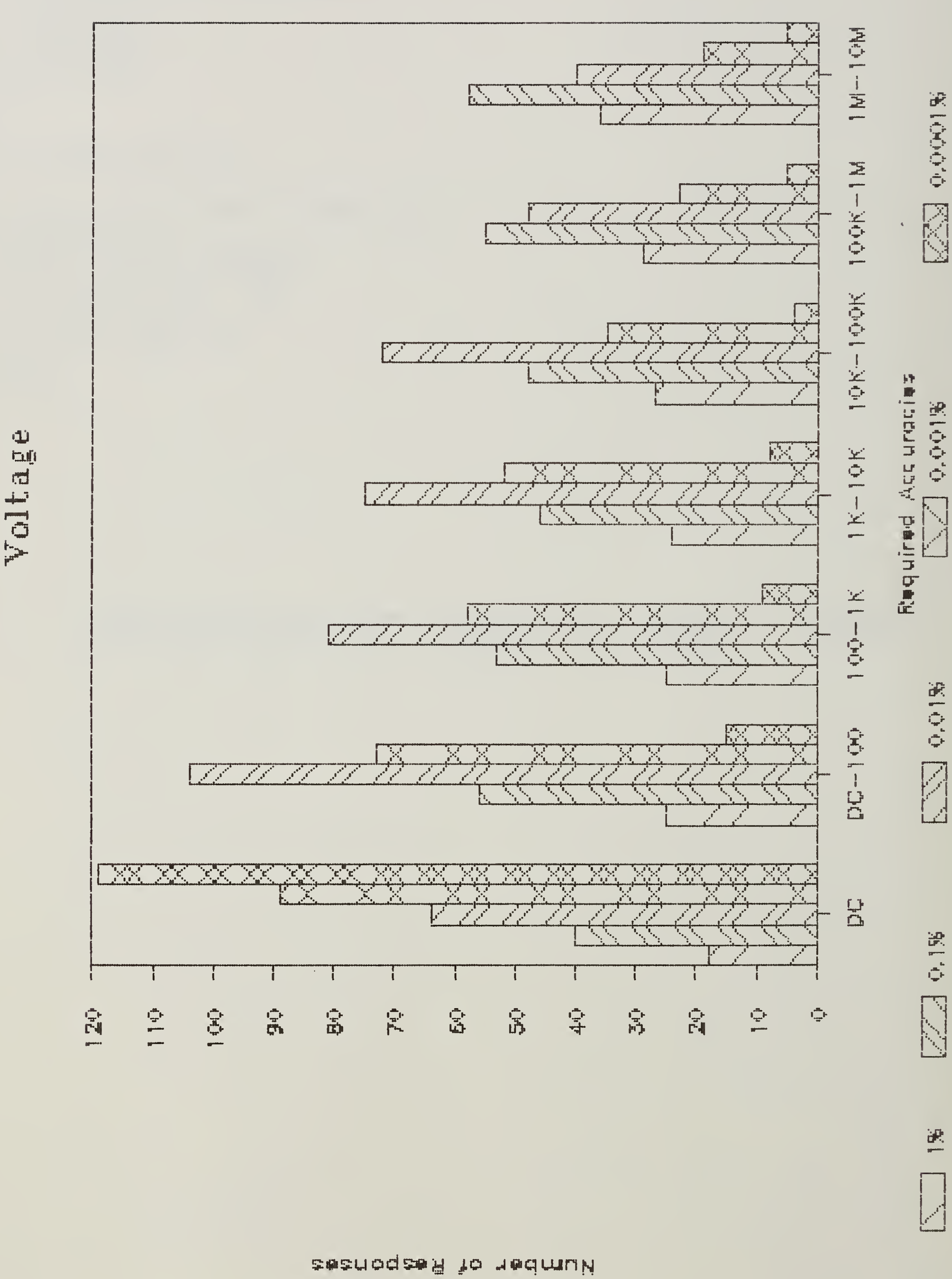
MINNESOTA DEPT. OF HEALTH
MISSISSIPPI POWER AND LIGHT, GRAND GULF NUCLEAR
MIT LINCOLN LABORATORY
MKS INSTRUMENTS
MOLYTEK, INC.
MORTON THIOKOL INC.
MOTOROLA COMMUNICATIONS
MOTOROLA GOVERNMENT ELEC. GROUP
MOTOROLA INC.
MOTOROLA SPS
MTS SYSTEMS CORP.
MT. SINAI MEDICAL CENTER
MUSTANG FUEL CO.
M-TRONICS, INC.
M/A COM MILLIMETER PRODUCTS, INC.
NASA
NASA LANGLEY RES. CTR.
NASA LYNDON B. JOHNSON SPACE CENTER
NASA RESEARCH CENTER
NASA-NTF
NASA, AMES RESEARCH CENTER
NAVAL AIR REWORK FACILITY
NAVAL AVIONICS CENTER
NAVAL ORDNANCE STATION
NAVAL RESEARCH LABORATORY
NAVAL SHIP SYS. ENGR. STA. (CODE 052E)
NAVY PRIMARY STANDARDS DEPT.
NAVY PRIMARY STANDARDS LABORATORY
NEWTON INSTRUMENT CO.
NIAGARA MOHAWK POWER CO.
NMERI/CERF
NORDSON CORPORATION
NORDSON CORP. PMA DIVISION
NORTHERN STATES POWER
NORTHROP DSD
NORTHROP PRECISION PRODUCTS DIVSION
NORTHRUP CORP., AIRCRAFT DIV.
NORTHWEST REGIONAL CALIBRATION CTR.
N.A.P. CONSUMER ELECTRONICS CORP.
OECO CORP.
OHIO EDISON CO.
OHIO STATE UNIVERSITY
ONEAC CORP.
ONTARIO HYDRO
OPUS ENGINEERING & SOFTWARE
ORLANDO TECHNOLOGY, INC.
ORMOND INC.
PALL CORP.
PHILLIPS ULTRASOUND
PHOTO RESEARCH DIV.
PICOSECOND PULSE LABS INC.
PIERCE CO. UTILITIES
PITTSBURG STATE UNIVERSITY
PITTSBURGH CORNING CORP.

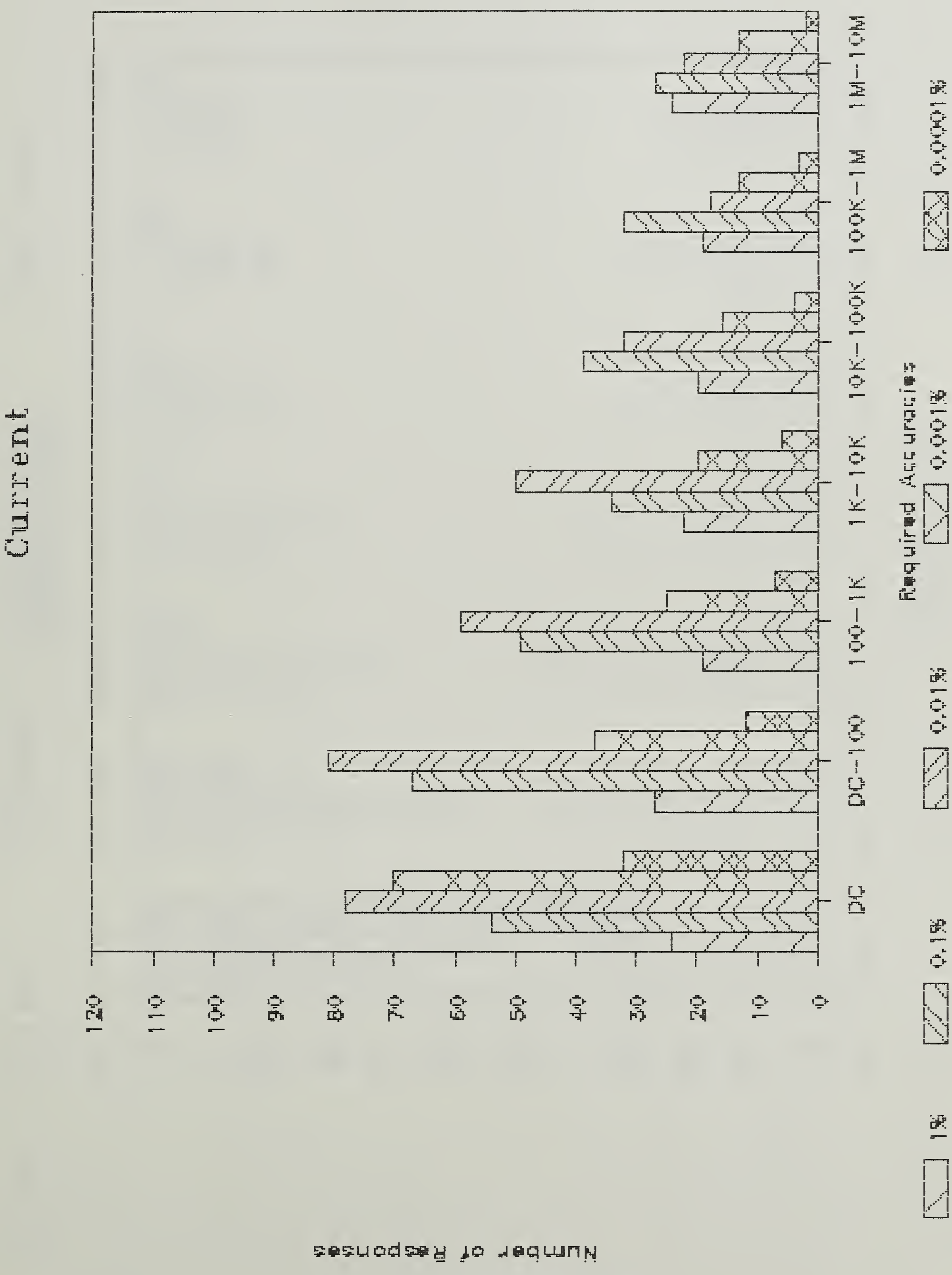
PRECISION MEASUREMENT
PREMIER MICROWAVE CO.
PROCESS & INSTRUMENTS CORP.
PUGET SOUND NAVAL SHIPYARD
PUGET SOUND POWER & LIGHT CO.
P.S.E. & RESEARCH CORP.
QVS INC.
Q-DOT, INC.
RAMSEY ENGINEERING CO.
RAYTHEON CO.
RAYTHEON CO. MISSILE SYSTEMS DIV.
RCA ASTRO-ELECTRONICS
RCA CONSUMER ELECTRONICS
RCA CORP.
RCA LABORATORIES
RCA-SSD
RCA, PMEL/E
RD TECHNOLOGY INC.
RED RIVER ARMY DEPOT
RELIANCE ELECTRIC CO. - MSE
RESURRECTION HOSPITAL
RETLIF TESTING LABORATORIES
REXNORD CHEMICAL PRODUCTS INC.
ROCHESTER GAS & ELECTRIC CORP.
ROCKWELL ENG. CO.
ROCKWELL HANFORD OPERATION
ROCKWELL INTERNATIONAL
ROCKWELL INTERNATIONAL, CTSD
ROCKWELL INTERNATIONAL, ROCKY FLATS
ROSEMOUNT, INC.
ROSS ENGINEERING CORP.
ROTEK INSTRUMENT CORP.
ROTTER ENGINEERING
RUSKA INSTRUMENT CORP.
RUTHERFORD RESEARCH
SACRAMENTO MUNICIPAL UTILITY DISTRICT
SANDIA NATIONAL LABORATORIES
SANGAMO WESTON, INC.
SARGENT INDUSTRIES
SASKATCHEWAN POWER CORP.
SCANTEK IND.
SECURITY TAG SYSTEMS INC.
SENSOTEC, INC.
SENTRY TEST SYSTEMS
SENTRY VHSIC
SEQUENCE, INC.
SHEPARD SCIENTIFIC
SIMCO ELECTRONICS
SOLAR ENERGY RESEARCH INST.
SOUTHWEST RESEARCH INSTITUTE
SOUTH CAROLINA ELECTRIC AND GAS
SPECTRA-PHYSICS, INC.
SPERRY
SPERRY, COMPUTER SYSTEMS DIV.

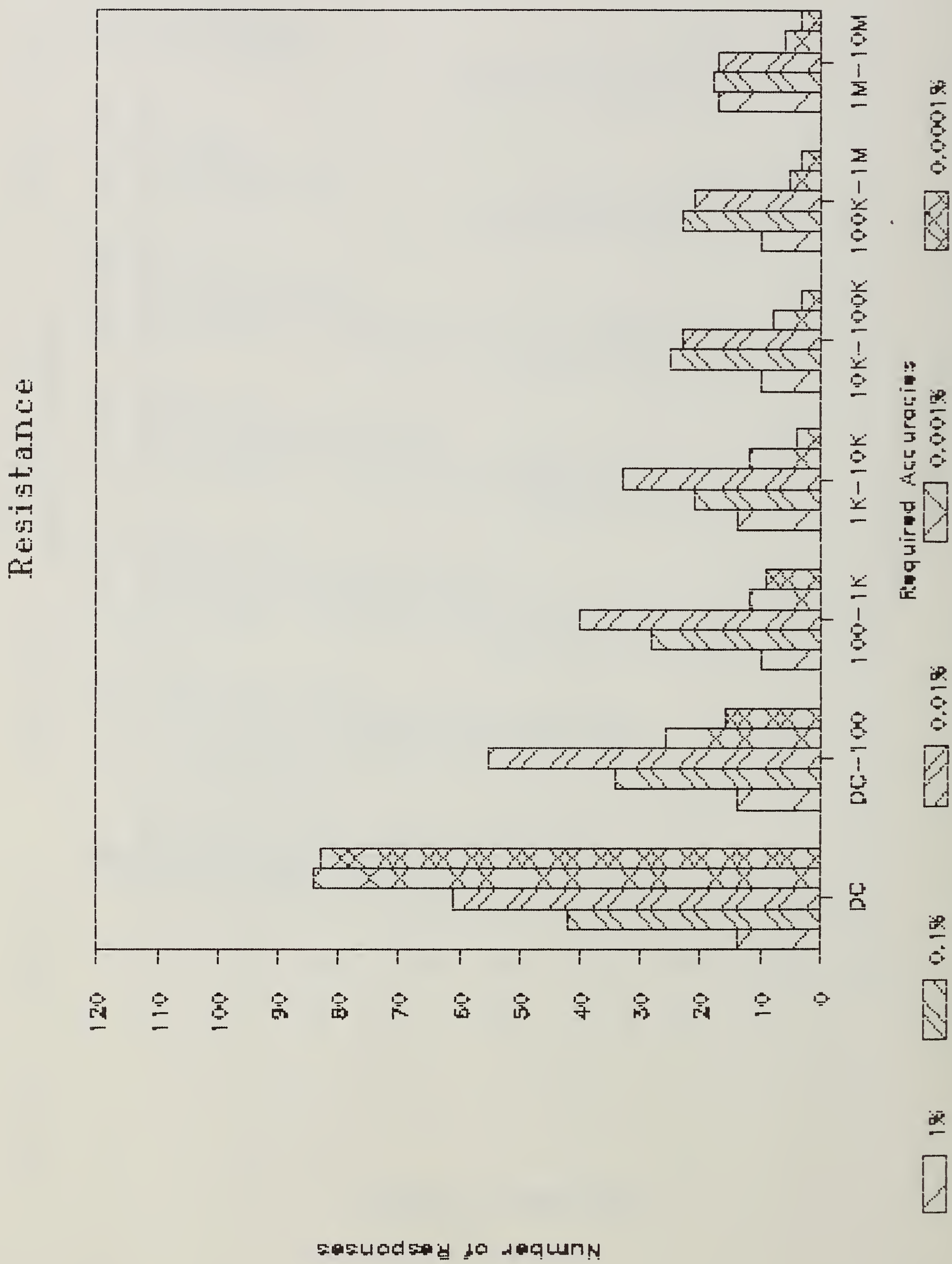
STONE & WEBSTER ENGINEERING CORP.
STUBBS OVERBECK & ASSOCIATES, INC.
SUN TEQ ENGINEERING INC.
SUNDSTRAND ATG.
SUNDSTRAND DATA CONTROL, INC.
STATE UNIVERSITY OF NEW YORK-BUFFALO
SVERDRUP & PARCEL ASSOC.
SYNERGY, INC.
SYNETIC DESIGN CO.
SYSTEM TEST
S. SENSIPER
TECHNICAL SERVICE LABORATORY
TEKTRONIX, INC.
TELEDYNE RYAN ELECTRONICS
TELEDYNE SYSTEMS CO.
TENNESSEE TECH. UNIVERSITY
TERADYNE INC.
TETTEX INSTRUMENTS INC.
TEXAS INSTRUMENTS, INC.
TEXAS STATE TECHNICAL INSTITUTE
THE BOEING CO.
THE CITADEL
THE UNIVERSITY OF TULSA
THERMO ELECTRIC (CANADA) LTD.
THERMOMETRICS INC.
TIGER COMMUNICATIONS
TMDE BRANCH, U. S. ARMY
TRACOR, INC.
TRANSMATION INC.
TRAVENOL LABORATORIES INC.
TRIPLETT CORP.
TRW
TRW DSSG
TUDOR TECHNOLOGY INC.
UAB EE DEPT.
UNIVERSITY OF CALIFORNIA AT BERKELEY
UNION CARBIDE CORP.
UNIVERSITY OF NEW MEXICO, NMERI
UNIVERSITY OF ARIZONA
UNIVERSITY OF ARKANSAS
UNIVERSITY OF LA VERNE
UNIVERSITY OF PITTSBURGH
UNIVERSITY OF SASKATCHEWAN
UNIVERSITY OF SOUTH FLORIDA
UNIVERSITY OF WASHINGTON
UNIVERSITY OF MINNESOTA
U. S. AIR FORCE
U. S. ARMY ARDC IEB NSD PAD
U. S. ARMY AREA TMDE SUPPORT OPERATION
U. S. GEOLOGICAL SURVEY, WRD
U. S. INSTRUMENT RENTALS
U.S.A. AREA CALIBRATION & REPAIR CTR.
USAF QUALITY ASSURANCE
UNIVERSITY OF TEXAS AT ARLINGTON

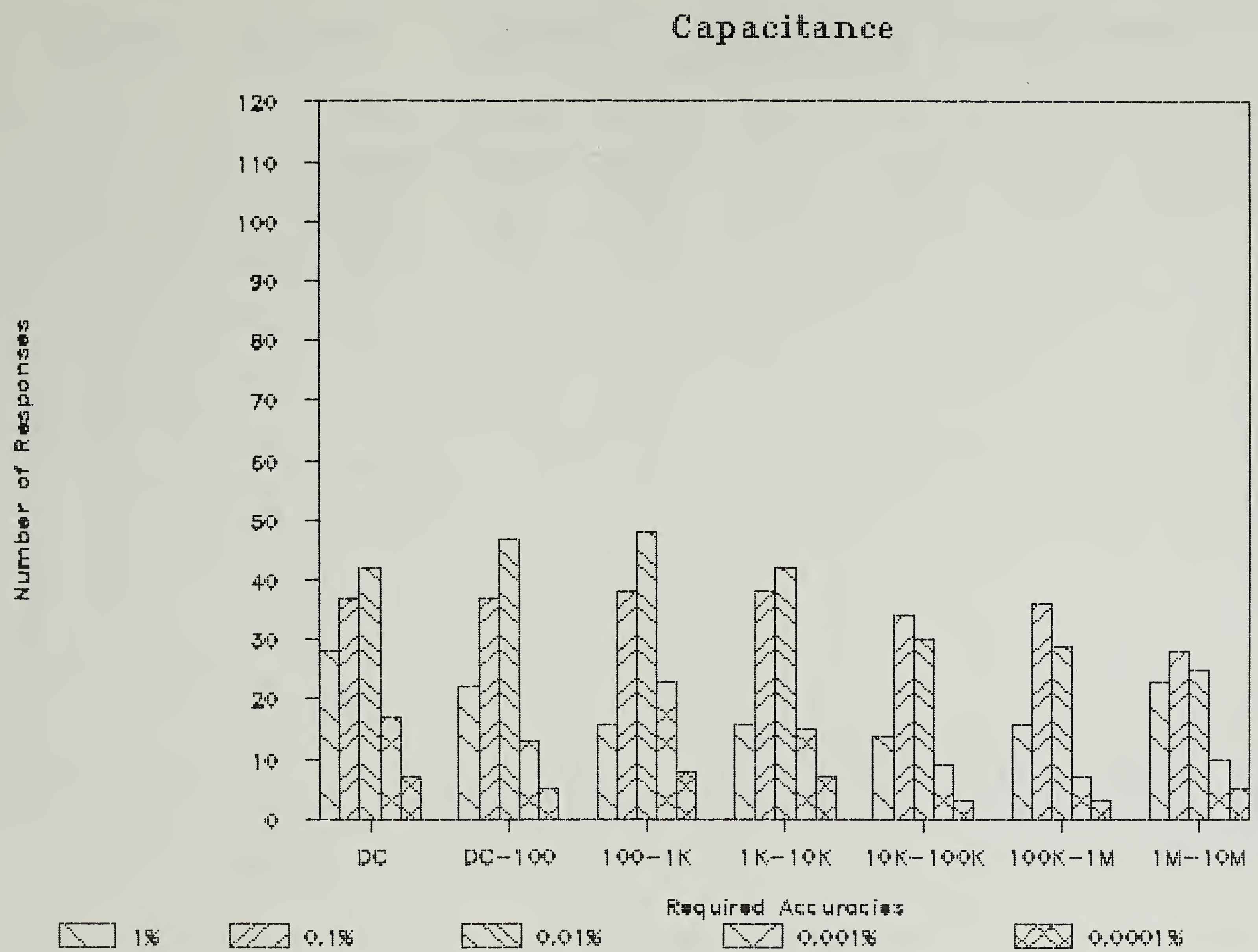
U. S. NAVAL ACADEMY
U. S. GEOLOGICAL SURVEY, WRD
U. S. NAVY CALIBRATION LABORATORY
U. S. WINDPOWER INC.
VALCOR ENG. CORP.
VARIAN ASSOCIATES
VECTRON LABS INC.
VEDA INC.
VISHAY
VOGELMAN DEVELOPMENT CO.
WEAC
WESTINGHOUSE ADVCD. ENERGY SYSTEMS DIV.
WESTERN ENGINE CO.
WEYERHAUSER FORESTRY RESEARCH
WILLIAMS INTERNATIONAL CORP.
WYANN TECHNOLOGY CORP.
YELLOW SPRINGS INST. CO.
3M COMPANY
55 AMS/MAAP

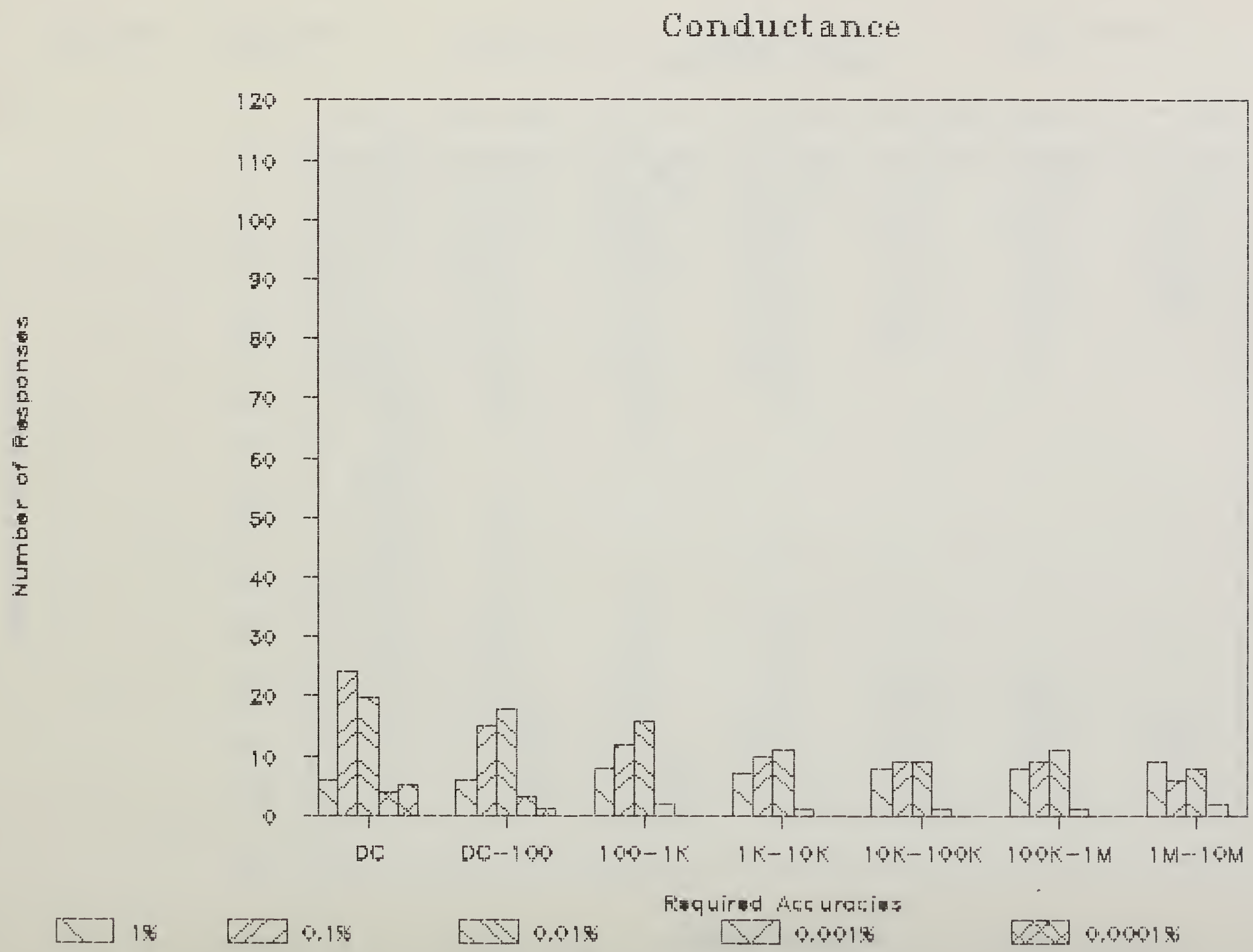
APPENDIX C - Section C Data Regarding Measurement Requirements
(accuracy vs. frequency) For The Given Quantities

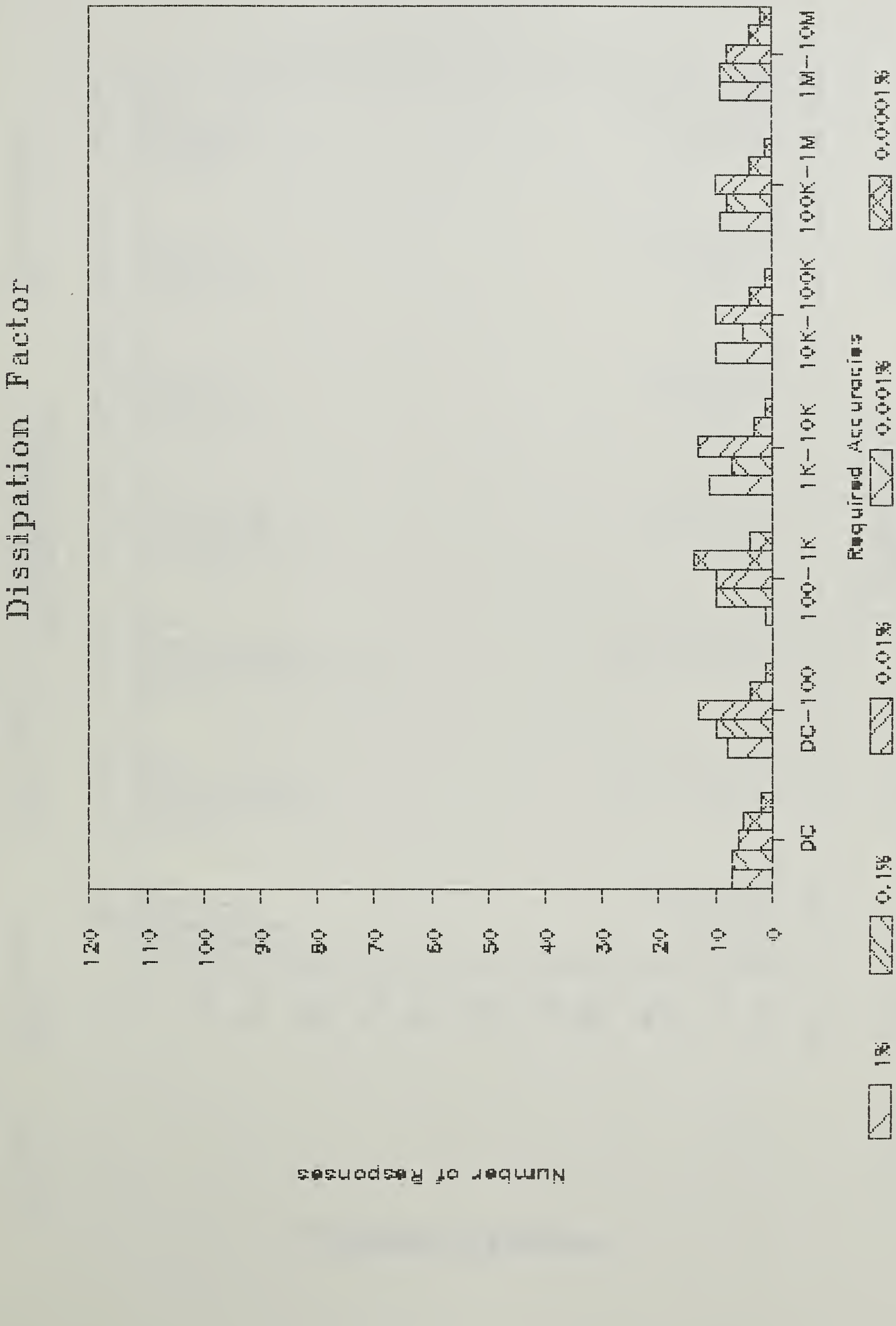

Voltage
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

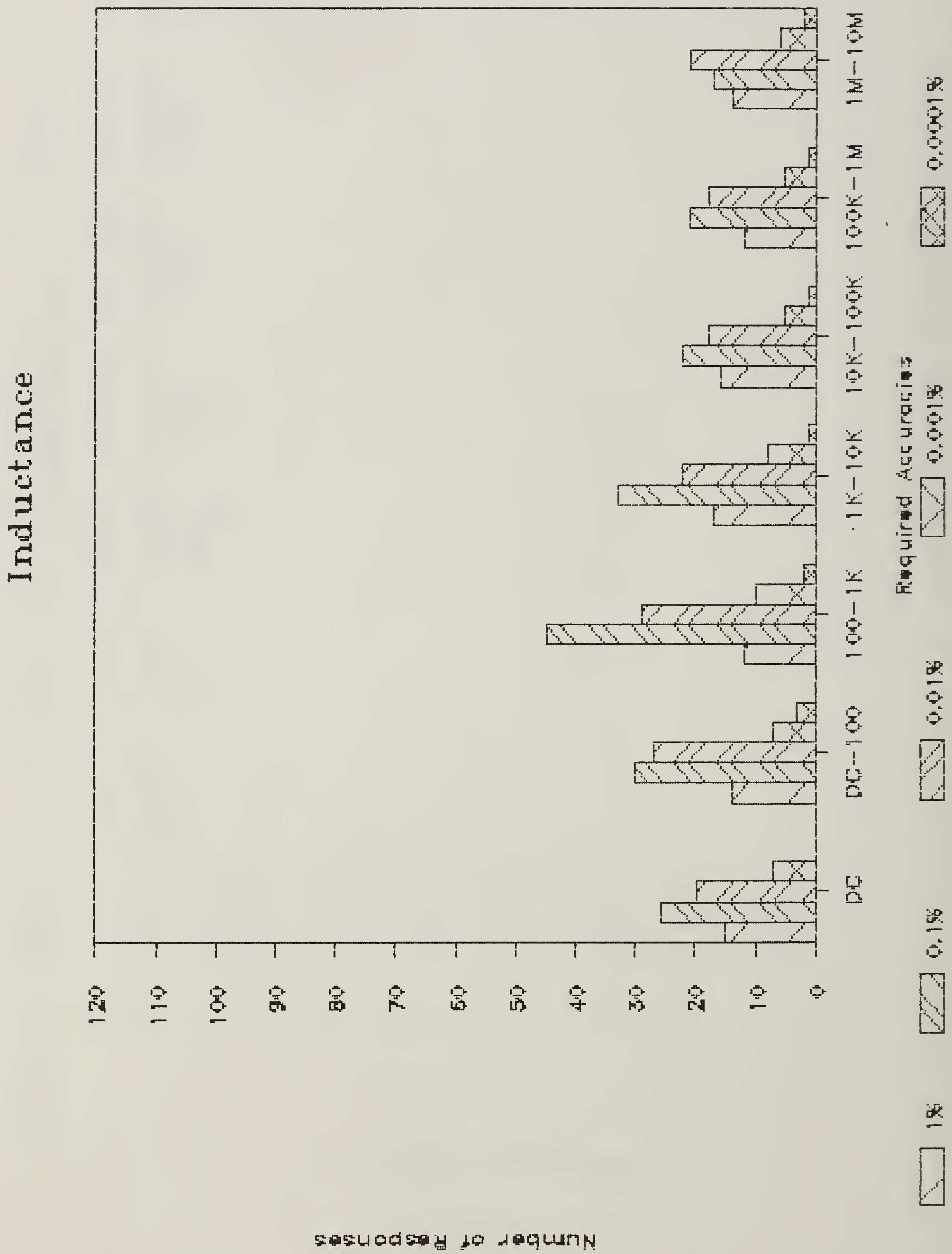

Current
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Resistance
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

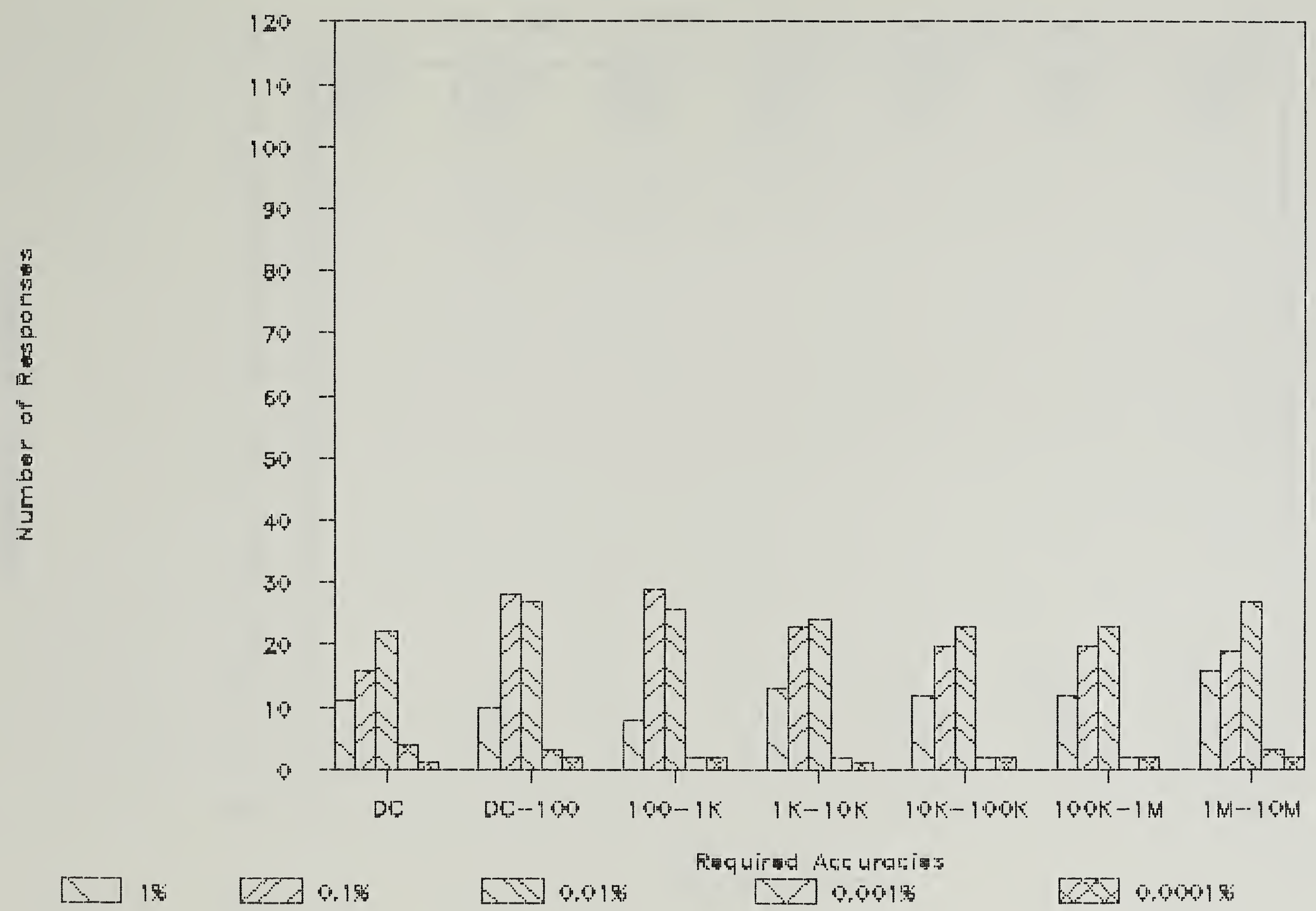

Capacitance
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

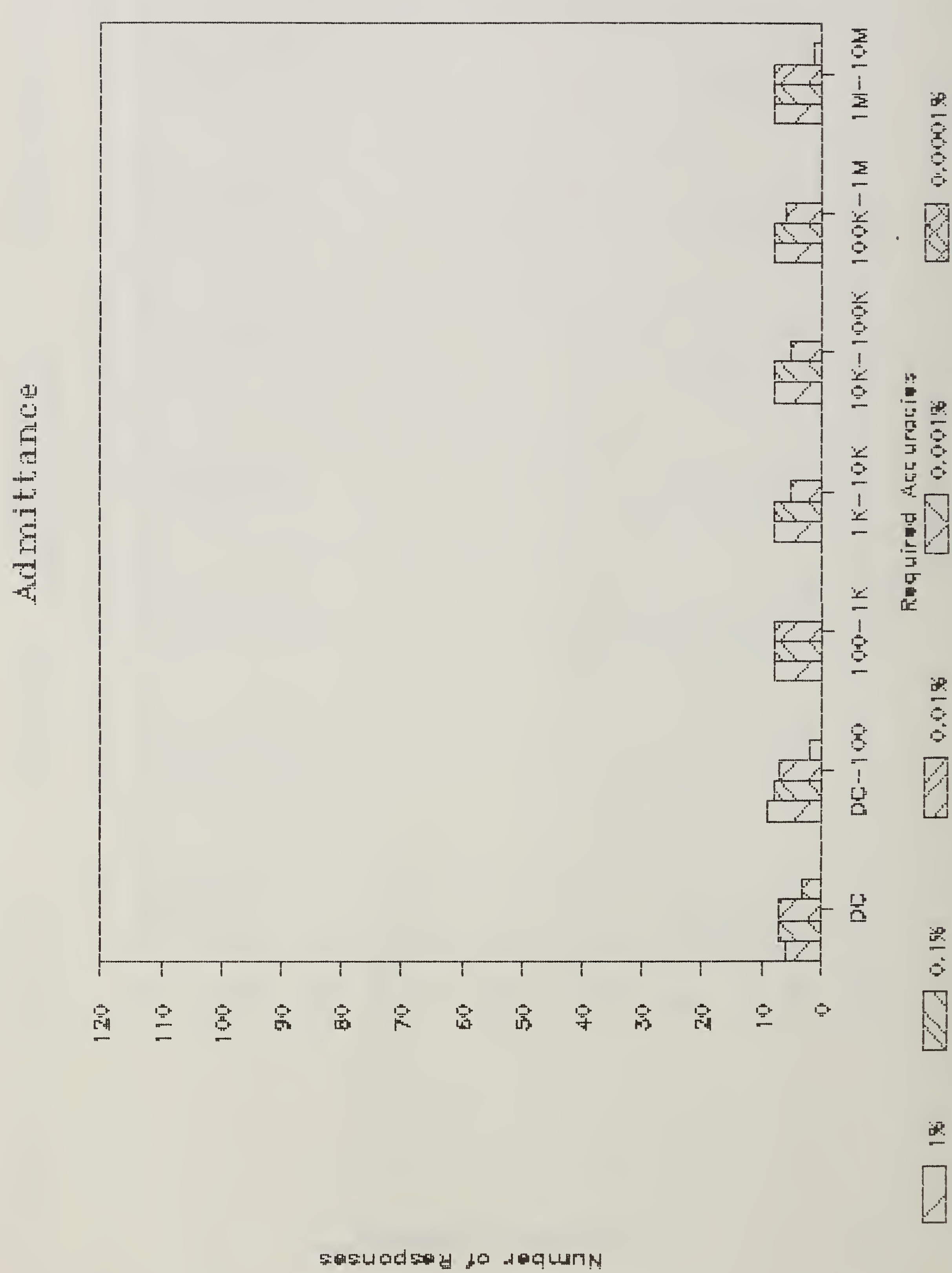

Conductance
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Dissipation Factor
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

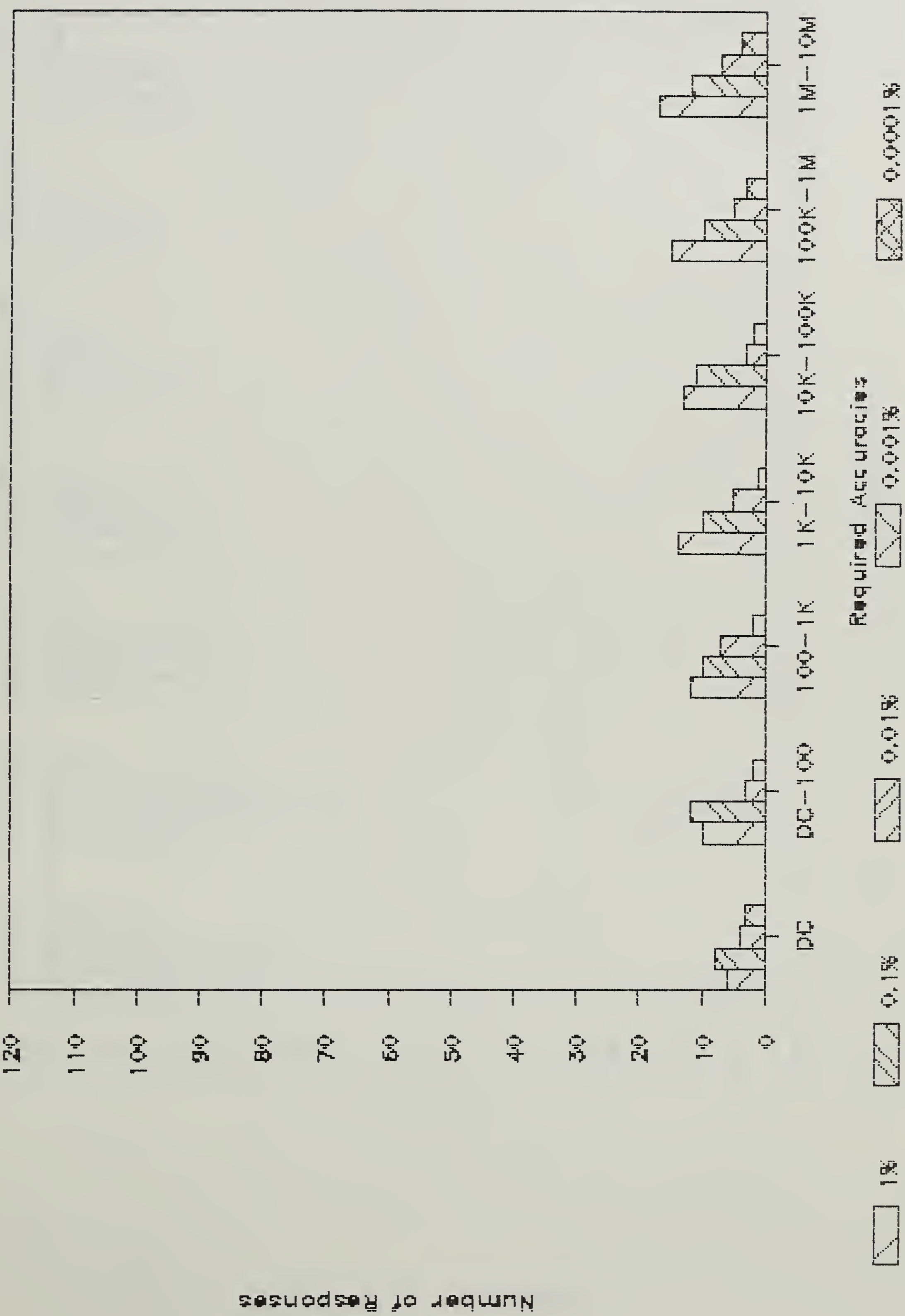

Inductance
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

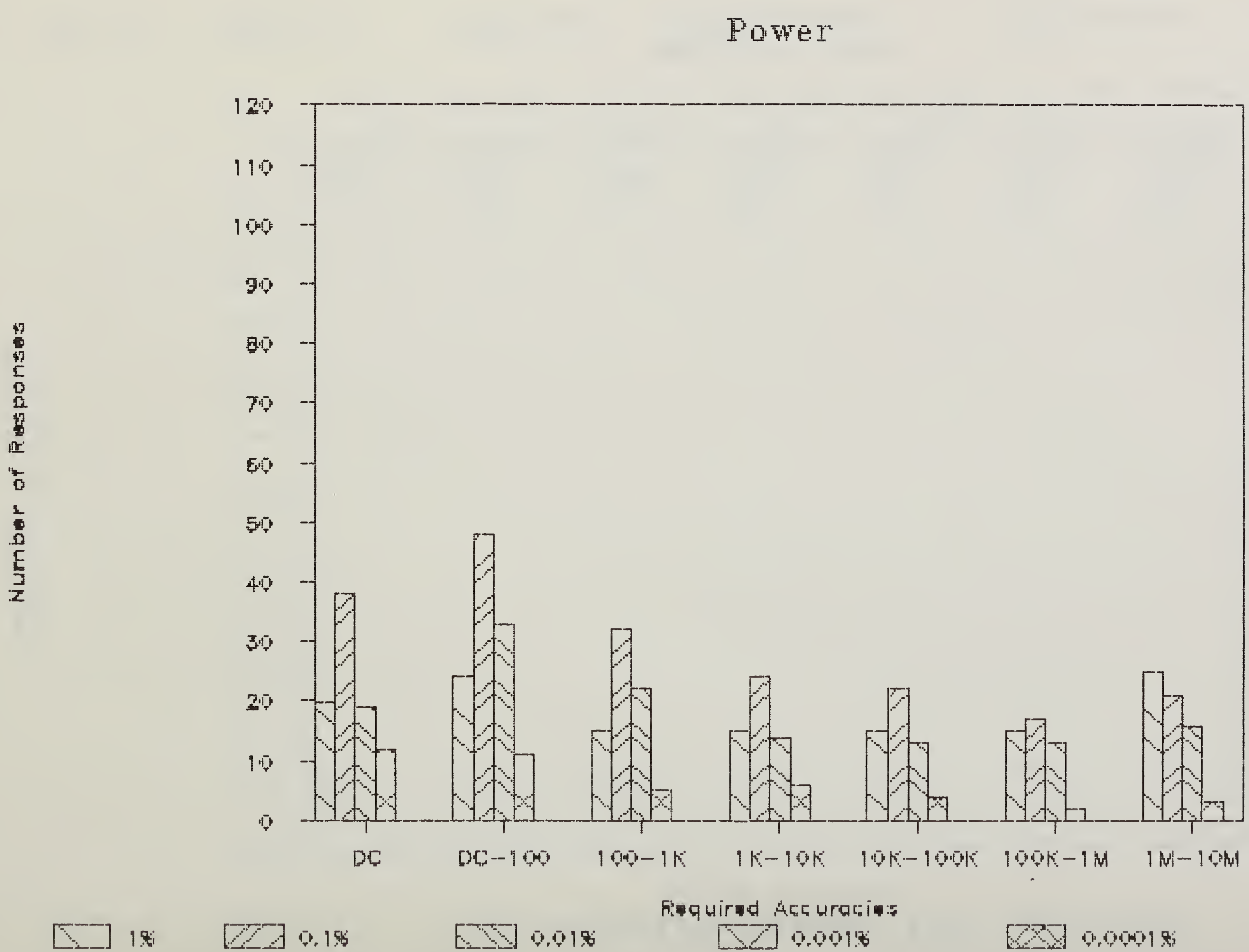
Impedance

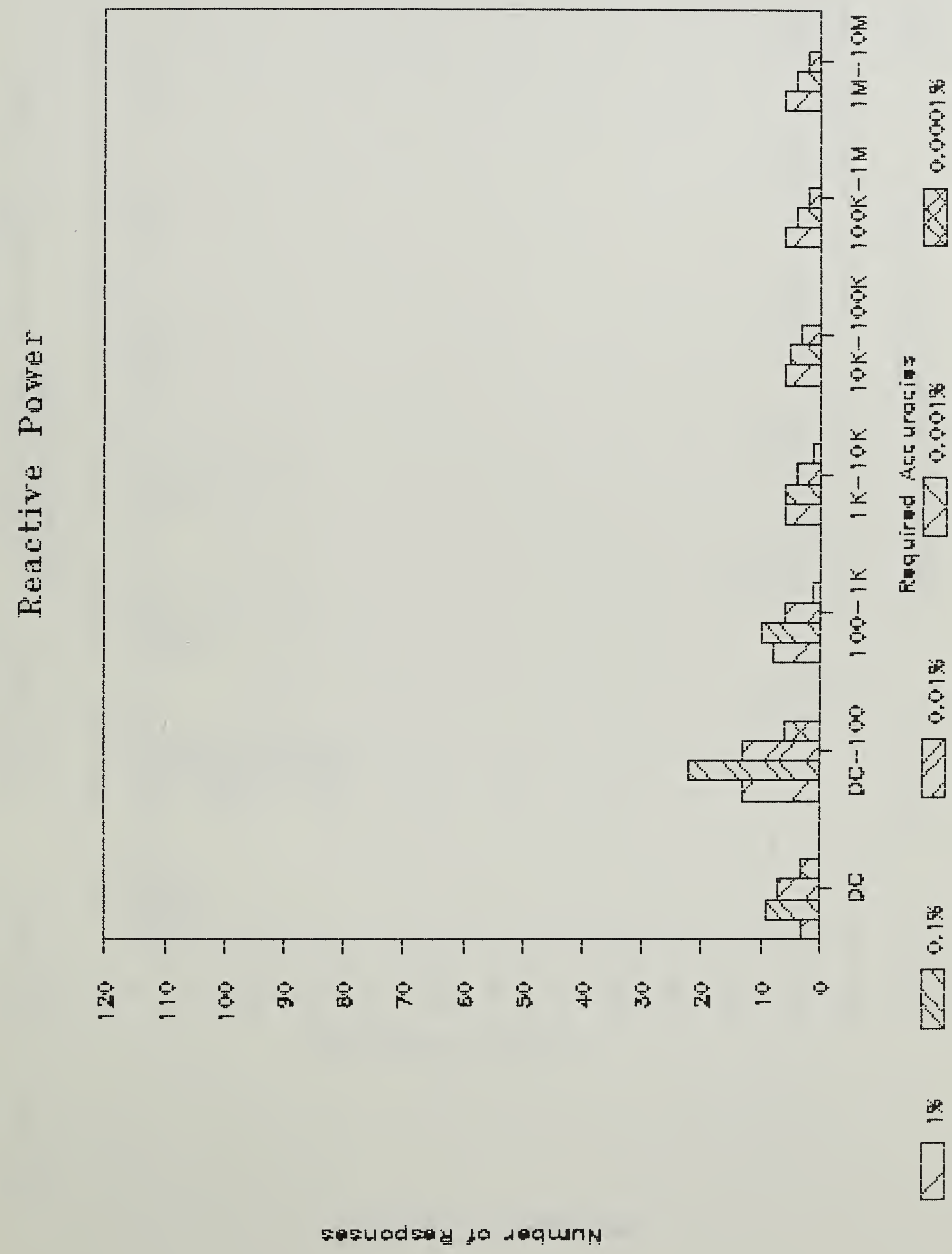

Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

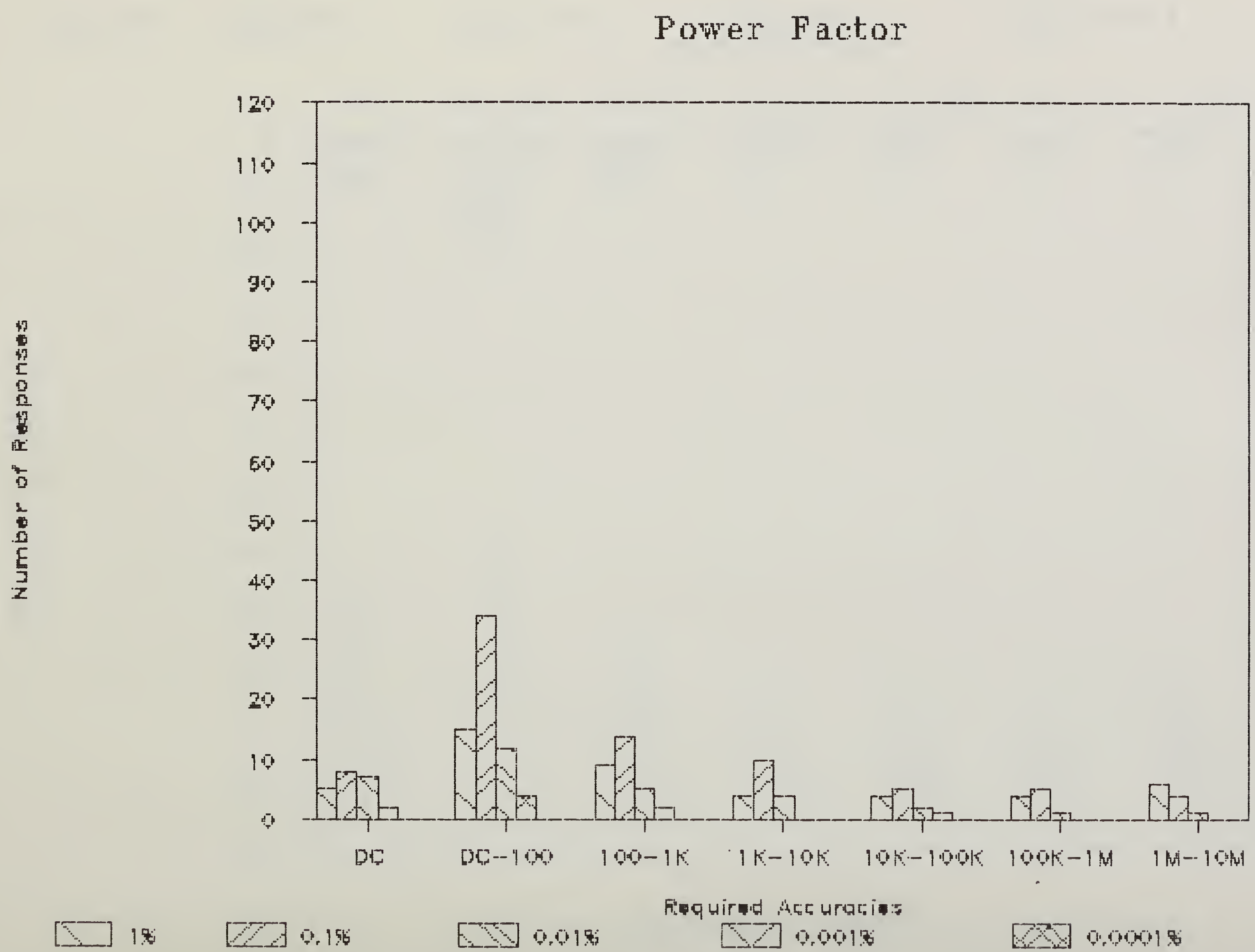

Admittance
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

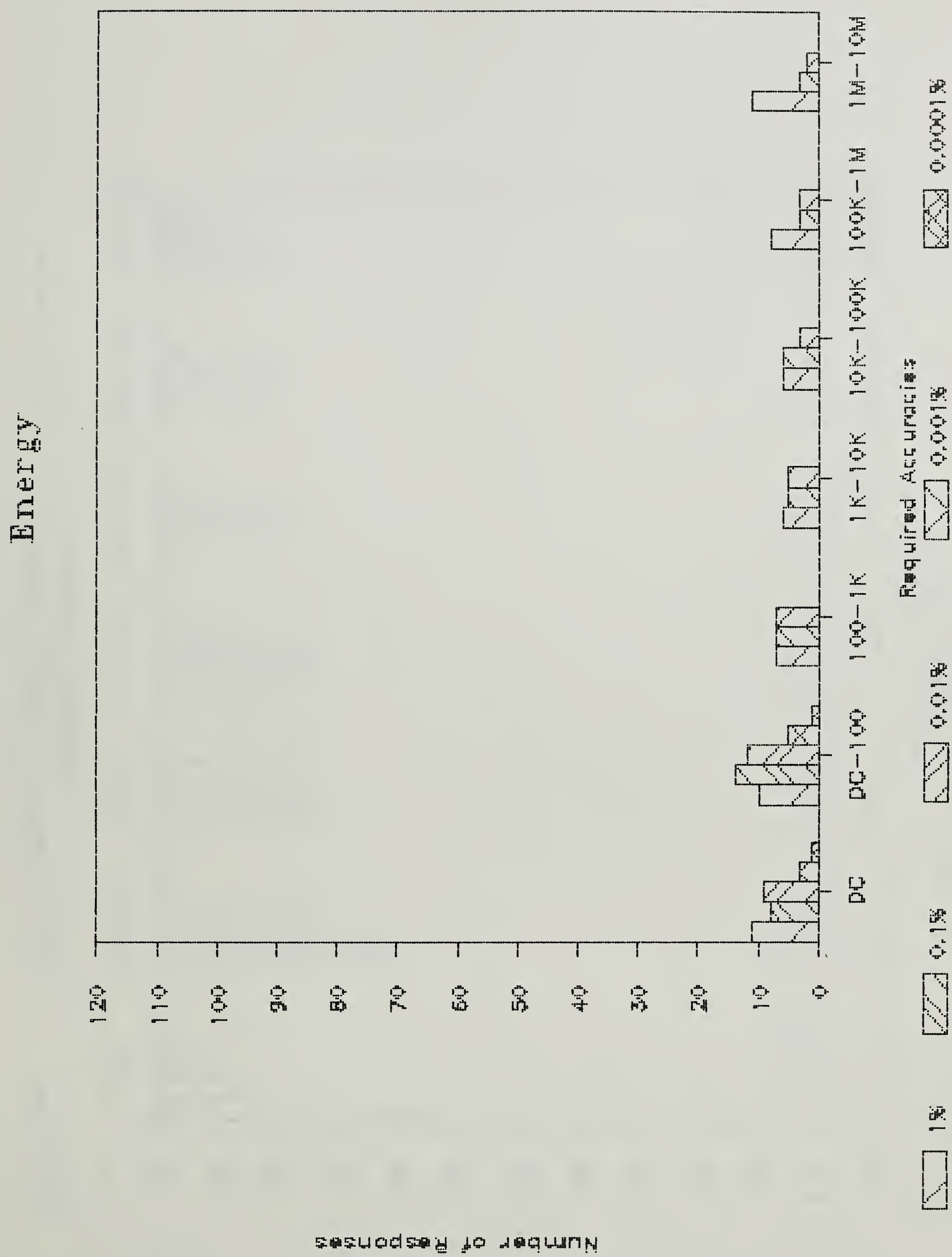
Quality Factor (Q)

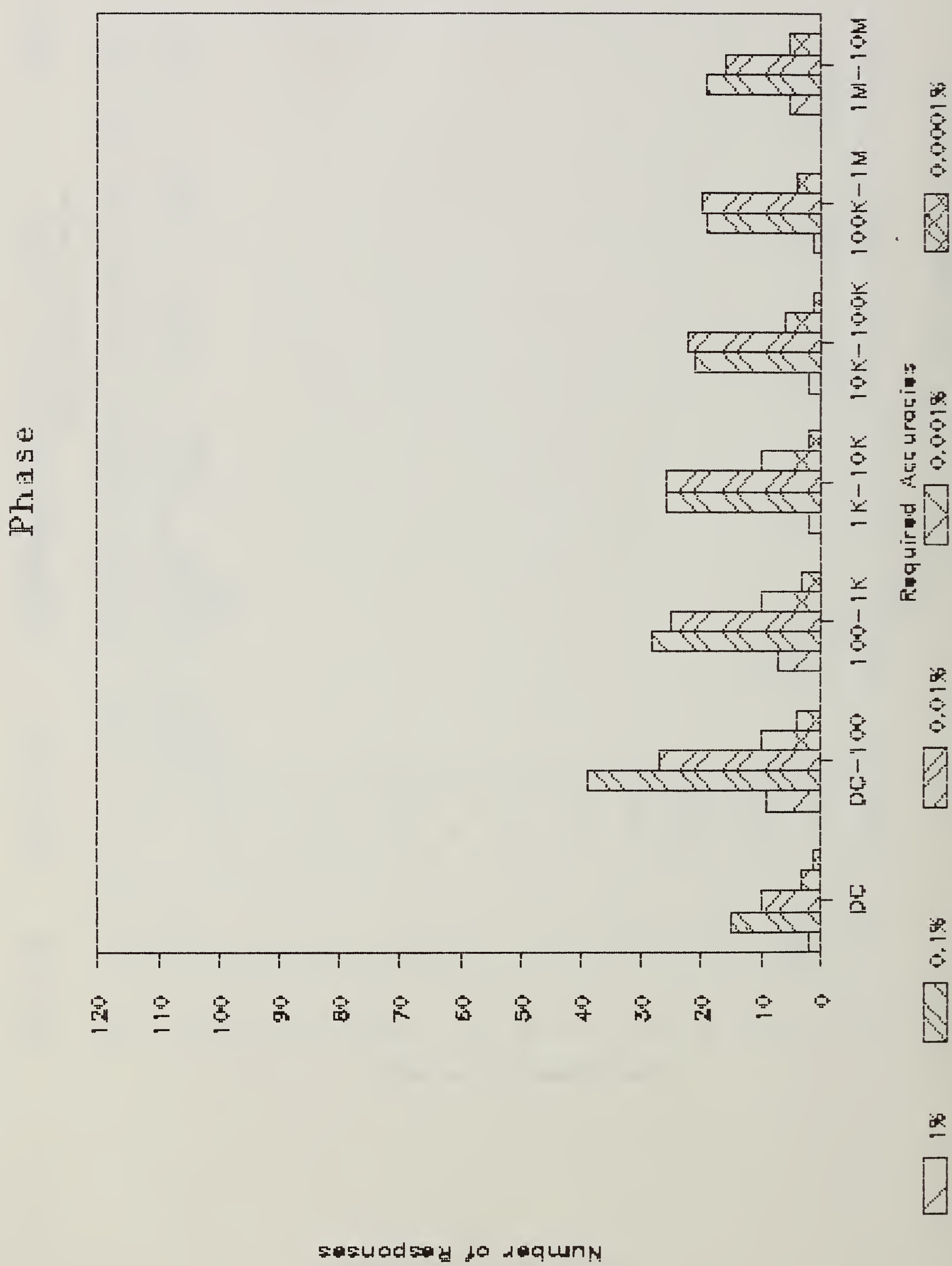


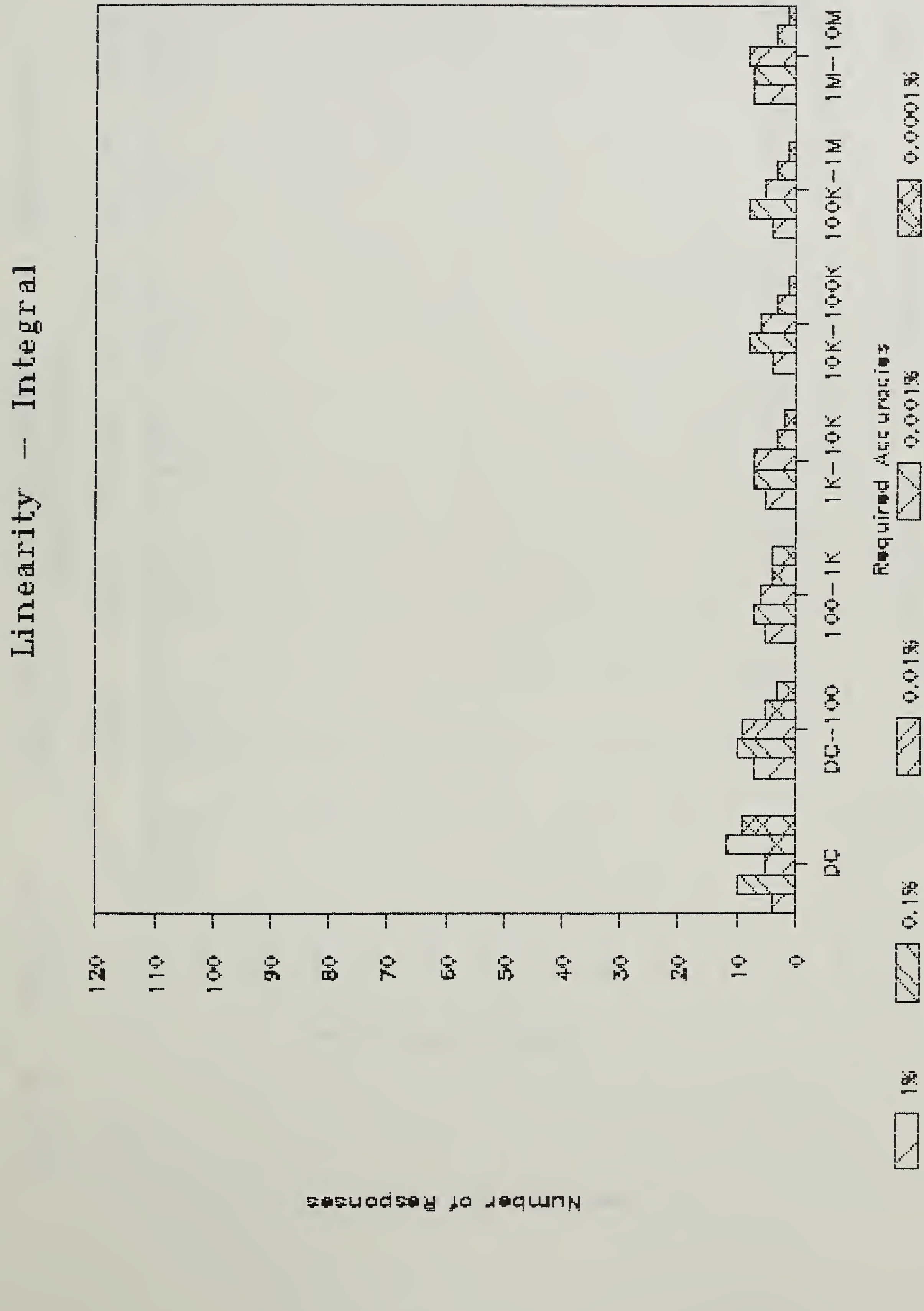

Power
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

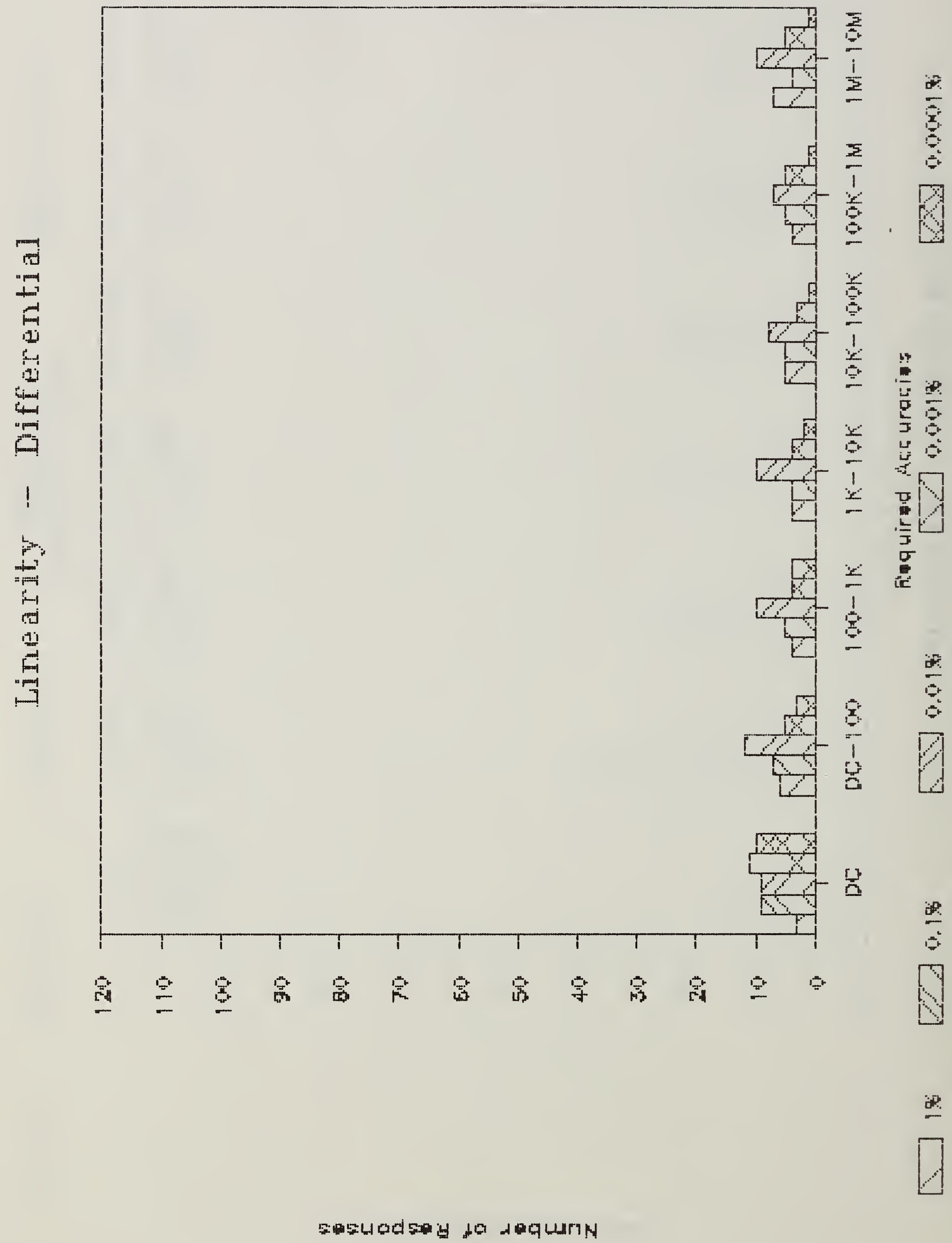

Reactive Power
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

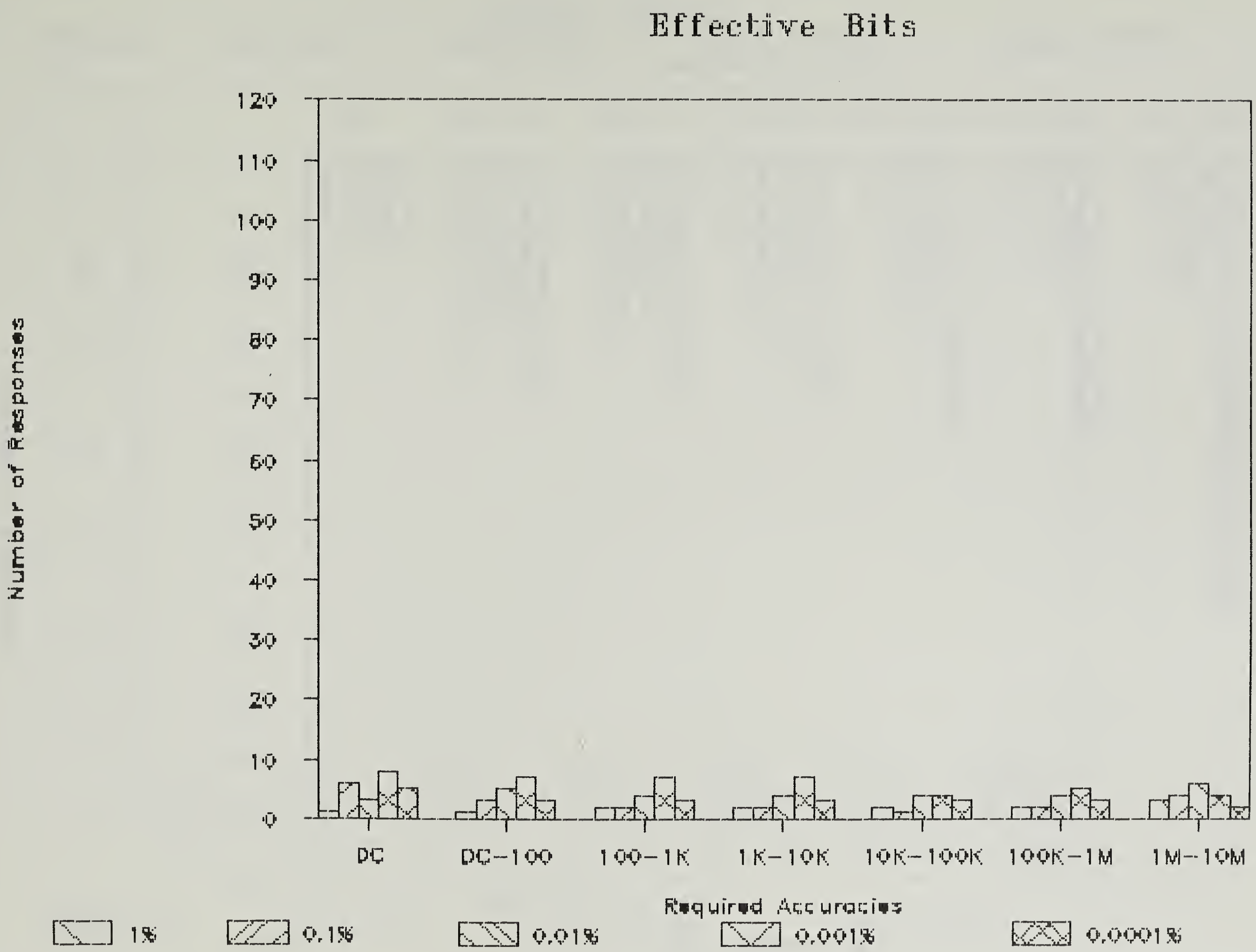

Power Factor
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC--100
100--1K
1K--10K
10K--100K
100K--1M
1M--10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Energy
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

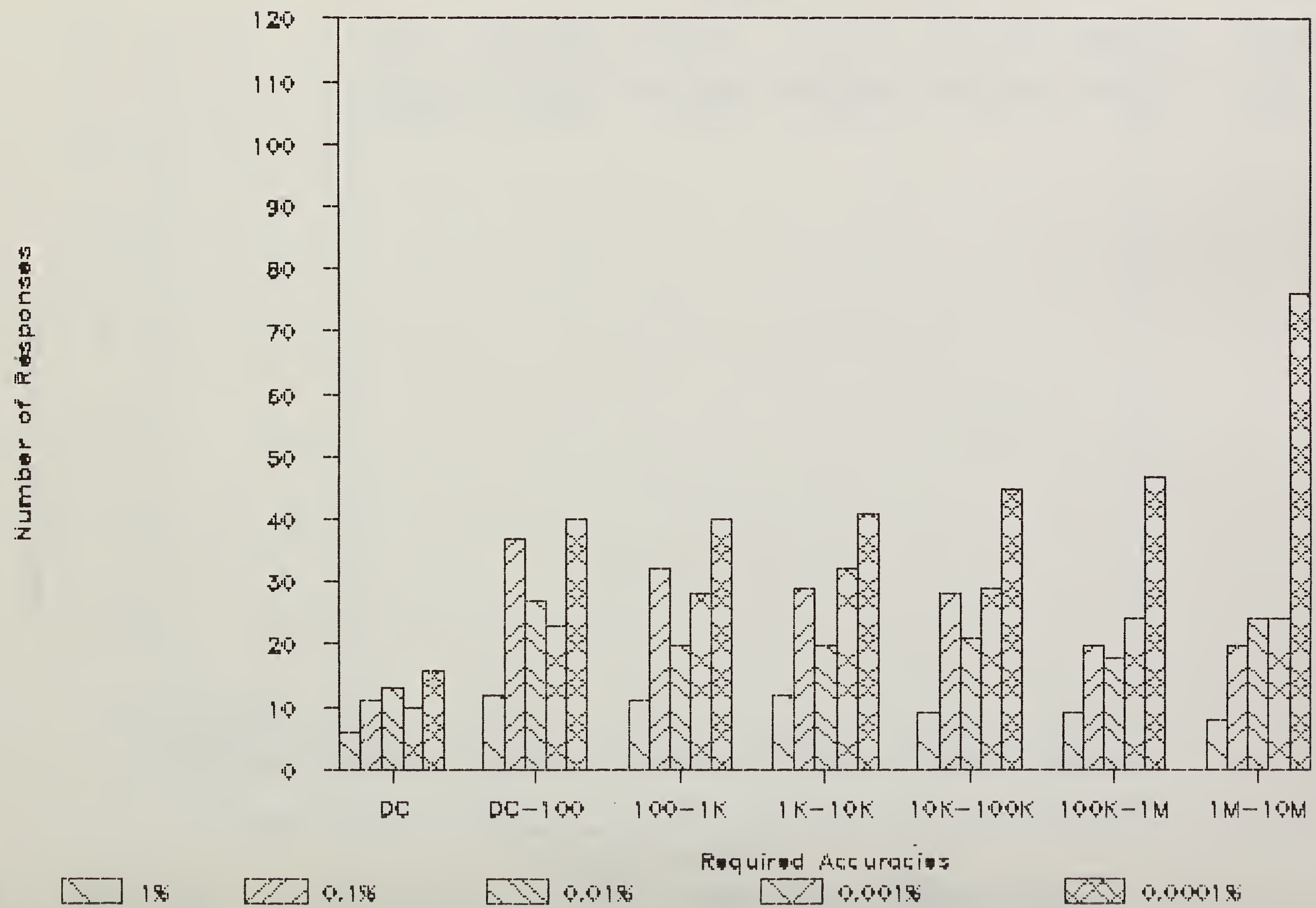

Phase
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

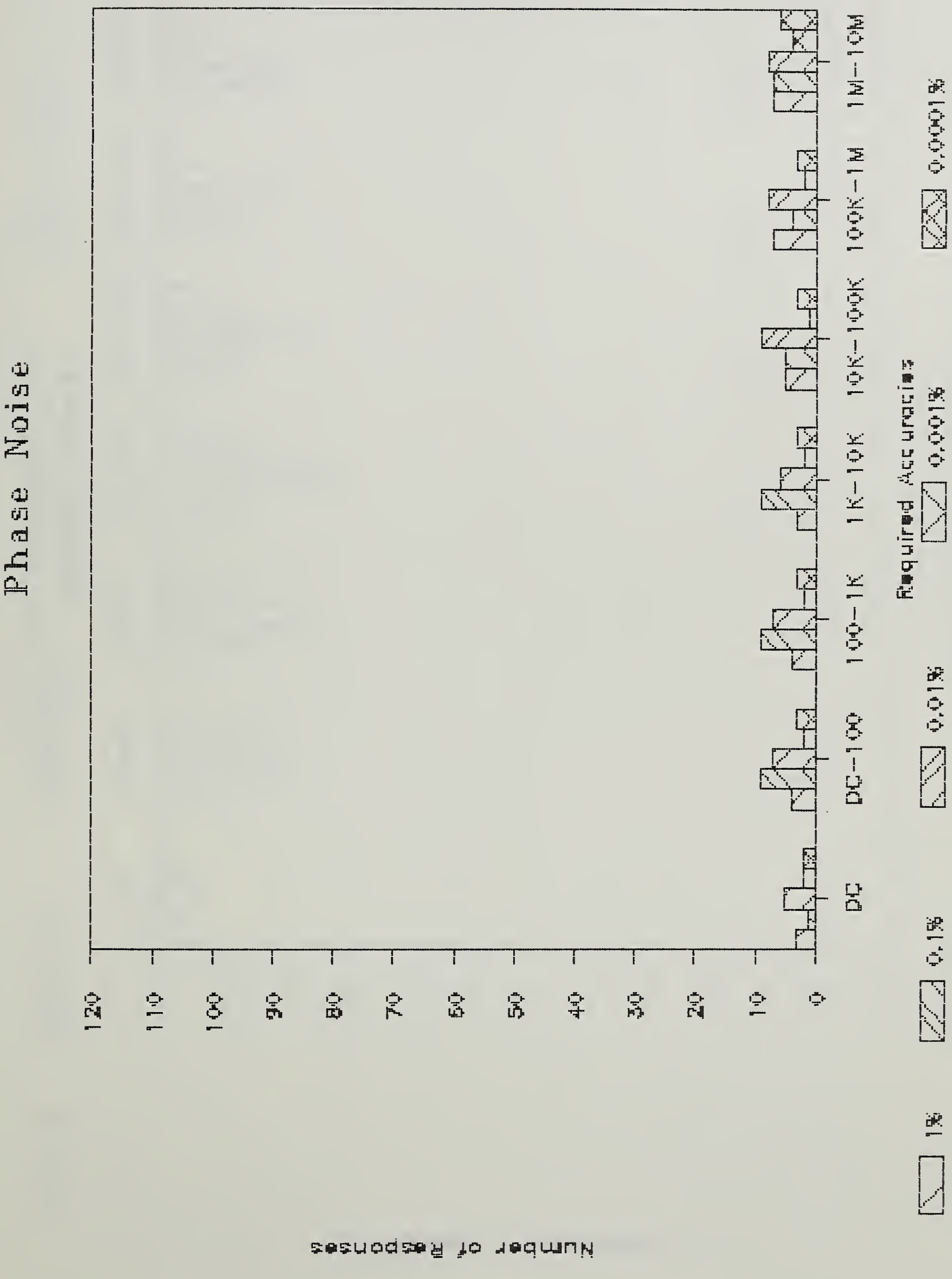

Linearity — Integral
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

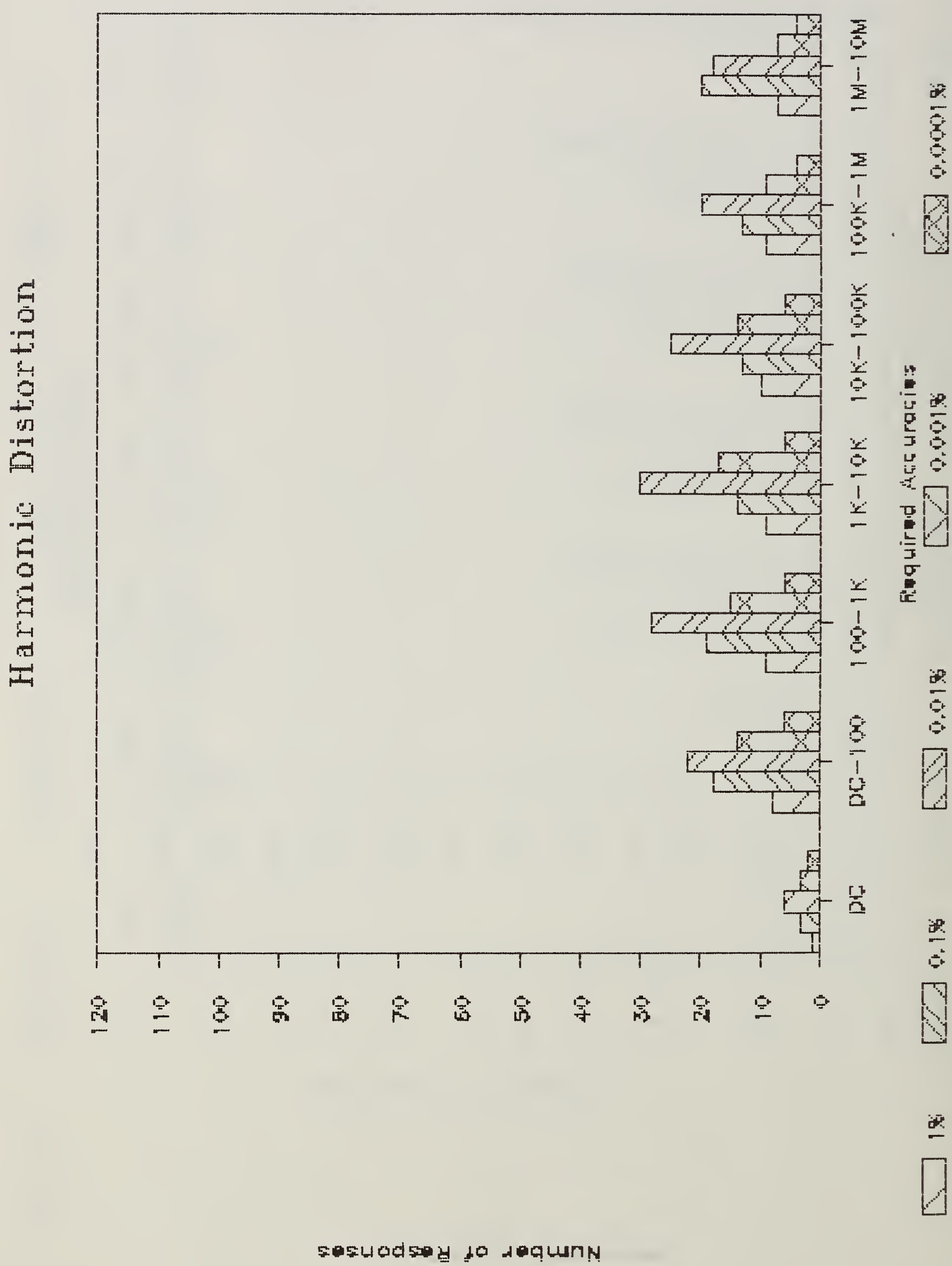

Linearity -- Differential
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Effective Bits
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

Frequency

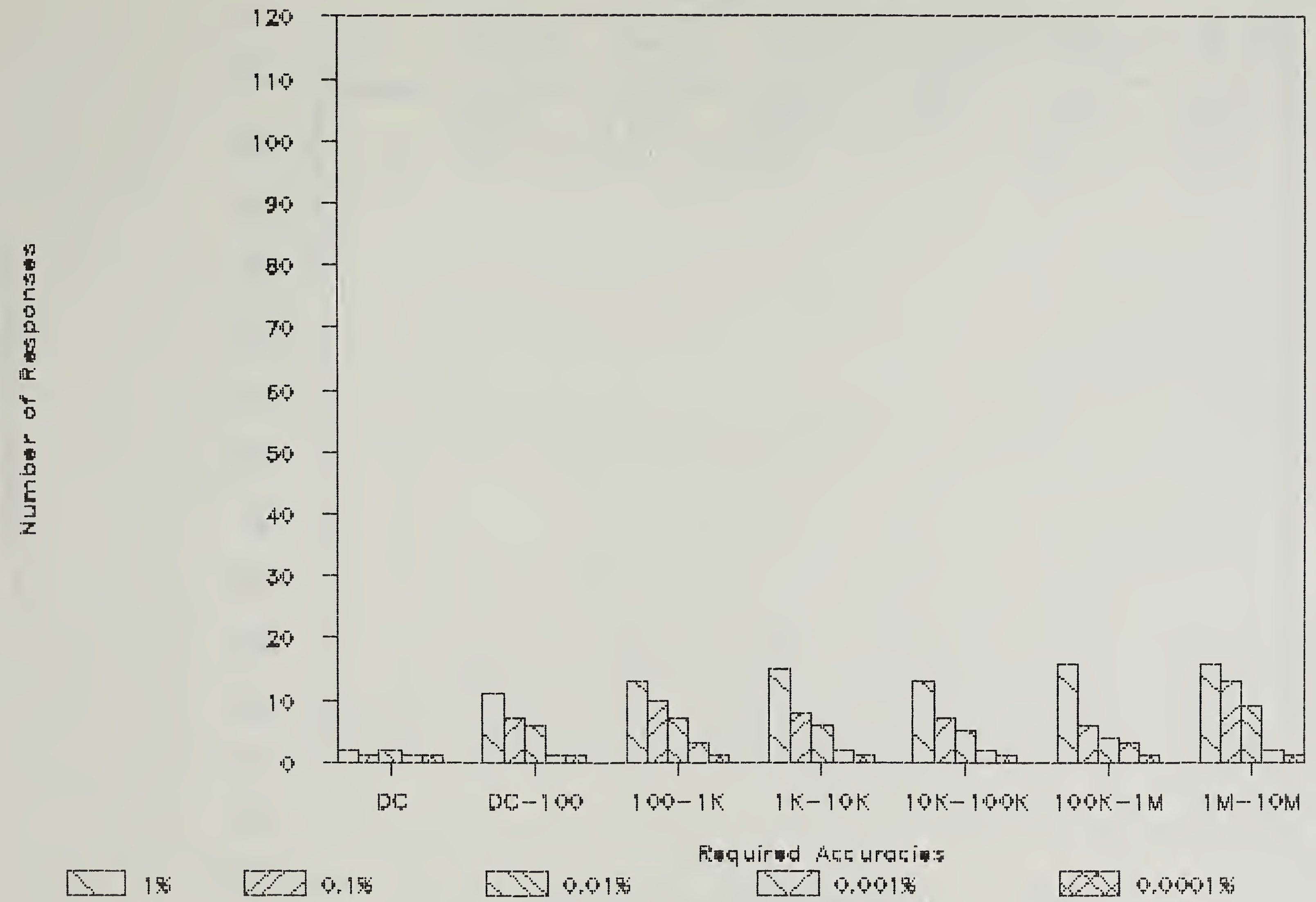

Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

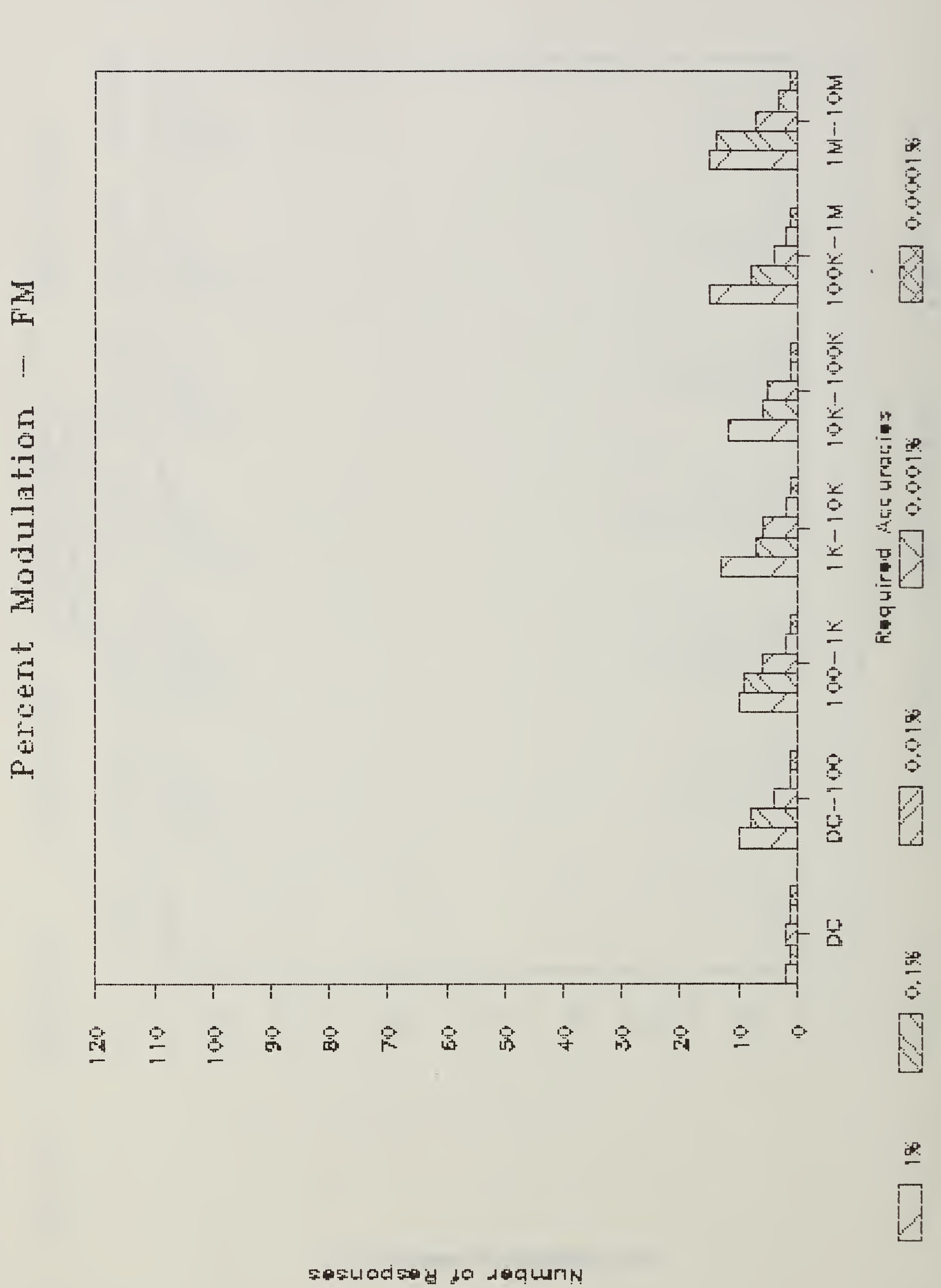

Phase Noise
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

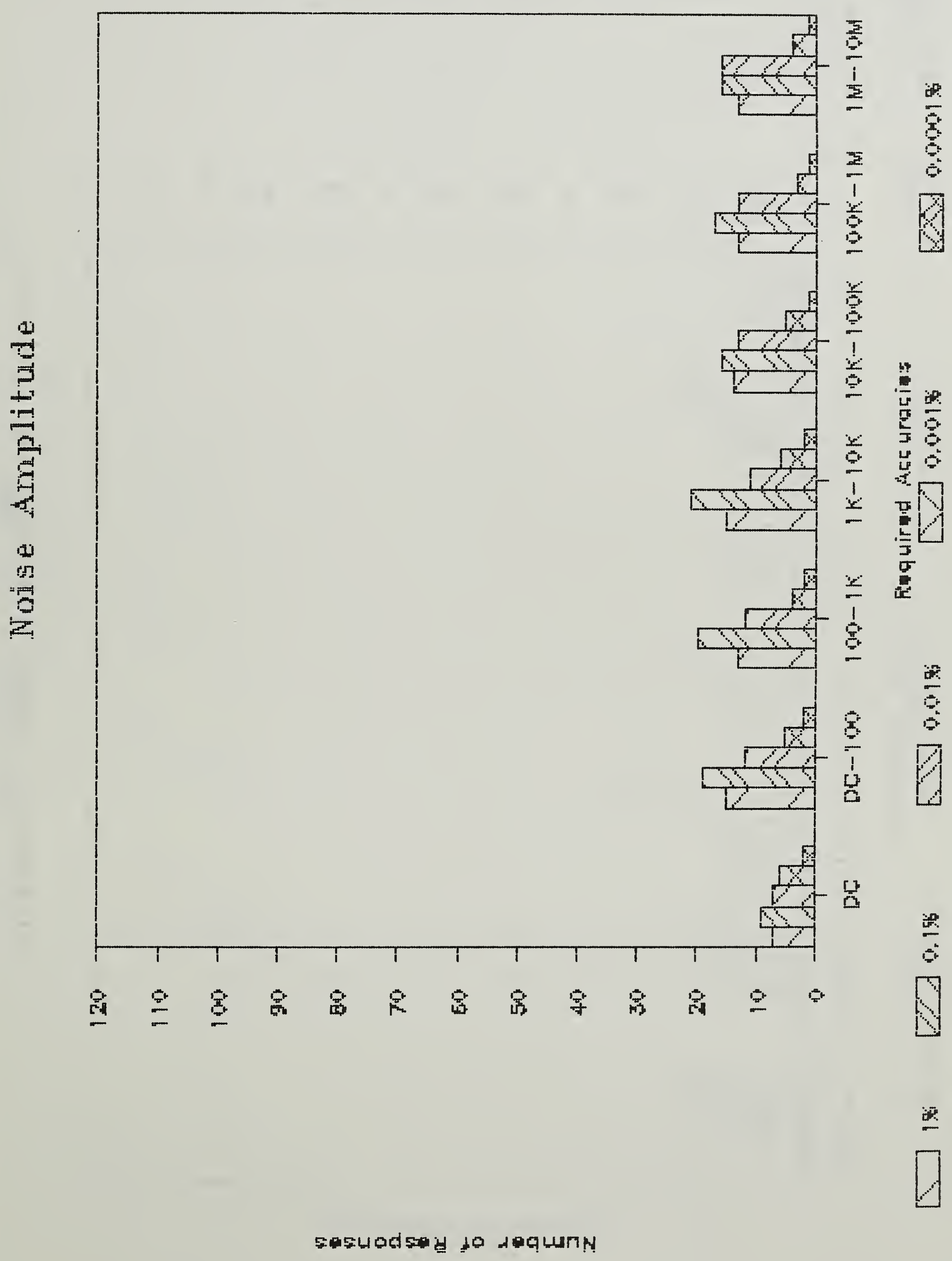


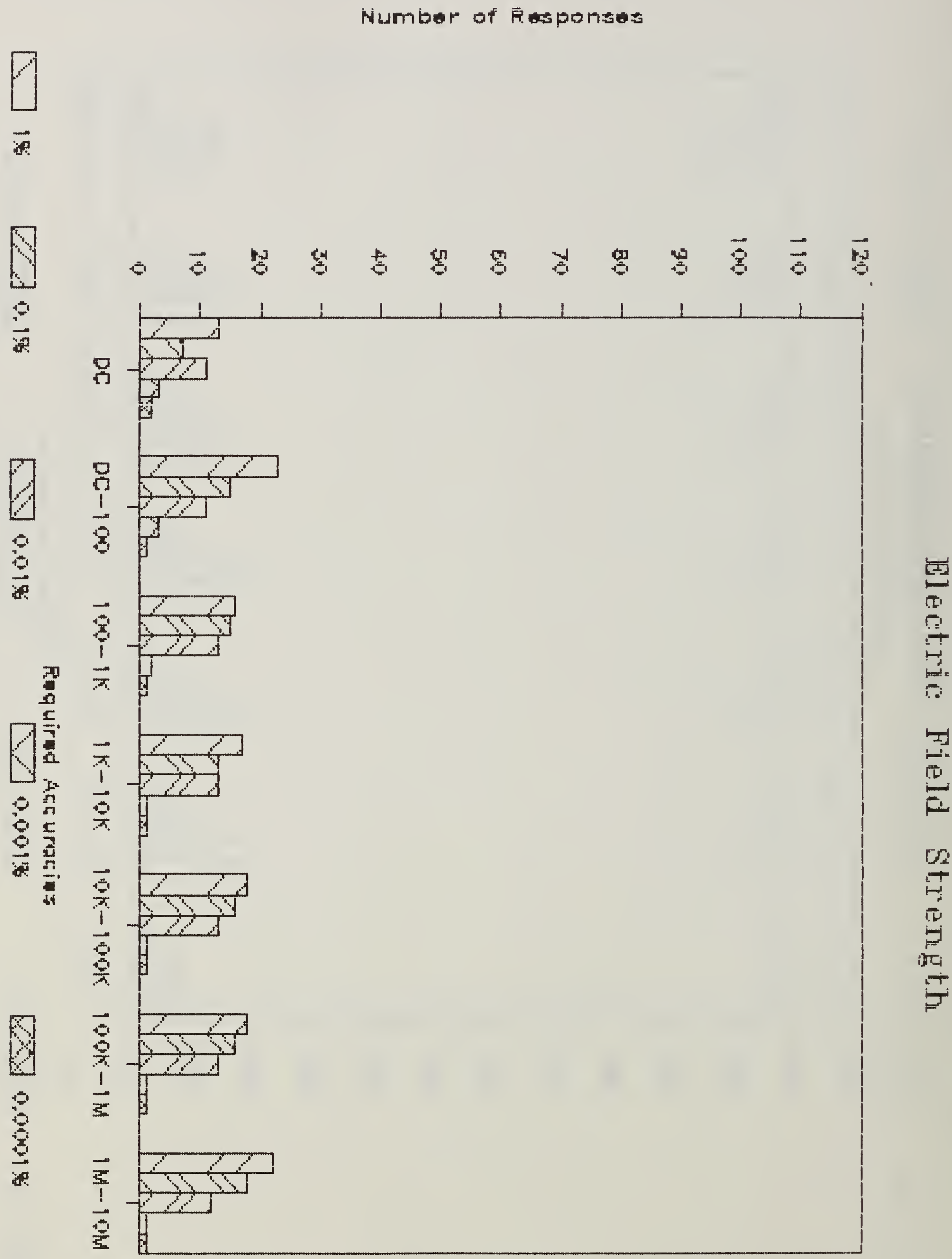
Harmonic Distortion
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

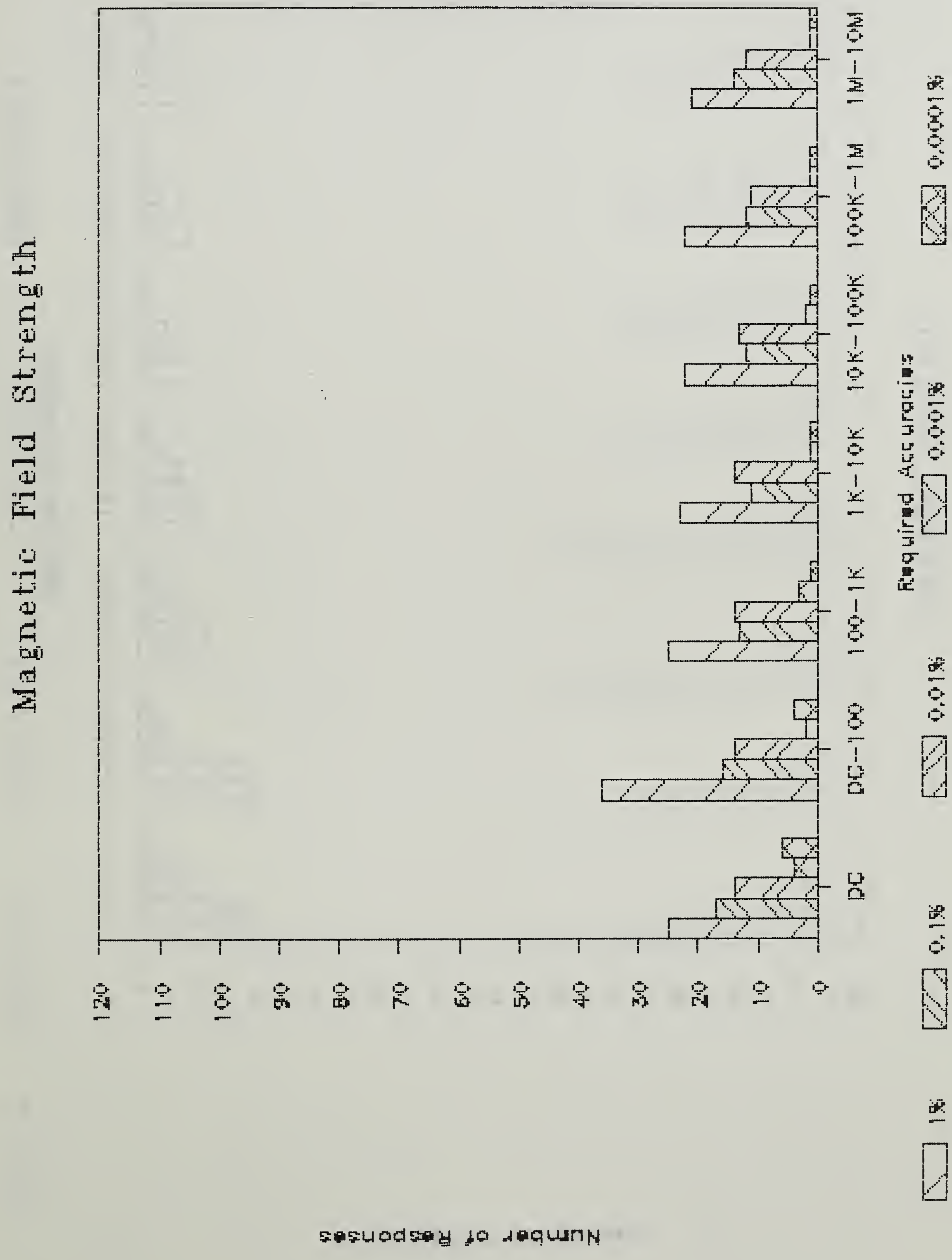
Percent Modulation - AM

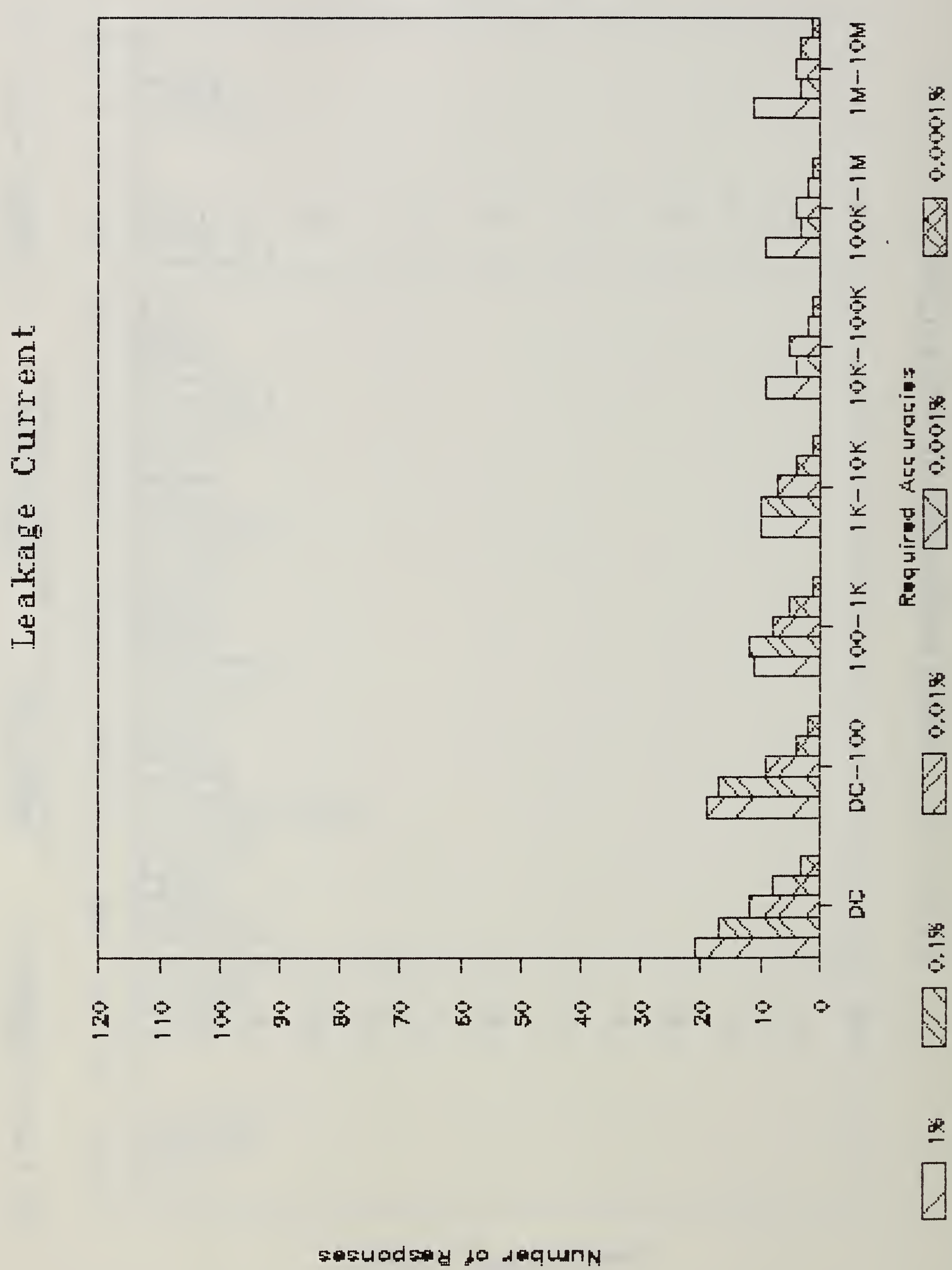


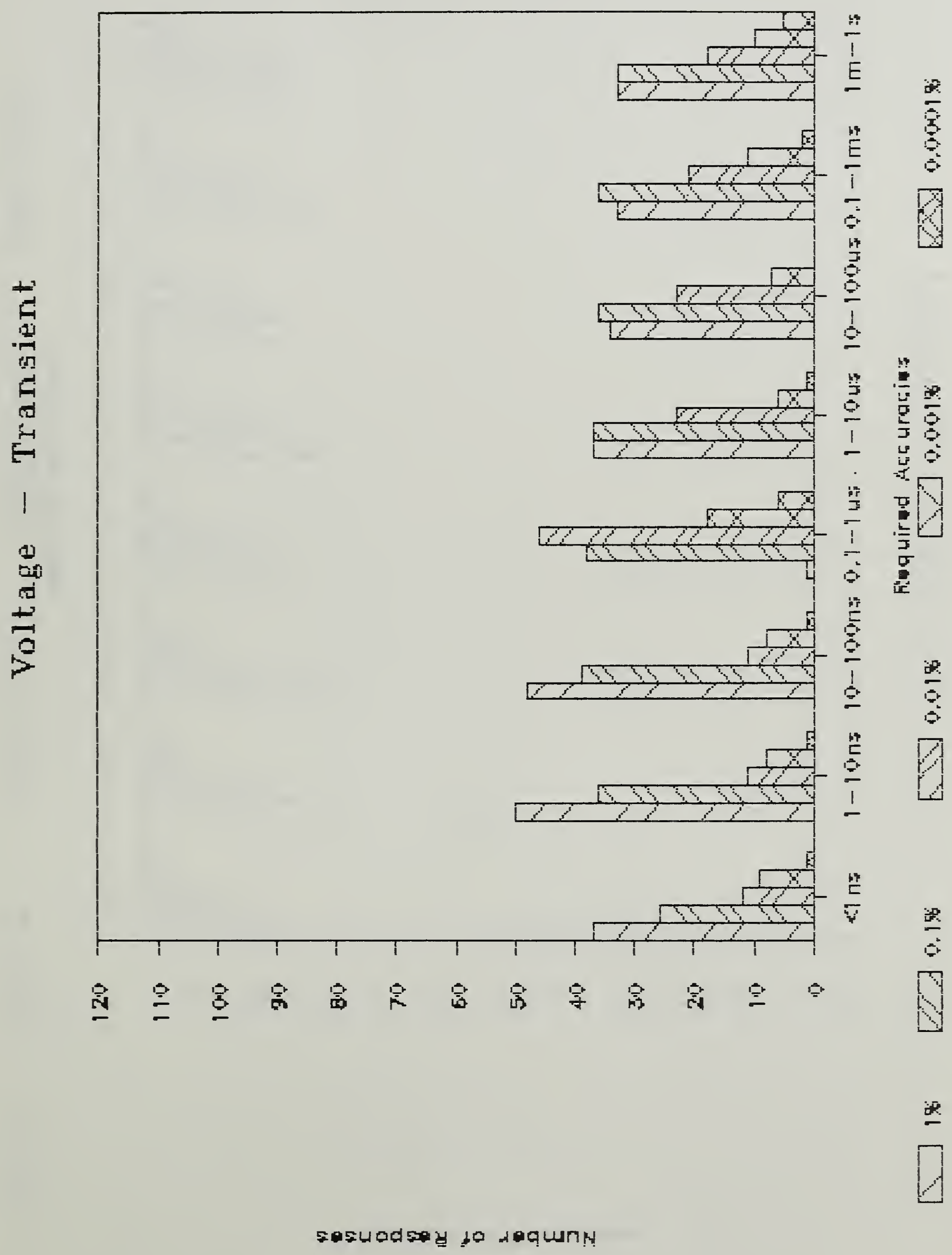

Percent Modulation — FM
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC–100
100–1K
1K–10K
10K–100K
100K–1M
1M–10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

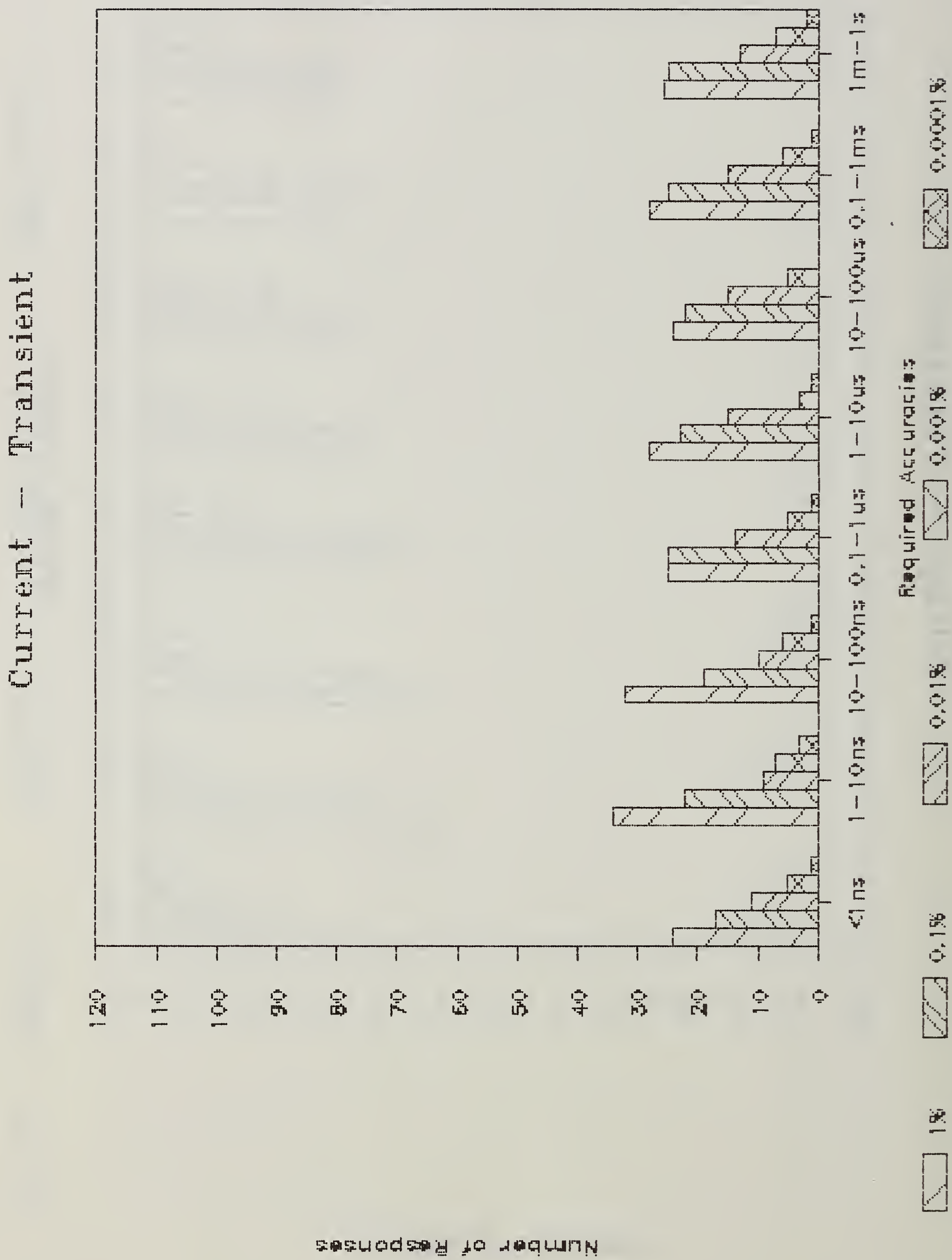

Noise Amplitude
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

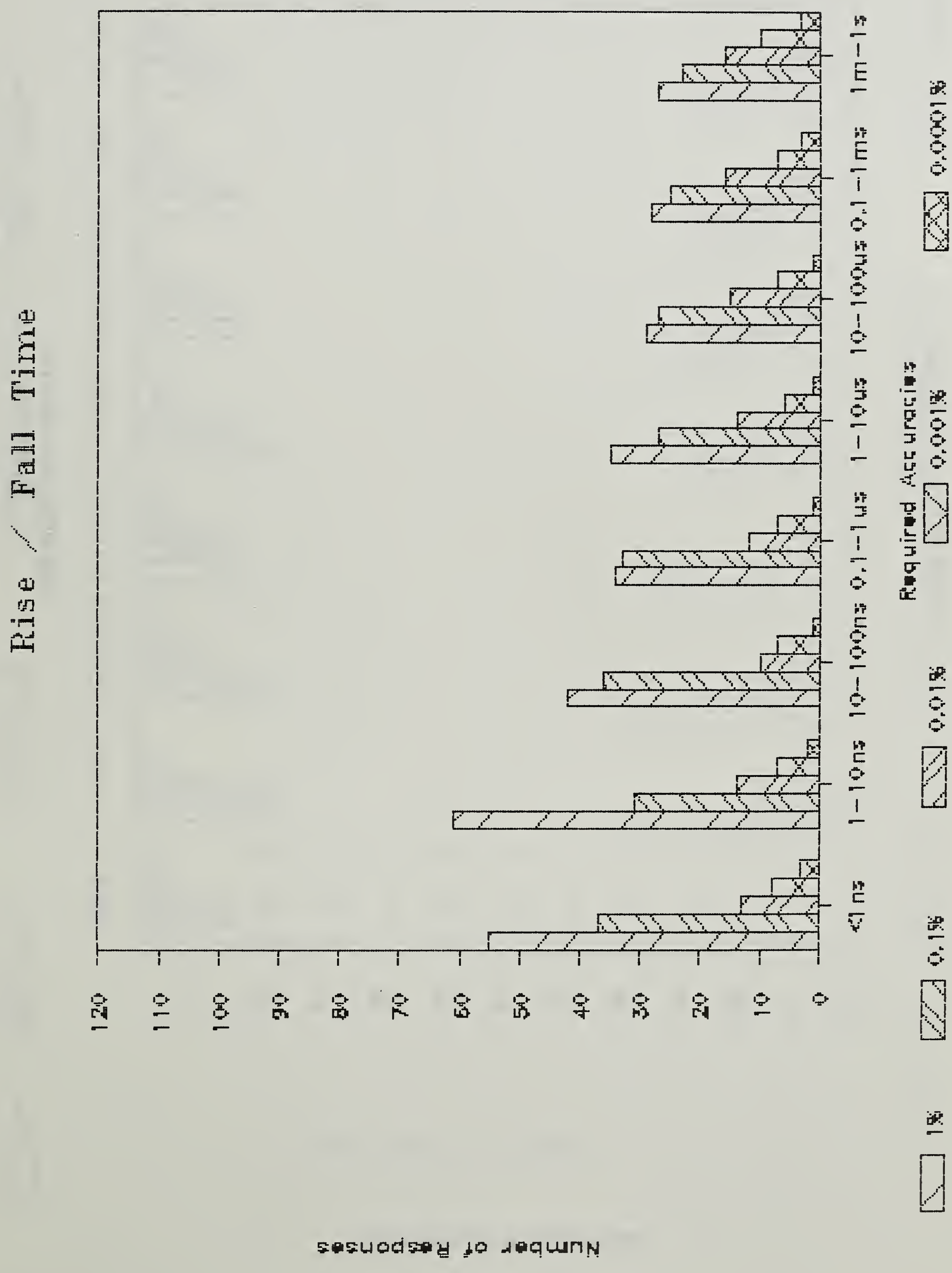

Electric Field Strength
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

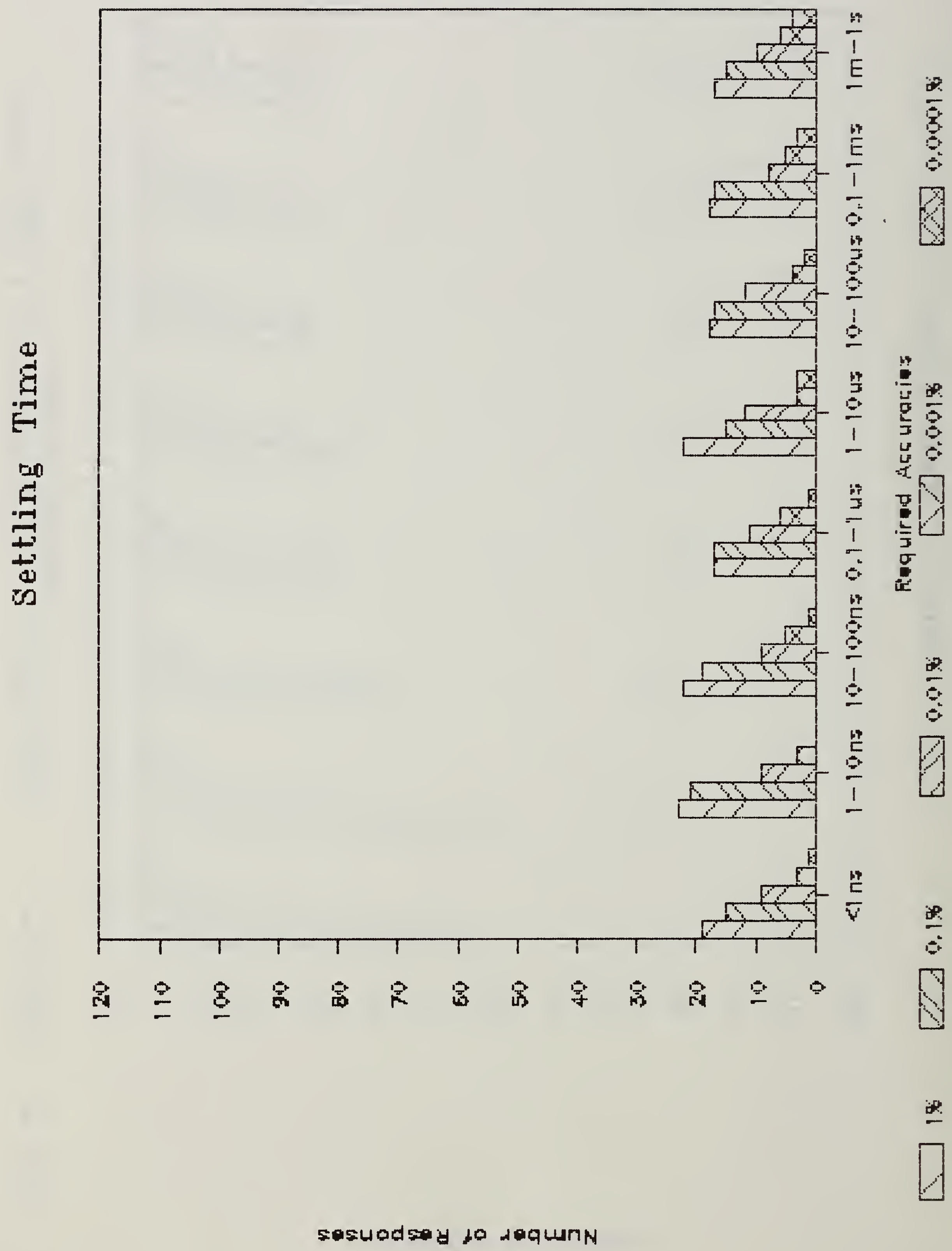

Magnetic Field Strength
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

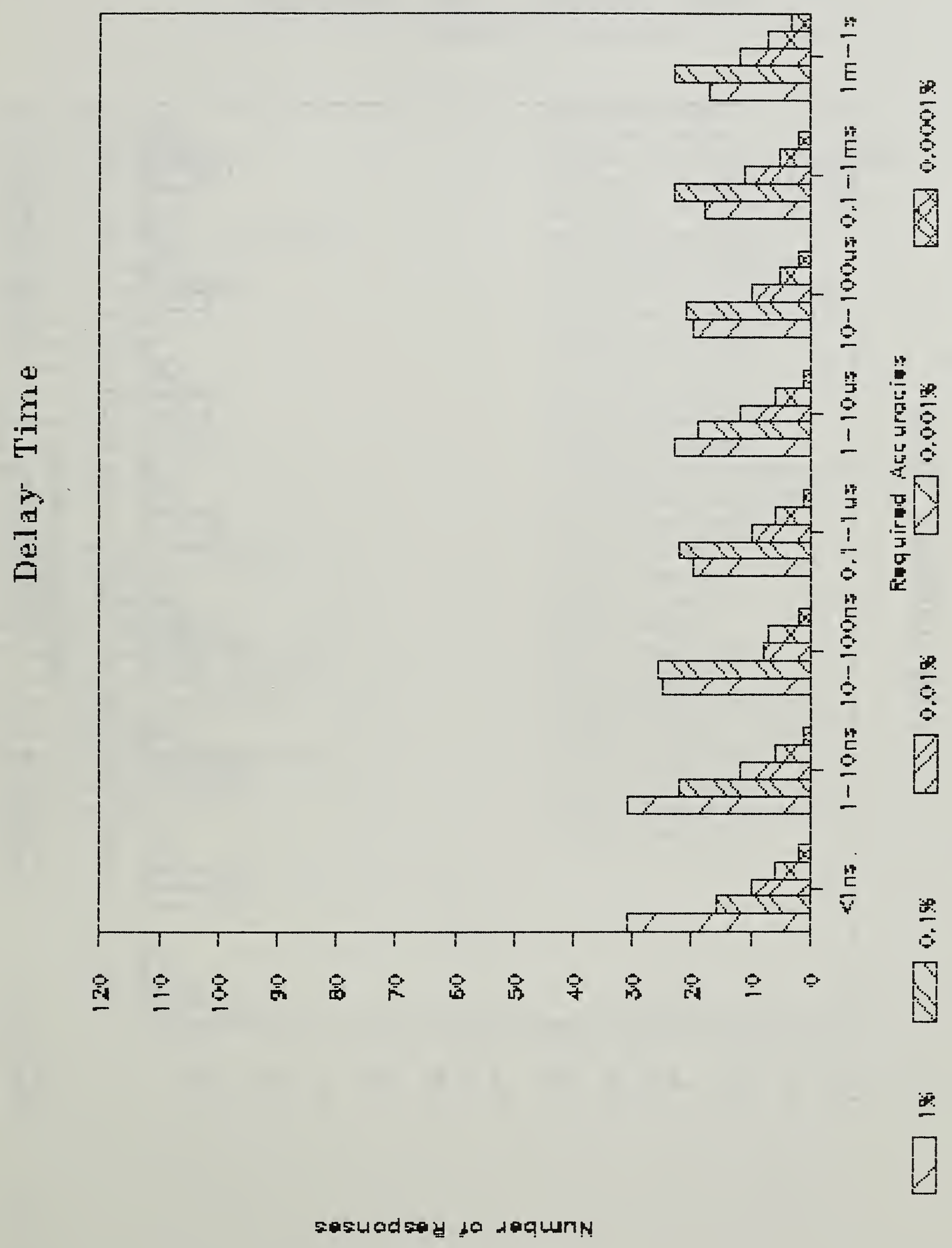

Leakage Current
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
DC
DC-100
100-1K
1K-10K
10K-100K
100K-1M
1M-10M
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

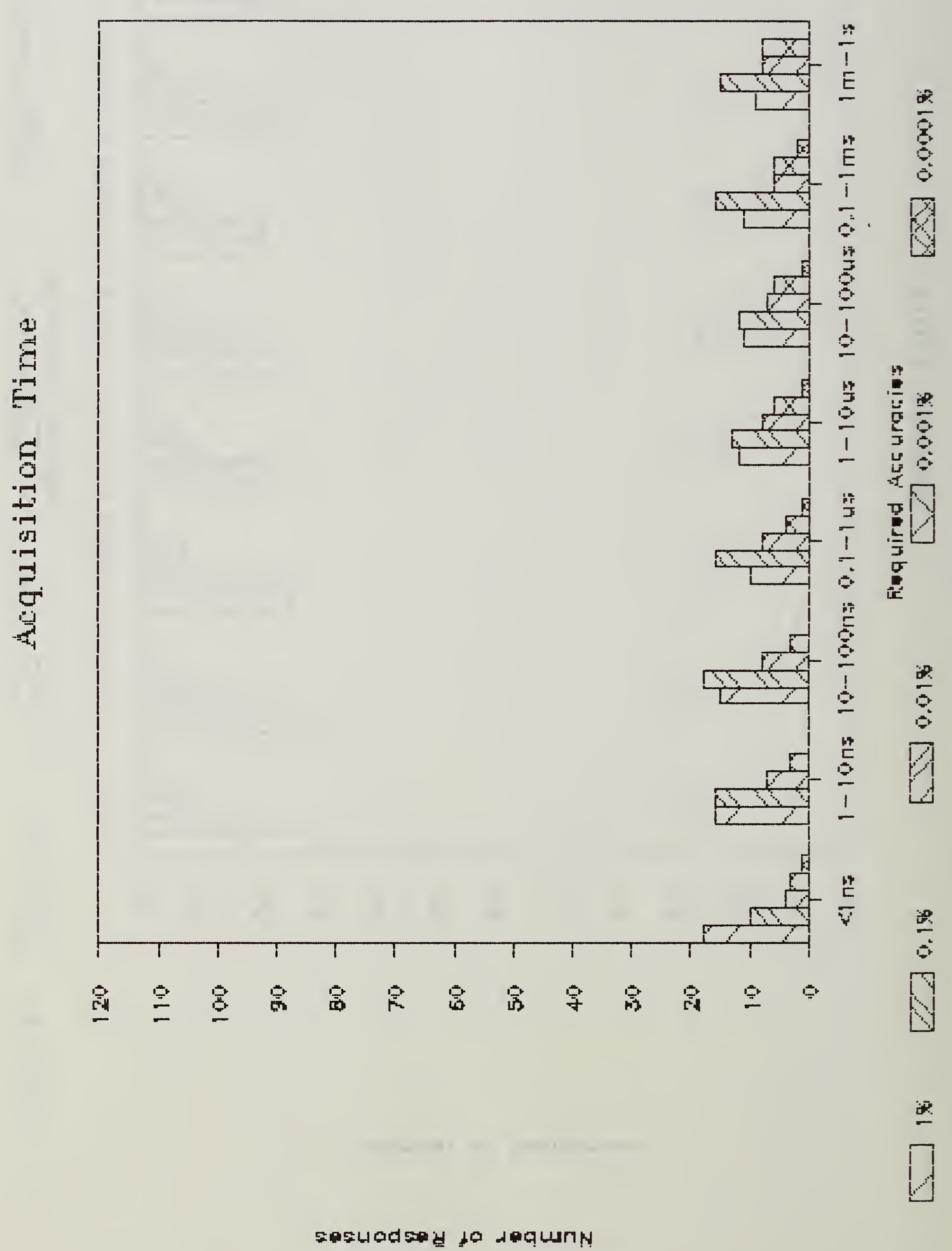

Voltage — Transient
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
<1 ns
1–10ns
10–100ns
0.1–1us
1–10us
10–100us
0.1–1ms
1m–1s
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Current -- Transient
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
<1 ns
1-10ns
10-100ns
0.1-1us
1-10us
10-100us
0.1-1ms
1m-1s
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Rise / Fall Time
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
<1 ns
1-10ns
10-100ns
0.1-1us
1-10us
10-100us
0.1-1ms
1m-1s
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Settling Time
Number of Responses
120
110
100
90
80
70
60
50
40
30
20
10
0
<1ns
1-10ns
10-100ns
0.1-1us
1-10us
10-100us
0.1-1ms
1m-1s
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Delay Time
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
<1ns.
1–10ns
10–100ns
0.1–1us
1–10us
10–100us
0.1–1ms
1m–1s
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%


Acquisition Time
Number of Responses
0
10
20
30
40
50
60
70
80
90
100
110
120
<1ns
1-10ns
10-100ns
0.1-1us
1-10us
10-100us
0.1-1ms
1m-1s
Required Accuracies
1%
0.1%
0.01%
0.001%
0.0001%

Appendix D - "Other" Instruments/Devices Listed by Respondents in Section D

Ammeters
Flux Meters
Current Generators
Resistance Meters
Mircroammeters
Optical Radiance Instruments
Colorimeters
Temperature Guages
Ratio Bridges
Thermocouples
Antennas
10-volt References
Thermopiles
Fluke 752A Divider
RTD Thermometry
Resistors
TVC
Electrostatic Voltmeters
Avtron Model T53
Accelerometers
Moisture Monitors
Primary Frequency Standard
Fiber Optic Power Meters
Transformer Comparators
Gauss Meters
Syncro/digital Converters
Wideband H.V. Divider
Angle (mechanical)
RTD
EM Field Sensors
Standard Cells
Fluke 732A Voltage Reference
Reference Voltage Diodes
Electric Field Probe
Network Analyzers
Capacitance Bridges
Microwave Attenuators
Microwave Power Meters
Power Amplifiers
Potential Divider, L&N Model 4399
Milliohmeters
Lock-in Amplifiers
Timing Equipment
Programmable Voltage Supplies
Resistance Standards
Sound Level Meters
Chromatograph
Hi-pot Tester
Cesium Standard
Shake Tables
Scaler Ratemeter
Data Loggers
Capacitors/inductors
Magnetic Field Probe
Strain Guage Devices
Voltage Dividers
Analog Tape Recorders
Charge Amplifier

Appendix E - "Other" Types of Involvement With ATE/Complex Measurement Systems

For in-plant use
For cal lab use
In-house ATE
Diagnostic X-Ray testing
Design for in-house use
Standards lab automation
Equipment specifications
Designer of small systems
Purchase for repair operations
Consultant to manufacturers
Component manufacturers
Instrument distributor
Diagnostics for scientific instruments
Calibrations
Medical equipment and standards
Custom ATE for specific products
ATE master calibration station
Build for internal use
ATE calibration support
In-house development
Evaluate and advise
Sales
Automated calibration systems
Research
Systems engineering
R&D ATE for government systems
Watthour billing meter
Sales - service and calibration
R&D Laboratory
Education and research
Maintainer/calibrator
Instrumentation/sensor testing
Consultants
Measurement Systems education
Data acquisition process controls
Government specification writers
General systems engineering for the Air Force
Design of prototype ATE
Consumer/user

Appendix E.2 - "Other" ATE/Complex Measurement Equipment listed by respondents in Section E

Mechanical component testers
Materials
TEM call control
TEMPEST
Fiber optic components
Spectrophotometry
Magnetic field quality
Data acquisition of pressure
EMI measurement systems
Microwave test systems
Specific equipment testers
Emulators
Oscillator testers
Quadrupole mass spectrometer
Electrical properties of living cells
GO/nogo systems
EMC tests
Probers/C-V plotters
Computerized EMP measurements
Satellite test systems
Process monitors
Computer controlled measurement systems
Cable testers
Biomedical test systems
Diagnostic/prognostic
TV measurements
Comparator board testers
Specialized product testers
Transient recorders
Process control - analytical
Fiber optic test and measurement
Data acquisition
Destructive tests
R&D test systems
Sensor test consoles
Testing DC/AC inverters
Instrumentation systems
Ballistic data acquisition
Plant control monitoring
Steel wire rope testers
System performancew testers

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 87-3549	2. Performing Organ. Report No.	3. Publication Date JUNE 1987

4. TITLE AND SUBTITLE

Summary Report on a Survey of Electronic Measurement Needs Below 10 MHz

5. AUTHOR(S)
John R. Sorrells

6. PERFORMING ORGANIZATION (*If joint or other than NBS, see instructions*)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (*Street, City, State, ZIP*)

10. SUPPLEMENTARY NOTES

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

11. 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 results of a survey to assess the electronic measurement needs from dc to 10 MHz are presented. The questionnaire used in the survey covered three broad areas of measurement need: (1) basic electrical quantities and related precision instruments, (2) automatic test equipment and other complex measurement systems, and (3) conducted electromagnetic interference. The data provided by 527 respondents are summarized, and the results of various analyses are described. Several conclusions, suggested by the analyses, are also discussed.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

automatic test equipment; ATE; complex measurement systems; electrical quantities; electronic measurement needs; precision instruments; questionnaire; survey

13. AVAILABILITY

☒ Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES
91

15. Price
$13.95

USCOMM-DC 6043-P80

NBSIR 87-3550

Mixing in Variable Density, Isothermal Turbulent Flow and Implications for Chemically Reacting Turbulent Flows

William M. Pitts
Takashi Kashiwagi

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

May 1987

Supported in part by:
.S. Air Force
'ffice of Scientific Research

NBSIR 87-3550

MIXING IN VARIABLE DENSITY, ISOTHERMAL TURBULENT FLOWS AND IMPLICATIONS FOR CHEMICALLY REACTING TURBULENT FLOWS

William M. Pitts
Takashi Kashiwagi

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

May 1987

Supported in part by:
U.S. Air Force
Office of Scientific Research

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

TABLE OF CONTENTS

	Page
List of Tables	iii
List of Figures	iv
Abstract	1
1. Introduction	1
2. Project Objectives	2
3. Research Accomplishments	3
3.1 Diagnostic Development	3
3.1.1 Concentration Measurement Using Rayleigh Light Scattering	4
3.1.2 Simultaneous Concentration and Velocity Measurement	5
3.1.3 Development of a Digital Line Camera for Concentration Measurement	9
3.2 Characterization of Mixing and Velocity Behavior in Axisymmetric Jets	14
3.2.1 Mixing in a Turbulent, Axisymmetric Jet of Methane	14
3.2.2 Simultaneous Measurements of Concentration and Velocity in a Propane Jet	15
3.2.3 Density and Reynolds Number Effects on Mixing in Axisymmetric Jets	16
4. Importance of Isothermal Studies to an Improved Understanding of Turbulent Reacting Flows	21
4.1 Similarity of Mixing in Isothermal and Reacting Flows	22
4.2 Lift-Off and Blow-Out of Turbulent Jet Diffusion Flames	23
4.3 Application of Isothermal Findings to Turbulent Mixing in Combustion Regions of Turbulent Jet Flames	28
4.4 Reynolds Number Effects in Diffusion Flames	31
5. Summary	32
6. References	34
7. Tables	39
8. Figures	40

LIST OF TABLES

Page
Table 1. Experimental parameters 39

LIST OF FIGURES

		Page
Figure 1.	The experimental configuration for real-time Rayleigh light scattering "point" measurements of concentration in binary gas mixtures is shown schematically. The flow system consists of a 6.35 mm diameter pipe with a sharpened edge enclosed within a 100 X 100 cm^2 square cylinder	43
Figure 2.	The quality of the data which can be acquired utilizing the Rayleigh light scattering technique for concentration is demonstrated. Radial profiles of concentration (in both mole and mass fraction terms) are plotted for a turbulent CH_4 jet flowing into a slow coflow of air. The downstream distance is $z/r_o = 35$ and the Reynolds number is 3950.	44
Figure 3.	Partial time-resolved data records recorded during a simultaneous Rayleigh light scattering and hot-film anemometry experiment are reproduced for a propane jet (Re = 3960) flowing into a slow coflow of air. The observation volume is located on the jet centerline at $z/r_o = 31.5$. The light scattering signals have been calibrated and are plotted in terms of mole fraction of propane. The raw data for the anemometer output is plotted along with the velocity calculated utilizing the calibrations of film response to changes in velocity and gas composition.	45
Figure 4.	The correlation is shown for the heat transfer from a hot-wire as a function of flow velocity for nine different gases. Experimental measurements are nondimensionalized by the use of the Nusselt number and Reynolds number. Corrections have been included for heat losses to the prongs of the hot-wire and thermal slip and accommodation effects at the surface of the probe. $(K_B)_x$ and $(K_A)_x$ are coefficients which are necessary to compensate for variations in molecular properties from gas to gas	46
Figure 5.	The camera which has been developed for recording real-time Rayleigh light scattering intensity along a line is shown. The top portion indicates the major components and their configuration. The actual appearance of the camera is shown below.	47

Page

Figure 6. The overall experimental configuration for real-time measurements of concentration along a line in turbulent flows is represented. Rayleigh light scattering is induced along a line in the flow field by the Ar^+ ion laser. Light scattering at 90° is recorded by the digital line camera system consisting of the line camera shown in figure 5, suitable interfaces, and a data acquisition minicomputer 48

Figure 7. An example of time-resolved line measurements of propane mole fraction across a turbulent jet of propane (Re = 3960) flowing into a coflow of air is reproduced. Propane mole fraction is represented by a seven level gray scale. The downstream position is 5 diameters and the line read out rate is 830 Hz 49

Figure 8. Time-averaged radial profiles of propane mole fraction are shown for five downstream positions in the development region of a propane (Re = 3960) jet flowing into a slow coflow of air. The growth of the boundary layers on either side of the potential core with increasing z and decrease of centerline concentration at the end of the potential core can be clearly observed. It is interesting to note that the data displayed represents 164,000 individual concentration measurements which were recorded during 1.54 s of actual acquisition time 50

Figure 9. The apparatus for recording time-resolved shadowgraphs is represented schematically. The light pulse generated by the chopper has a temporal profile which is triangular in shape and has a total duration of 310 μs 51

Figure 10. Three time-resolved shadowgraphs are shown for a SF_6 jet (Re = 3950) flowing into a slow coflow of air. Three different downstream positions recorded at different times are represented. Note particularly the formation of a fountain by the SF_6 at a downstream position of ≈ 37.5 r_o 52

Figure 11. Shadowgraphs are reproduced for jets of SF_6 (Re = 7890 and 11,860) entering slow coflows of air. For each jet four views of the flow recorded at different times and positions in the jet are superimposed. Note that the fine scale turbulence becomes more pronounced with increasing Re, but that the overall spreading rate of the jet does not appear to be affected. 53

Page

Figure 12. Five sets of superimposed shadowgraphs are shown for jets of one gas flowing into a second gas. With the exception of the SF_6 flow, the Reynolds numbers are roughly the same. The effects of variations in the global density ratio appear as changes in the development region of the flow and modifications in the eddy structure at downstream positions where the flows are close to fully-developed. 54

Figure 13. Superimposed shadowgraphs are reproduced for propane jets at three Re entering into slow coflows of air. The development of finer turbulent scales with increasing Re can be clearly seen. It is also evident that increasing the Re results in a shortening of the distance required for the development of vortical structures near the nozzle. The overall spreading behavior of the jets is independent of Re supporting the supposition that entrainment is determined by large scale turbulent structures. 55

Figure 14. Values of $Y_o/\overline{Y}_m$ ($\overline{Y}_c = \overline{Y}_m$ is the centerline concentration at z/r_o and Y_o is the mass fraction of jet fluid at the jet exit) are plotted as a function of z/r_o for six different jet/coflow gas combinations. The solid lines are linear least squares fits of the results. Note the decreasing slopes and upstream movement of the virtual origins (z where $Y_o/\overline{Y}_c \rightarrow 0$) which occur as the jet/coflow density ratio is increased 56

Figure 15. Predicted values of inverse centerline mass fraction (denoted as $1/\overline{C}_m$) based on the analysis of Thring and Newby [35] are plotted as functions of z/r_o for the six jet/coflow gas pairs which have been experimentally investigated. Comparison of figures 14 and 15 shows that there is good agreement between prediction and experiment. 57

Figure 16. Values of centerline unmixedness are plotted as a function of z/r_o for the six jet/coflow gas pairs listed. Values of $Y_m'/\overline{Y}_m$ for each jet approach a common asymptote of ≈ 0.23, but the flow distance required increases dramatically as the jet/coflow density ratio increases 58

Figure 17. The centerline unmixedness values shown in figure 16 are replotted as a function of z/r_ϵ. The collapse of the data onto a single curve suggests that r_ϵ is the proper scaling parameter for correlating the growth of unmixedness in these variable density flows 59

Page

Figure 18. Centerline unmixedness values for three different Re jets of propane entering slow coflows of air are plotted as functions of z/r_o. Flows at higher Re require longer flow distances in order to achieve the asymptotic value of unmixedness even though the value of the asymptote does not change 60

Figure 19. The concentration contour corresponding to that for which the laminar flame speed of an ethylene/air mixture is a maximum (Y_1 = 0.073) is plotted as functions of z/r_o and r/r_o. The virtual origin for the plot is assumed to be at z = 0. Two representations are shown. On the right the radial and axial axes have the same scaling, while on the left the radial scale is expanded by a factor of 3. 61

Figure 20. Experimental values [47] of lift-off height (h) are plotted against jet exit velocity for turbulent jet flames of methane, ethylene, and propane. These measured values are compared with values (solid lines) predicted using eq (5) and the known velocity and mixing behaviors of the jets. The agreement is excellent. 62

Figure 21. Experimental [53] (symbols) and calculated values (lines) of blow out velocity are plotted as a function of jet radius for axisymmetric turbulent jet flames of five organic fuels. Calculated values are derived by using eqs (6) and (7). The agreement of the predicted values with experiment is very good 63

Figure 22. Approximate radial density profiles for three nondimensional downstream distances are shown for turbulent jet diffusion flames of hydrogen and a typical organic fuel (methane). These curves are based on measurements reported by several different authors [63,67] 64

ABSTRACT

This report summarizes the research findings of a project which has been jointly funded by the Air Force Office of Scientific Research and the National Bureau of Standards. The goal of the research was to improve the fundamental understanding of chemically reacting turbulent flow. The approach which was taken was to investigate mixing in variable density flows in order to better understand the role of local density fluctuations (which result from chemical heat release) on the turbulent mixing behavior. The development of new experimental diagnostics having excellent spatial and temporal resolution is described. These techniques have been utilized to investigate a wide range of mixing properties in variable density flows. These results are summarized along with a discussion of their importance to an improved understanding of chemically reacting flow.

1. INTRODUCTION

This report summarizes the major findings of a four-year study on chemically reacting turbulent flow. This project was jointly funded by the Air Force Office of Scientific Research (contract numbers ISSA-83-00012, ISSA-84-00005, ISSA-85-00012, and ISSA-86-00008) and the National Bureau of Standards. The period covered is October 1, 1982 to September 30, 1986.

In the following sections the overall objectives of the research project are discussed, significant research accomplishments are listed and briefly described, and the significance of the findings to the understanding of chemically reacting turbulent flow is discussed.

2. PROJECT OBJECTIVES

The primary objective of this research program was the improvement of the fundamental understanding of chemically reacting turbulent flow. The most complicated aspect of this problem is the complex coupling of fluid mechanics and heat release which occurs for most flows in this class. Despite intense efforts for several decades, this complicated process has remained poorly characterized. This is unfortunate since chemically reacting turbulent flows are of paramount importance in a wide range of combustion devices and other chemical reactors which have military and industrial significance. An improved understanding of the interactions of fluid dynamics and heat release is not only necessary to improve device efficiencies and contribute to the conservation of dwindling fuel and feed stocks, but also to allow new types of designs which can limit the release of undesirable pollutants.

In order to meet the above objective an approach was chosen in which the effects of global density variations on turbulent mixing of axisymmetric jets were investigated. This path was chosen since it was felt that one of the major sources of coupling between heat release and fluid motion in a turbulent flow is through the density variations introduced by chemical heat release. In order to characterize these effects, it is first necessary to understand the effects of global density differences.

The study of mixing in variable density, turbulent flows (or any turbulent flow for that matter) is complicated by the wide range of spatial and temporal scales which are of importance. These scales vary from the full dimensions of the flow field down to the smallest scales where turbulent dissipation occurs. It is clear that in order to obtain an improved characterization of these processes diagnostics having high spatial and temporal resolution are required. Since suitable diagnostics were not available, an important secondary goal for the project became the development of new experimental techniques for the study of concentration and velocity fluctuations in variable density flows. The importance of large scale turbulent structures in these flows fields necessitated the development of multi-point diagnostics capable of high temporal and spatial resolution. A digital line camera was designed and a prototype constructed. Preliminary experiments utilizing the camera have been encouraging and development is continuing.

3. RESEARCH ACCOMPLISHMENTS

In the subsection which follows, the development of new diagnostics are described. The findings of an extensive study of mixing in variable density turbulent flows are then summarized. Work in this laboratory, as well as elsewhere, has demonstrated the importance of these findings to an improved understanding of chemically reacting turbulent flow. This point is discussed in the last subsection.

3.1 DIAGNOSTIC DEVELOPMENT

Throughout the course of this project there was an emphasis on the acquisition of real-time data having high spatial resolution and accuracy. Very few suitable experimental techniques were available and a great deal of effort was directed toward the development of unique capabilities for the measurement of concentration and velocity in variable density flow fields. Significant progress has been made on the development of the necessary diagnostic tools.

3.1.1 Concentration Measurement Using Rayleigh Light Scattering

The development of Rayleigh light scattering as a real-time diagnostic of concentration fluctuations within small spatial volumes of turbulent binary gas mixtures was completed during the very early stages of the project period. Building on earlier work [1,2] it was demonstrated [3,4] that Rayleigh light scattering can be utilized to measure a wide range of properties in these flow fields.

The intensity of light scattered by a gas is proportional to the Rayleigh scattering cross section. This scattering cross section is in turn related to the index of refraction of the gas. Since the refractive indices of individual gases vary, scattering intensity varies from gas to gas. For mixtures, the scattering cross sections for the different gases are additive. A measurement of scattering intensity from a binary gas mixture, following calibration in the pure components, allows the concentrations of the two gases in the observation volume to be determined.

Figure 1 shows the experimental apparatus which was developed for Rayleigh light scattering measurements. In order to test this system, real-time concentration data were recorded in the turbulent flow field formed by an axisymmetric jet of methane (Re = 4130) flowing into a slow coflow of air. It was demonstrated [3,4] that this system is capable of recording real-time measurements of methane concentration at data rates as high as 10 kHz for observation volumes as small as 0.0003 mm^3 . The accuracy of individual measurements was estimated to be ≈ 1.9% at the highest data rate.

From the resulting real-time data records such flow properties as the time-averaged concentration, root mean square (RMS) in the concentration fluctuations, and the concentration skewness and kurtosis were calculated.

Figure 2 shows the behavior of the time-averaged methane concentration in the radial direction for a downstream distance of 30 r_o. By using fast Fourier transform analysis it was also possible to calculate the frequency spectrum and correlation functions for the concentration fluctuations.

The availability of real-time data allowed a determination of whether or not jet fluid was present in the imaged volume during the observation time. In this manner, the intermittency function (based on the presence or absence of jet fluid) could be determined and then utilized to provide conditionally-sampled measurements for the properties described above.

Even though the results [3,4] of this work were of a preliminary nature, they represented the most extensive and complete set of data for a variable density flow available in the literature at the time of their publication. Where comparisons were possible, results [3,4] were found to be in excellent agreement with measurements reported in the literature.

3.1.2 Simultaneous Concentration and Velocity Measurement

The development of the Rayleigh light scattering technique provided a powerful means for monitoring concentration behavior in a turbulent flow field of two gases. However, in order to more fully characterize turbulent behavior in variable density flows, measurements for velocity are also required. Of particular importance is the capability for simultaneous measurements of concentration and velocity which allows such parameters as the cross-correlation coefficient (R_{uc}) of velocity and concentration to be calculated. Such correlations are very important since they often appear in models which attempt to provide closure for the Navier-Stokes equations and in treatments which utilize Favre averaging [5]. Such measurements have been very difficult to make in the past and very few comparisons between theoretical estimates and experimental findings are available.

Either of two techniques, hot-wire anemometry (HWA) and laser Doppler velocimetry (LDV), are usually employed for real-time velocity measurement. LDV requires seeding of the flow with particles. This results in a strong Mie scattering which completely obscures the Rayleigh light scattering signal necessary for concentration measurement. Even though experiments have demonstrated that simultaneous measurements of concentration and velocity are possible in lightly seeded flows [6], it has not been possible to make real-time measurements. For this reason, HWA was chosen as the velocity diagnostic.

HWA in variable density flows is complicated by the variations in molecular thermal conductivity which occur as the composition of the gases around the probe changes. As a result, the response of the HWA is not only sensitive to velocity changes, but also to concentration variations. This sensitivity has been used as the basis for probes designed to measure concentration in binary gas mixtures [7]. By combining two probes having different heat transfer properties it has also been possible to make simultaneous measurements of concentration and velocity [8,9]. However, these measurements require extensive calibrations and data manipulation and have not come into widespread or routine use.

By combining the HWA and Rayleigh light scattering techniques it is possible to mitigate some of the limitations of HWA for velocity measurements in variable density flow fields consisting of two gases. The Rayleigh light scattering technique provides real-time concentration measurements which can be utilized to correct the response of the HWA for variations in gas composition once the velocity probe has been calibrated in a series of mixtures. The necessary calibrations are considerably simpler than those required when two hot-wires are employed. Limitations of such an approach include the need for an obtrusive probe and the necessity of physically separating the observation volume for the Rayleigh light scattering and the position of the hot-wire (to avoid scattering).

Experimental work [10] has shown that the limitations mentioned above are not serious and that the combination of Rayleigh light scattering and HWA can be utilized for accurate, real-time measurement of concentration and velocity in variable density flows. Figure 3 shows an example of the real-time behavior of concentration and velocity for a turbulent jet of propane flowing into a coflow of air. Such data records were utilized to calculate time-averages, rms values, and cross-correlation values for the velocity and concentration fluctuations of propane and methane jets. In all cases the experimental measurements were in excellent agreement [10] with the limited data available in the literature.

The measurements reported in [10] are for a single hot-wire (or hot-film) aligned so that the probe is sensitive to velocity in the axial direction of the jet flows. It is possible to also utilize an "X-probe" consisting of two wires oriented at 45° in order to measure both the axial and radial components of velocity. During the past year the response of such a probe to variable density flows as well as the effects of flow direction have been extensively investigated. In the near future this X-probe will be combined with the Rayleigh light scattering system in order to form an experimental system which can make real-time measurements of concentration and two components of velocity in variable density flow fields. This system will be capable of characterizing variable density turbulent flow fields to a degree which has heretofore been impossible.

As part of the calibration work necessary to employ these HWA probes, various correlations available in the literature for the heat loss from a cylinder were considered. It was discovered that none of these correlations were successful in correlating an extensive series of calibrations performed in ten different gases [11,12]. The most widely quoted correlation for different gases utilized a correction based on the Prandtl number (Pr) to correct for variations in molecular properties [13-15]. This correlation was found to be unsatisfactory for the gases investigated during this study. Extensive analysis [11,12] of the data showed that it is necessary to consider the temperature dependence of the molecular properties in order to obtain accurate correlations. Figure 4 is a plot of the heat transfer behavior (in terms of the nondimensional Nusselt number) as a function of flow velocity (in terms of the nondimensional Reynolds number based on the probe diameter). The correlation of the results for the nine gases shown is excellent.

Other heat transfer characteristics such as thermal slip and surface accommodation were also investigated during the course of this study [11,12]. In particular, it was shown that the heat transfer from a cylinder to helium is strongly influenced by surface accommodation. Using theories previously developed for treating this process [16] it was possible to correct the measurements for this effect and obtain an accurate correlation of the heat transfer behavior of helium with the results for other gases. The helium data included in figure 4 have been analyzed in this manner. The measurements also yielded an vastly improved understanding of the dependence of the heat transfer process on Re and transitions in flow behavior which occur as the Re is varied.

The manuscripts which resulted from this work [10,11,12] are not only significant for their importance to researchers who wish to utilize HWA in different gases, but are also important for the much wider field of heat transfer. The results considerably modify current concepts concerning the role of molecular properties in heat transfer behavior.

Extensive measurements [17] have also been made for mixtures of gases. For these mixtures the procedure described above does not provide accurate correlations for the heat transfer measurements. Systematic variations are observed with the mole fractions of the components which have tentatively been ascribed to the effects of thermal diffusion on the heat transfer behavior. If thermal diffusion is indeed the source of the variations, it is required that its effects on heat transfer be roughly ten times larger than reported in the literature. Dr. Howard Baum is currently developing a theory [17] for this process which is designed to allow a test of this hypothesis.

3.1.3 Development of a Digital Line Camera for Concentration Measurement

The flow diagnostic techniques described above are designed to allow accurate point measurements of velocity and concentration. Measurements utilizing these techniques as well as findings in other laboratories have suggested the importance of large scale structures for mixing in turbulent flows such as axisymmetric jets. The availability of real-time point measurements allows some characterization of these structures through the determination of intermittency functions and conditional sampling. However, such measurements provide very limited information about individual structures and their role in the entrainment of surrounding gases. Clearly, simultaneous measurements at many different points in space would provide much more information concerning the structure and role of these large scale structures in the turbulent mixing process.

Recently there has been a great deal of research activity (e.g., [18-23]) on the development of optical diagnostics which are capable of nonobtrusive, multi-point measurements in flow fields. Such imaging experiments have been reported along lines [18], in planes [19-21], and in three dimensions [23]. A wide range of optical processes such as Rayleigh [19,23], Raman [20], Mie scattering [19] and fluorescence [18,21,22] have been employed. Even though there are exceptions, most of these experiments are characterized by the need for image intensification (due to the relative insensitivity of the solid-state detectors which are usually employed) and the use of high-powered lasers which provide sufficient signal levels to allow the optical measurements, but which limit the experiments to low repetition rates.

Due to the ability of imaging experiments to provide a more complete characterization of large scale structures in turbulent flows, it was clear that a system utilizing Rayleigh light scattering for quantitative mass fraction measurement would be very useful. A short proposal was prepared and the necessary funding for the development of a digital line camera system was provided internally by the National Bureau of Standards. Note that a similar unintensified system has been utilized for concentration measurements in a water jet [22].

A set of design goals were developed for the camera. The most important of these are listed here:

1. A spatial resolution of 400 μm along the line.

2. Line readout rates greater than a kHz.

3. Concentration measurements having an absolute accuracy of a few percent.

4. Utilization of an existing CW Ar ion laser and data acquisition system.

5. Use of commercially-available components.

The first three of these goals were chosen to be consistent with the capabilities of our experimental system for single point measurements of concentration. The last two were required to minimize the cost of the system and simplify its design and construction. These criteria were found to be in competition with one another and it was necessary to make compromises in the design of the camera.

An analysis [24] of the intensity of scattered light from the Ar^+ ion laser beam and the sensitivity of commercially available solid-state line detectors indicated that image intensification would be required in order for the line camera to operate at the required data rates. This requirement turned out to be the most difficult technical challenge of the camera design.

There are two major types of image intensifiers available commercially. These are known as generation I (gen I) and generation II (gen II). Gen I tubes consist of a photocathode, accelerating and focusing electronics for electrons emitted by the photocathode, and a phosphor screen. The optical gain of the device results from the fact that a single accelerated electron striking the phosphor screen results in the production of many photons.

Gen II tubes are similar to gen I tubes with the exception that a microchannel plate (MCP) is inserted between the photocathode and the phosphor screen. The MCP is an active device which can produce electron gains of

10^3-10^4. Since the channels which form the MCP are aligned, any electron "image" present on the input face is maintained at the other end of the MCP.

Electrons emitted by the photocathode of a gen II image intensifier are focused (either by proximity or electrically) onto the MCP and the resulting amplified electron image from the MCP is focused onto a photocathode. Since the MCP provides a very high gain, a single gen II image intensifier has a much higher light gain than a single gen I tube. It is necessary to cascade two or three gen I tubes in order to obtain intensification comparable to a single gen II tube.

In most flow imaging experiments reported thus far gen II tubes have been utilized. However we discovered [24] that for real-time imaging there is a serious problem due to the maximum light output which can be generated by this type of image intensifier. This limitation results from the limited output current of the individual channels of the MCP. Calculations indicated that the maximum brightness which can be generated by a gen II tube is comparable to that available from the Rayleigh light scattering experiment and is not sufficient for real-time detection using commercial, solid-state line detectors. Since only moderate light gains were necessary, a gen I tube was chosen as the image intensifier. These tubes can operate at much higher current levels than the second generation devices and can therefore produce more intense light outputs.

Measurements at data rates greater than a kHz also require consideration of the response time of the phosphor screen used in the intensifier. The P-20 phosphor employed for standard tubes has a long-lived tail in its temporal decay and for this reason is unsuitable for this application. A P-47 phosphor screen was chosen instead. This screen has a submicrosecond lifetime, but it is less efficient than P-20 and the overall gain of a single stage is significantly reduced. The final selection for the image intensifier consisted of two stages of gen I tubes equipped with P-47 phosphor screens.

The detector chosen for the camera was a Reticon RL128S* line detector which consists of 128 pixels on 25 μm centers. A 4:1 reduction fiber optic taper was utilized to couple the detector and the image intensifier. The camera was completed by the addition of a f/1.9 1:1 focusing lens for imaging the scattered light onto the image intensifier. With this arrangement each pixel corresponds to a 100 μm length of the image so that the entire line image covers 12.8 mm. Figure 5 shows a schematic for the prototype camera.

The line detector is equipped with electronics which generate voltages that are proportional to the light detected during the integration period on an individual pixel. The voltages for the 128 pixels appear sequentially on the output. These voltages are digitized and stored in the memory of a minicomputer. Since the maximum data rate for the acquisition system used is 333 kHz, the maximum line read-out rate is limited to 2.2 kHz. Figure 6 shows the overall system for line measurements of concentration including the digital line camera, the flow system, and the Ar^+ ion laser.

In order to test the system, line measurements of propane mole fraction for a propane jet flowing into a slow coflow of air have been recorded. Figure 7 shows an example of the concentration behavior across the radial profile of the jet at a downstream distance of 5 jet diameters and a line read-out rate of 837 Hz. The total data acquisition time was ≈ 300 ms. Even

*Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards nor does it imply the instruments or equipment are necessarily the best available for the purpose.

though the time resolution is not sufficient to fully resolve small details, the importance of large scale structures is clear. The results of such measurements can be time-averaged to yield the contour of the radial profile. Figure 8 shows the results for five downstream positions. The growth and spread of the turbulent boundary layers is evident.

While the performance of the initial camera prototype has been very encouraging, it has not been possible to reach the full time resolution potential of the camera due to limitations in the gain of the image intensifier. A new, three-stage tube has been ordered and will be installed shortly. This gen I image intensifier will provide a higher gain due to the additional stage of amplification. It is also equipped with P-46 phosphor screens which have the same short lifetime properties of P-47, but which have outputs at longer wavelengths (green). Green light is more efficiently transmitted by the fiber optic taper and detected more efficiently by the line scanner. This modification should therefore increase the sensitivity of the tube significantly.

3.2 CHARACTERIZATION OF MIXING AND VELOCITY BEHAVIOR IN AXISYMMETRIC JETS

3.2.1 Mixing in a Turbulent, Axisymmetric Jet of Methane

As part of the development of Rayleigh light scattering as a diagnostic for concentration, extensive measurements of such flow properties as time-averaged concentration, unmixedness, skewness, kurtosis, concentration fluctuation spectra, and correlation functions were made [3,4]. The existence of time-resolved data records also allowed the intermittency functions for the flow field to be determined and from these it was possible to generate conditionally-averaged measurements of these flow properties.

Data were recorded at various positions along the jet centerline and across the radial profile of the jet for one downstream position ($z/r_o = 35$). In all cases where literature sources were available for comparison there was excellent agreement. The availability of real-time data allowed the existence of large-scale ramp-like structures in the intermittent region of the flow field to be identified. Such structures are believed [25,26] to be the primary mechanism by which jet entrainment occurs and for this reason their characterization is crucial.

Even though the findings of the study [3,4] were of a preliminary nature, they were chosen for comparison purposes with conserved scalar measurements in a hydrogen jet flame [27,28]. These authors felt the measurements were the most complete and accurate available at the time. A remarkable similarity was found between mixing in the isothermal and combusting flows. The significance of this finding is discussed below.

3.2.2 Simultaneous Measurements of Concentration and Velocity in a Propane Jet

As a test of the combined hot-probe anemometry and Rayleigh light scattering diagnostic, real-time concentration and velocity data were recorded in jet flows of propane entering a slow coflow of air [10]. Preliminary measurements which were recorded are significant due to the limited number of such measurements which have been reported in the literature for variable density flows. For instance, time-averaged measurements of centerline velocity showed that the data could be fit in the form

$$U_o/\overline{U}_c = K_u(z-z_o)/r_\epsilon \qquad (1)$$

where r_ϵ is the effective radius defined as $(\rho_0/\rho_\infty)^{1/2}r_0$. A least squares fit of the results gave $K_u = 0.082$ which is close to the value of 0.081 recommended by both List [29] and Chen and Rodi [30]. Values of the correlation coefficients for velocity and concentration were also calculated as a function of downstream position. Literature comparisons were very scare, but measurements by Antonia et al. [31], Chevray and Tutu [32], and Catalano et al. [33] showed that values of R_{uc} measured in this study were consistent with previous measurements. The findings suggest that R_{uc} grows to an asymptotic value of ≈ 0.39 on the jet centerline in this variable density flow.

3.2.3 Density and Reynolds Number Effects on Mixing in Axisymmetric Jets

An extensive study [34] of the effects of density and Reynolds number variations on mixing in turbulent axisymmetric jets was performed. Qualitative information concerning the flows was obtained using time-resolved shadowgraphs while Rayleigh light scattering was utilized to investigate quantitatively the centerline mixing behavior. Table 1 lists the gas pairs investigated in this study, the ratio of jet to coflow densities, Re based on the jet diameter, and whether or not shadowgraph and Rayleigh data were taken.

Figure 9 shows the experimental arrangement used to record shadowgraphs of the variable density jet flows. The diameter of the shadowgraphs is 76 mm and the light pulse has a measured FWHM of 165 μs with a total duration of 310 μs. It must be remembered that shadowgraphs provide an integrated view of the flow field and that the signal is proportional to the second derivative of the index of refraction variations which occur along the path of the light beam.

For these reasons, extreme caution must be utilized in drawing conclusions from such photographs. However, with this in mind, it is possible to characterize some of the effects of density and Reynolds number variations on jet mixing behavior from the series of shadowgraphs which have been recorded.

Figure 10 provides a dramatic example of the effects of density differences on the mixing behavior of a turbulent jet. Shadowgraph are shown for a jet flow of sulfur hexafluoride into air with Re = 3950. The initial jet density is 5.1 times higher than that of the surrounding air. As is clearly shown by the shadowgraph covering the downstream region from $z/r_o = 25$ to 45 , the initial momentum of the jet is not high enough to overcome the negative buoyancy (the jet is orientated vertically) of the flow and the jet forms a fountain with jet fluid falling back through the surrounding coflow. Interestingly, as can be seen in figure 11, this effect disappears for Re of 7890 and 11860.

Shadowgraphs for flows covering jet to coflow density ratios of 0.14 to 5.1 are shown in figure 12. The following conclusions have been drawn concerning the effects of density and Re differences on mixing in these flows from these and other shadowgraphs.

1. The initial density ratio effects the shape of the vortices at downstream positions in the flow field. Increasing density ratios result in lengthening of vortices in the axial direction.

2. Changes in the density ratio effect the initial development of turbulence in the jets. For smaller values of ρ_o/ρ_∞ the flow distance required for initial growth of vortices is shorter.

Figure 13 shows shadowgraphs recorded for jet flows of propane into air at three different Re. From these photographs as well as those shown in figure 11, the general effects of changes in Re can be summarized as

1. As the Re is increased the turbulent structures in the flow field extend to smaller scales.

2. Increasing the Re has very little effect on the angle of spread for a given gas pair.

3. Turbulent structures develop at shorter flow distances as the Re is increased.

Even though the shadowgraphs provided qualitative information concerning mixing in variable density turbulent flows, very little quantitative information could be obtained. Rayleigh light scattering was utilized to perform quantitative measurements of fluid concentration behavior along the centerlines of the jets.

Time-averaged concentration measurements provide an excellent example of how significantly density differences can modify mixing. Figure 14 shows experimental values of inverse time-averaged mass fraction ($1/\overline{Y}_m$) plotted as a function of nondimensionalized downstream position for different jets having a wide range of density ratio. The data fall on straight lines having slopes which decrease with increasing density ratio and virtual origins (value of z where $1/\overline{Y}_m$ extrapolates to zero) which move upstream as the density ratio increases.

In the early 1950's Thring and Newby [35] suggested that the centerline mixing behavior of axisymmetric turbulent jets could be correlated using an expression which can be written as

$$1/\overline{Y}_m = K_c z/r_\epsilon + (\rho_\infty/\rho_o - 1)K' \tag{2}$$

where r_ϵ is the effective radius defined earlier and K_c and K' are constants which are determined by radial integrations of velocity and concentration across the flow field. This equation can be derived utilizing conservation equations and assuming self-similarity. It is strictly valid only for downstream positions where $\overline{\rho}_m \approx \rho_o$.

The predicted behavior of plots of $1/\overline{Y}_m$ versus z/r_o using eq (2) are shown in figure 15 for $K_c = 0.114$ and $K' = 0.5$. Comparison with the experimental results in figure 14 shows that there is excellent agreement. The dependence of the slopes of the plots on ρ_o/ρ_∞ has been documented in the literature previously (e.g., [36,37]), but to our knowledge, this is the first time that the predicted dependence of z_o on the this parameter has been confirmed.

Similar data were recorded for axisymmetric jets in which the Reynolds number was varied. These measurements showed that the principal effect of increasing the Re was to shift the virtual origin, z_o, downstream. Slopes of plots of $1/\overline{Y}_m$ versus z/r_o were independent of Re. This suggests that the centerline mixing behavior in these flow fields is due primarily to large scale turbulent structures which should be independent of Re (i.e., inviscid flow).

The availability of time-resolved measurements allowed the behavior of centerline unmixedness (defined as the RMS of the concentration fluctuations, Y_m', divided by $\overline{Y}_m$) to be determined as a function of ρ_o/ρ_∞ and Re. Figure 16 is a plot of $Y_m'/\overline{Y}_m$ versus z/r_o for six variable density flows. It is clear that in each case unmixedness values are approaching a common asymptote of $\approx$ 0.23, but that the flow distance required to attain this value is strongly dependent on ρ_o/ρ_∞ with higher ratio flows requiring longer flow distances. There are very few measurements or theoretical predictions of unmixedness in variable density flows reported in the literature. This study was the first to provide data for a wide range of ρ_o/ρ_∞.

In order to gain some understanding of the role of density ratio on the flow distance required to attain the unmixedness asymptote, the experimental values of $Y_m'/\overline{Y}_m$ were replotted as a function of z/r_ϵ as shown in figure 17. It is clear that plotting the data in this manner results in a collapse of the growth curves for unmixedness and that r_ϵ serves as a scaling parameter for the growth. This conclusion is surprising in that the unmixedness development is occurring in a flow region where the condition $\overline{\rho}_m \approx \rho_o$ is not met and the development which leads to the definition of r_ϵ is not strictly valid. At the same time it does suggest that r_ϵ is a true scaling parameter which not only results in a collapse of time-averaged data, but also scales the development of turbulent structure in the flow field.

Similar measurements in C_3H_8/air (see fig. 18) and SF_6/air flows have shown that the asymptotic value of unmixedness is independent of Re, but that the flow distance required to attain the asymptote increases as the Re is increased. The longer flow distances required for turbulence growth in the higher Re flows results in the downstream shifts of the virtual origins observed for plots of $1/\overline{Y}_m$ as functions of z/r_o. The observed Re dependence of the flow distance required to attain fully-developed flow was surprising since fully-developed turbulent behavior is generally associated with high Re. The independence of the asymptotic value of $Y_m'/\overline{Y}_m$ on Re once again highlights the importance of large scale structures in turbulent mixing behavior.

It was hypothesized [34] that the longer flow distances required for fully-developed flow at higher Re is connected with development of smaller scale vortices in the flow fields at higher Re. If a "pseudo-equilibrium" exists between the different vortical scales, a longer flow distance would be required for the entire turbulent structure to come into equilibrium at the higher Re. More sophisticated experiments will be necessary to test this hypothesis. Whether or not this hypothesis is correct, a more complete characterization of the growth of centerline unmixedness in these flows is required so that parameters which control the growth of turbulence in flow fields can be identified.

The time records were also used to calculate skewness (third moment) and kurtosis values (fourth moment) for concentration fluctuations. Distinct effects of density ratio were observed on the centerline behavior of these parameters, but in the absence of theoretical guidance it was not possible to relate these variations to physical modifications of the mixing behavior.

The manuscript which was written to describe these results [34] contains extensive comparison with previous literature findings. Generally, quantitative agreement is excellent. Possible sources of disagreement, such as the effects of buoyancy and the use of a coflow, were also analyzed and were generally found to be minor perturbations. It was concluded that the results are indicative of mixing behavior in free axisymmetric jets. The use of a wide range of density ratios and Re resulted in the identification of dependencies in the mixing behavior which had not been reported previously.

4. IMPORTANCE OF ISOTHERMAL STUDIES TO AN IMPROVED UNDERSTANDING OF TURBULENT REACTING FLOWS

The significance of findings from the isothermal flow studies for improving the understanding of the more complicated case of chemically reacting flows was considered where appropriate. These analyses resulted in a more clearly defined perception of the role of density variations (both global and local) in chemically reacting turbulent flows. Consideration of mixing behavior in the isothermal mixing regions of lifted and blown out turbulent jet diffusion flames resulted in new correlation procedures for describing these stabilization characteristics and suggested new physical models to understand the behaviors. The role of local Re variations on mixing in chemically reacting turbulent flows has been assessed. These points are discussed in this section.

4.1 Similarity of Mixing in Isothermal and Reacting Flows

Numerical data from the original Rayleigh light scattering study of methane [3,4] were provided to investigators at General Electric Corporate Research and Development Center for comparison with extensive experimental measurements recorded for a turbulent hydrogen jet flames. Drake et al. [27,28] found that radial profiles of the first four moments of concentration fluctuations (time-average, RMS, skewness, and kurtosis) for the isothermal and reacting flow (in terms of the conserved scalar concentration, ζ [38]) were very similar. Such agreement suggests that heat release and combustion have very little effect on the probability distribution functions (PDF) of scalar mixing in turbulent reacting flows. This conclusion is extremely important because it implies that the results of isothermal mixing studies can be applied directly to chemically reacting turbulent flows and thus provides additional justification for the approach taken in our own study. Theorists have long used isothermal mixing results as the basis for models of chemically reacting turbulent flow [39].

Drake et al. [27,28] also utilized the isothermal results of our earlier study along with their own findings to test a parametric expression developed by Effelsberg and Peters [40] which divided the conserved scalar PDF into nonturbulent, fully turbulent, and superlayer parts. These authors concluded that the measurements were not consistent with this model since the results required that more than 50% of the PDF be due to superlayer contributions. An alternate interpretation was offered in which the "apparent" superlayer was attributed to the presence of large scale "ramp-like" structures in the flow field. Such structures have been observed in time records recorded in our earlier work [3,4] and by other researchers (e.g., [31,41,42]).

4.2 Lift-off and Blow-Out of Turbulent Jet Diffusion Flames

There are certain properties of combusting jets for which isothermal findings are directly applicable. In particular, lift-off and blow out of turbulent jet diffusion flames must depend on the concentration and velocity behavior of the turbulent flow upstream of the region where combustion or blow out occurs. The results of our isothermal studies as well as other findings available in the literature have been utilized [54] to develop a procedure which is capable of accurately predicting experimental lift-off heights as a function of jet exit velocity and blow out velocities as a function of jet diameter for turbulent jet diffusion flames of many different fuels. Interestingly, only time-averaged properties have been considered and it has not been necessary to consider the actual turbulent behavior of the flow. This is significant since most theoretical treatments either assume flame stability is due to an equilibrium of flow velocities and turbulent flame speeds (which depend on small scale turbulent structure) [43-47] or to flame extinction processes in small scale structures [48-51].

A radically different explanation for flame stability has been suggested by Broadwell et al. [52]. These researchers have argued that flame stability is determined by the reentrainment of hot combustion gases (expelled by the passage of earlier large scale structures) by large scale structures in the flow field. These gases are rapidly mixed with the jet gases and if the turbulent mixing time, τ_d is longer than the chemical ignition time, τ_c, of the fuel/air mixture in the jet, the structure will be ignited and the combustion stabilized. When the mixing time becomes shorter than the chemical reaction time ($\tau_c > \tau_d$) combustion can no longer be sustained.

The impetus for our investigation of flame stability mechanism was the extensive experimental investigations of lift-off [47] and blow out [53] of turbulent jet flames by Kalghatgi. He found that his results for lift-off heights as a function of velocity for different fuels were well correlated by an expression which can be approximated as

$$h = C_h (U_o/(S_b)^2_{max}) \nu_o (\rho_o/\rho_\infty)^{1.5}, \tag{3}$$

where C_h is a constant, $(S_b)_{max}$ is the maximum laminar flame speed for the fuel and air, and the density term is an approximation for a more complicated expression. The form of this equation was based on dimensional analysis. The inclusion of ν_o in the expression reflects the important role small scale turbulent structures are believed to play in this stability behavior.

Blow out velocities as a function of jet diameter were found to have a similar dependence on density and ν_o [53]. This correlation can be written as

$$(U_o)_b = C_b r_\epsilon (S_b)^2_{max}/(Y_s \nu_o (\rho_o/\rho_\infty)^{1.5}), \tag{4}$$

where C_b is a constant and Y_s is the mass fraction of fuel in a stoichiometric mixture with air.

Attempts to predict the exponent of 1.5 for the density ratios in eqs (3) and (4) in terms of the known concentration and velocity fields of isothermal, variable density turbulent jets were not successful. On the other hand, correlations in which the term $\nu_o (\rho_o/\rho_\infty)^{1.5}$ were omitted from eqs (3) and (4) were found to accurately correlate Kalghatgi's experimental findings. The simplicity of these correlations suggested that the time-averaged properties of the flow field might be employed to predict lift-off heights and blow out velocities. Subsequent calculations [54] have shown this to be the case.

The first step in the procedure is to calculate the time-averaged mass fraction contour in the flow field along which the laminar flame speed is a maximum. Both theory [43-45] and measurements [44,45,55] in turbulent jet flames have shown that the most probable location for the shortest distance between the nozzle and the instantaneous flame position is along this contour. Figure 19 shows the form of this contour for an ethylene jet. In order to make these calculations, the centerline mixing behavior is taken from our variable density study and the radial behavior is based on expressions given in Chen and Rodi's book [30]. Shifts in virtual origin with density ratio and Re have been ignored.

An empirical procedure was then utilized to derive an expression for the local velocity (U_1) along the contour which results in the proper dependencies [47] of lift-off heights on jet diameter (nearly independent) and exit velocity (linearly dependent). The resulting expression has the form

$$U_1 = C_h'' z^2 (S_b)^2_{max} Y_1^2 / r_\epsilon \qquad (5)$$

where Y_1 is the mass fraction of fuel necessary for $(S_b)_{max}$. The corresponding velocity at the jet exit is then calculated utilizing the known axial and radial dependencies for velocity [30]. C_h'' is a constant parameter which has the units of an inverse kinematic viscosity. In order to determine C_h'' a single experimental measurement of h for ethylene from the turbulent jet flame data of Kalghatgi [47] was utilized. A value of $C_h'' = 0.0484$ s/cm^2 resulted.

This calculational procedure was utilized to calculate values of the lift-off height as a function of exit velocity for different fuels. Figure 20 reproduces the results of the calculation [54] for fuel jets of methane, ethylene, and propane and compares the predictions with the experimental results of Kalghatgi [47]. The agreement is excellent.

The success of the calculational procedure in reproducing the experimental findings for lift-off heights of turbulent jet diffusion flames suggests that small scale vortices may not be important in flame stability since only global mixing properties which are independent of Re have been utilized. The role of small scale structures cannot be total discounted since it is possible that their properties may be correlated with the variables included in eq (5) in some manner. The fluctuation properties of the concentration and velocity in the radial positions where these calculations have been made are not well enough characterized to test this.

The form of eq (5) is consistent with the model for turbulent combustion suggested by Broadwell et al. [52] in which flame stability is determined by the behavior of large scale turbulent structures. However, it should be noted that the authors reported, but did not test, an expression for lift-off heights which is not consistent with the experimental observations of Kalghatgi [47]. If their model is correct, eq. (5) suggests that the chemical reaction time is inversely proportional to $(S_b)^2_{max}$ and that the turbulent mixing time is proportional to z^2/r_ϵ. The latter proportionality suggests that two lengths scales are necessary to characterize the mixing time; one which increases as z/r_ϵ and a second which scales as z. It has already been shown that z/r_ϵ is the proper nondimensionalizing length scale for centerline mixing. Previous studies [30,36] have concluded that the radial spreading rate as a function of downstream distance is linearly dependent on z and independent of density ratio. It is therefore expected that τ_d will scale with the product of z and z/r_ϵ.

The appearance of the Y_1^2 in eq (5) is at first perplexing. Calculations have shown that it serves to make the calculated values of U_o independent of Y_1. This is consistent with the absence of this parameter in the correlation shown in figure 20 and suggests that τ_d may be independent of radial position in these flows.

It was possible to extend this calculational procedure to the prediction of blow out velocities [54]. It is known [44,45,53] that blow out occurs in these flames well before the contour represented in figure 19 reaches the jet centerline. This suggests that flame extinction occurs when

$$U_1 > U_b, \tag{6}$$

where U_b is a well-defined velocity. In order to reproduce the experimental finding of Kalghatgi [53] for $(U_o)_b$ as functions of jet radius and fuel it is necessary that

$$U_b = C_b (S_b)^2_{max} r_o. \tag{7}$$

A value of $C_b = 1.5\ s/cm^2$ was determined using one of Kalghtgi's experimental measurements [53]. Figure 21 compares predicted blow out behaviors (solid lines) with Kalghatgi's experimental results for five fuels. The agreement is outstanding.

Broadwell et al. [52] showed that their hypothesis concerning the role of large scale structures in the stability of turbulent jet diffusion flames led to an expression which also accurately correlated Kalghatgi's [53] blow out data. Equation (7) is very similar to their development with the exception that it is based on the local flow velocity while Broadwell et al. [52] found it necessary to assume that flame extinction occurred when the centerline mass fraction fell to some constant percentage of the value for stoichiometric burning. The similarity of the two expressions lends support to their flame stability theory.

4.3 Application of Isothermal Findings to Turbulent Mixing in Combusting Regions of Turbulent Jet Flames

The similarity of the isothermal measurements of turbulent structure [3,4] and those made in a hydrogen/air diffusion flame [27,28] suggests that the combustion process may not significantly alter turbulent mixing behavior. If this is the case, it is expected that the principal effect of combustion on turbulent mixing arises from the density variations induced by heat release.

In an earlier manuscript [54] the role of these density fluctuations on mixing in turbulent jet flames has been discussed. Several particular cases were identified for which these density variations might be expected to approximate those in isothermal flows having global density variations. As summarized here, experimental findings suggest this approach may have some validity in certain downstream positions of combusting flow fields.

Figure 22 is a representation of radial density profiles in turbulent jet flames of hydrogen and a typical hydrocarbon (methane). One of the interesting aspects of the hydrogen jet flame is that the heated products and the cold fuel have very nearly the same densities. In the near field of the jet, combustion occurs primarily in the outer regions of the flow so that the density is constant over nearly the full radial range of the turbulent flow. For this reason, the mixing behavior of the flow near the jet exit should be very similar to that observed for a constant density, isothermal flow. Experimental evidence supporting or contradicting this conclusion was not available in the literature.

Similar arguments lead to a different conclusion for the near-field mixing behavior in hydrocarbon turbulent jet diffusion flames. Since the heated combustion products are much less dense than the cold fuel, in the near field the flow consists of a dense inner turbulent jet flowing into considerably less dense surroundings (see fig. 22). This view is supported by shadowgraphs recorded by Wohl et al. [56] and by the recent schlieren study of Savas and Gollahalli [57] which show a more dense turbulent fuel jet entering an apparently laminar, less dense surroundings.

Several groups (e.g., [58] and [59]) have recorded concentration measurements in the near fields of both isothermal and combusting jets of hydrocarbon fuel gases. In general, the flame jets have longer potential cores, develop turbulent behavior further downstream, and have centerline fuel mass fractions which fall off less rapidly with downstream distance than in the corresponding isothermal flows. Based on the isothermal findings discussed above, these behaviors are exactly those expected for a dense jet flowing into less dense surroundings.

As the combusting jet move further downstream the most likely position for combustion moves closer to the centerline and the radial density profiles are modified. In the case of the hydrogen flame the result is that the central part of radial profile has a density which remains nearly constant, but in the outer regions of the flow there is a rapid increase in density (see fig. 22, $z/r_o = 80$). The condition necessary for the application of the isothermal findings (namely, $\bar{\rho}_m \approx \rho_\infty$) is not fulfilled and it is not expected that the centerline decay will obey a relation having the form of eq (2).

Detailed measurements of conserved scalar concentrations in turbulent jet flames of hydrogen are available [60,61]. In general, the authors have not analyzed their data in the form suggested by eq (2), but it appears that the centerline decay of conserved hydrogen concentration does not have a hyperbolic fall off with increasing downstream distance.

In the case of hydrocarbon fuels Hans Kremer (as described by Ebrahimi and Kleine [59] and Lenze and Günther [62]) has developed an analysis procedure similar to that described here to predict the fall off of the centerline conserved scalar concentration. Ebrahimi and Kleine [59] have shown that this analysis gives accurate predictions of ζ along the jet centerline for $20 < z/r_o < 100$ when ρ_∞ was assumed to be that for heated combustion gases ($T_f = 1600$ K, $\rho_f/\rho_\infty = 4.9$).

For larger downstream distances ζ was found to fall off more quickly than predicted. The authors attributed this to a buoyancy effect (i.e., an increase in jet momentum). However, it is possible that the analysis fails due to changes in the radial density profiles which invalidate the conditions for which eq (2) was derived. As figure 22 shows, the radial density profiles for the hydrocarbon flame are greatly modified at large downstream distances (e.g., $z/r_o = 160$). Such radial profiles cannot be considered as that of either a heavy jet into light surroundings or for a constant density jet. In order to predict the centerline behavior of ζ in this flow region it may be necessary to have a better understanding of the effects of local density variations on turbulent mixing. Further experimentation is required to clarify the roles buoyancy-induced momentum and radial density profiles on turbulent mixing.

For regions of turbulent jet flames where direct comparisons of isothermal mixing results are valid, it should also be possible to predict centerline values of unmixedness. Measurements of unmixedness in several different jet flames are available [59-61,63]. These suggest that unmixedness levels in turbulent jet diffusion flames are of the same order as measured in isothermal flows, but there are systematic variations in most of the measurements which make direct quantitative comparison impossible.

As the above discussion suggests, isothermal measurements in variable density flows can provide important insights into the mixing behaviors of turbulent jet diffusion flames. Further work is required to determine for which conditions direct comparisons are valid and when it will be necessary to allow for local radial density variations due to the heat release of combustion.

4.4 Reynolds Number Effects in Diffusion Flames

The investigation of Re effects on mixing in variable density flows has important implications for mixing in turbulent jet diffusion flames [54]. It is well known that local Reynolds numbers, Re_l, for turbulent flames are much lower than calculated based on the room temperature properties of the flow at the nozzle. This is due to the large increase in kinematic viscosity which occurs when gases are heated.

The isothermal studies [34] have shown that the centerline mixing behavior is independent of Re except for downstream shifts in virtual origins and longer flow distances required to attain asymptotic values of unmixedness which are found with increasing Re. This suggests that the mixing behavior of these turbulent flow fields is determined by large scale structures and that as long as the local Reynolds number is high enough to insure the development of large scale vortices, mixing in combustion regions of the flow field will be independent of Re_1. This conclusion is supported by the observations of Becker and Yamazaki [64] who noted that flame lengths of turbulent jet diffusion flames were independent of Re_1 even when the turbulent structure was "fairly primitive, having little more than an appropriate large-eddy structure".

For isothermal flows it has been shown that centerline unmixedness attains asymptotic behavior over shorter flow distances at lower Re. This suggests that for the lower Re characteristic of combusting flows, the flow field should be able to respond to density fluctuations resulting from heat release over relatively short flow distances. This conclusion may be very helpful in understanding and predicting the effects of local density variations on mixing in complex chemically reacting flows.

5. SUMMARY

During the four years of this joint AFOSR/NBS research program significant progress has been made toward the goal of improving the understanding of chemically reacting turbulent flow. The results of experiments in this laboratory as well as measurements elsewhere on turbulent jet diffusion flames have justified the original choice to investigate flows having global density differences. It is anticipated that the experimental findings and the data base which were generated will be utilized by researchers who are attempting to develop calculational procedures for describing chemically reacting flows. The real-time nature of the studies and the conclusion that vortical structures are modified by global density differences will be of particular interest for workers who are attempting to develop sophisticated calculational procedures to describe the time behavior of turbulent flows (e.g., see [65] and [66]).

During the past four years the use of Rayleigh light scattering for characterizing turbulent mixing behavior in isothermal, variable temperature, and combusting flows has become more widespread and many laboratories are now utilizing the technique. It is gratifying that the original careful characterization of the technique in this laboratory has contributed to this growth. It is anticipated that the development of new diagnostics for simultaneous point measurement of concentration and velocity and for line measurements of concentration will lead to further utilization of this unique and powerful technique.

REFERENCES

[1] Graham, S.C.; Grant, A.J.; and Jones, J.M. AIAA J. 12(8): 1140-1142; 1974 August.

[2] Dyer, T.M. AIAA J. 17(8): 912-914; 1979 August.

[3] Pitts, William M.; Kashiwagi, Takashi. The application of laser-induced Rayleigh light scattering to the study of turbulent mixing, Nat. Bur. Stand. (U.S.) NBSIR 83-2641; 1983 January. 114 p.

[4] Pitts, William M.; Kashiwagi, Takashi. J. Fluid Mech. 141: 391-429; 1984 April.

[5] Hinze, J.O. Turbulence. 2nd ed. New York: McGraw-Hill; 1975. 800 p.

[6] Schefer, R.W.; Dibble, R.W. AIAA J. 23(7): 1070-1078; 1985 July.

[7] Brown, G.L.; Rebollo, M.R. AIAA J. 10(5): 649-652; 1972 May.

[8] Way, J.; Libby, P.A. AIAA J. 34(8): 1567-1573; 1971 August.

[9] McQuaid, J.; Wright, W. Intl. J. Heat Mass Transfer. 17(2): 341-349; 1974 February.

[10] Pitts, William M.; McCaffrey, Bernard J.; Kashiwagi, Takashi. "A New Diagnostic for Simultaneous, Time-Resolved Measurements of Concentration and Velocity in Simple Turbulent Flow Systems," Presented at the Fourth Symposium on Turbulent Shear Flows, Karlsruhe, W. Germany; 1983 September 12-14.

[11] Pitts, William M.; McCaffrey, Bernard J. Response behavior of hot-wires and films to flows of different gases. Nat. Bur. Stand. (U.S.) NBSIR 85-3203; 1985 July. 123 p.

[12] Pitts, William M.; McCaffrey, Bernard J. J. Fluid Mech. 169: 465-512; 1986 August.

[13] Wu, P.; Libby, P.A. Intl. J. Heat Mass Transfer. 14(8): 1071-1077; 1971 August.

[14] McQuaid, J.; Wright, W. Intl. J. Heat Mass Transfer. 16(4): 819-828; 1973 April.

[15] Simpson, R.L.; Wyatt, W.G.; J. Phys. E: Sci. Instrum. 6(10): 981-987; 1973 October.

[16] Andrews, G.E.; Bradley, D.; Hundy, G.F. Intl. J. Heat Mass Transfer. 15(10): 1765-1786; 1972 October.

[17] Baum, Howard R.; McCaffrey, Bernard J.; Pitts, William M. unpublished work.

[18] Aldén, M.; Edner, H.; Holmstedt, G.; Svanberg, S.; Högberg, T. Appl. Optics. 21(7): 1236-1240; 1982 April 1.

[19] Escoda, M.C.; Long, M.B. AIAA J. 21(1): 81-84; 1983 January.

[20] Long, M.B.; Fourguette, D.C.; Escoda, M.C.; Layne, C.B. Optics Lett. 8(5): 244-246; 1983 May.

[21] Kychakoff, G.; Howe, R.D.; Hanson, R.K.; Drake, M.C.; Pitz, R.W.; Lapp, M.; Penney, C.M. Science. 224(4647): 382-384; 1984 April 27.

[22] Koochesfahani, M.M; Dimotakis, P.E. AIAA J. 23(11): 1700-1707; 1985 November.

[23] Yip, B.; Long, M.B. Optics Lett. 11(2): 64-65; 1986 February.

[24] Pitts, William M. Development of a line camera for real-time measurements of concentration in turbulent flow fields. Proceedings of the International Congress on Applications of Lasers and Electro-Optics: Flow and Particle Diagnostics; Vol. 58; The Laser Institute of America; 1986 November 10-13. 7-15.

[25] Gibson, C.H.; Friehe, C.A.; McConnell, S.O. Phys. Fluids. 20(10, pt. 2): S156-S167; 1977 October.

[26] Chevray, R. Prog. Energy Combust. Sci. 8(4): 303-315; 1982.

[27] Drake, M.C.; Shyy, W.; Pitz, R.W. Superlayer contribution to conserved scalar PDFS in a H_2 turbulent jet diffusion flame. Presented at the Fifth Symposium on Turbulent Shear Flows; Ithaca, New York; 1985 August 7-9.

[28] Drake, M.C.; Pitz, R.W.; Shyy, W. J. Fluid Mech. 171: 27-51; 1986 October.

[29] List, E.J. Mechanics of turbulent buoyant jets and plumes. Turbulent Jets and Plumes, W. Rodi, ed. New York: Pergamon Press; 1982. 1-68.

[30] Chen, C.J.; Rodi, W . Vertical turbulent buoyant jets--a review of experimental data. New York: Pergamon Press; 1980. 88 p.

[31] Antonia, R.A.; Prabhu, A.; Stephenson, S.E. J. Fluid Mech. 72(3): 455-480; 1975 December 9.

[32] Chevray, R.; Tutu, N.K. J. Fluid Mech. 88(1): 133-160; 1978 Septemer 13.

[33] Catalano, G.D.; Morton, J.B.; Humphris, R.R. AIAA J. 14(9): 1157-1158; 1976 September.

[34] Pitts, William M. Effects of global density and Reynolds number variations on mixing in turbulent, axisymmetric jets. Nat. Bur. Stand. (U.S.) NBSIR 86-3340; 1986. 172 p.

[35] Thring, M.W.; Newby, M.P. Combustion length of enclosed turbulent jet flames. Fourth symposium (intl) on combustion. Pittsburgh, PA: The Standing Committee on Combustion; 1953. 789-796.

[36] Sunavala, P.D.; Hulse, C.; Thring, M.W. Com. Flame. 1(2): 179-193; 1972 June.

[37] Wilson, R.A.M.; Danckwerts, P.V. Chem. Eng. Science. 19: 885-895; 1964.

[38] Bilger, R.W. Prog. Energy Com. Science. 1(2/3): 87-109; 1976.

[39] Williams, F.A. Combustion Theory, 2nd ed. Reading, MA: Benjamin/Cummings; 1985. 680 p.

[40] Effelsberg, E.; Peters, N. Com. Flame. 50(3): 351-360: 1983 April.

[41] Gibson, C.H.; Chen, C.C.; Lin, S.C. AIAA J. 6(4): 642-649; 1968 April.

[42] Screenivasan, K. R.; Tavoularis, S. J. Fluid Mech. 101(4): 783-795; 1980 December 29.

[43] Vanquickenborne, L.; van Tiggelen, A. Com. Flame. 10(1): 59-69; 1966 March.

[44] Hall, L.; Horch, K.; Günther, R. Brennstoff-Wärme-Kraft. 32(1): 26-31; 1980 January.

[45] Günther, R.; Horch, K.; Lenze, B. The stabilization mechanism of free jet diffusion flames. First specialist meeting (intl) of the combustion institute. Pittsburgh, PA: The Combustion Institute; 1981. 117-122.

[46] Eickoff, H.; Lenze, B.;, and Leuckel, W. Experimental investigation on the stabilization of jet diffusion flames. Twentieth symposium (intl) on combustion. Pittsburg, PA: The Combustion Institute; 1984. 311-318.

[47] Kalghatgi, G.T. Com. Science. Tech. 41(1+2): 17-29; 1984.

[48] Byggstøyl, S.; Magnussen, B.F. A model for flame extinction in turbulent flow. Turbulent Shear Flows 4, eds. Bradbury, L.J.S. et al., Springer-Verlag, Berlin; 1985. 381-395.

[49] Janicka, J.; Peters, N. Prediction of turbulent jet diffusion flame lift-off using a PDF transport equation. Nineteenth symposium (intl) on combustion. Pittsburg, PA: The Combustion Institute; 1982. 367-374.

[50] Peters, N.; Williams, F.A. AIAA J. 21(3): 423-429; 1983 March.

[51] Peters, N. Partially premixed diffusion flamelets in non-premixed turbulent combustion. Twentieth symposium (intl) on combustion. Pittsburgh, PA: The Combustion Institute; 1984. 353-360.

[52] Broadwell, J.E.; Dahm, W.J.A.; Mungal, M.G. Blowout of turbulent diffusion flames. Twentieth symposium (intl) on combustion. Pittsburgh, PA: The Combustion Institute; 1984. 303-310.

[53] Kalghatgi, G.T. Com. Science Tech. 26(5 and 6): 233-239; 1981.

[54] Pitts, William M. The effects of global density and Reynolds number variations on mixing in turbulent, axisymmetric jets--implications for turbulent jet diffusion flames. Proceedings of the 2nd ASME/JSME Joint Thermal Engineering Conference, Book #10219S, Volume 1; Honolulu, HI 1987 March 23-27.

[55] Sobiesiak, A.; Brzustowski, T.A., On the structure of the stabilization region of lifted turbulent diffusion flames. Presented at the 1986 Spring Meeting of the Western States Section of the Combustion Institute, Banff, Canada; 1986 April 27-30.

[56] Wohl, K.; Gazley, C.; Kapp, N. Diffusion Flames. Third symposium on combustion, flame, and explosion phenomena. Baltimore, MD: Williams and Wilkins; 1949. 288-300.

[57] Savas, Ö.; Gollahalli, S.R. AIAA J. 24(7): 1137-1140; 1986 July.

[58] Chigier, N.A.; Strokin, V. Com. Science Tech. 9(3 and 4): 111-118; 1974.

[59] Ebrahimi, I.; Kleine, R. The nozzle fluid concentration fluctuation field in round turbulent free jets and jet diffusion flames. Sixteenth symposium (intl) on combustion. Pittsburgh, PA: The Combustion Institute; 1977. 1711-1723.

[60] Kennedy, I.M.; Kent, J.H. Measurements of a conserved scalar in turbulent jet diffusion flames. Seventeenth symposium (intl) on combustion. Pittsburgh, PA: The Combustion Institute; 1979. 279-287.

[61] Drake, M.C.; Bilger, R.W.; and Stårner, S.H. Raman measurements and conserved scalar modeling in turbulent diffusion flames. Nineteenth symposium (intl) on combustion. Pittsburgh, PA: The Combustion Institute; 1982. 459-467.

[62] Lenze, B. and Günther, R. Brennstoff-Wärme-Kraft. 27(10): 387-394; 1975 October.

[63] Günther, R. Prog. Energy Com. Science. 9(1/2): 105-154; 1983.

[64] Becker, H.A. and Yamazaki, S. Com. Flame. 33(2): 123-149; 1978.

[65] Grinstein, F.F.; Oran, E.S.; Boris, J.P. AIAA J. 25(1): 92-98; 1987 January.

[66] Ghoniem, A.F. and Sethian, J.A. AIAA J. 25(1): 168-171: 1987 January.

[67] Lockwood, F.C. and Moneib, H.A. Com. Flame. 47(3): 291-314; 1982 September.

TABLE 1

Experimental Parameters

Jet/Coflow	ρ_o/ρ_∞	Re	Experiments (R = Rayleigh, S = Shadowgraph)
He/air	0.14	3950	R,S
CH_4/air	0.55	3950	R,S
C_3H_8/CO_2	1.02	3960	R,S
C_3H_8/air	1.55	3960	R,S
C_3H_8/air	1.55	7890	R,S
C_3H_8/air	1.55	11860	R,S
CF_4/air	3.01	3960	R
CF_4/air	3.01	7920	R
SF_6/air	5.11	3950	R,S
SF_6/air	5.11	7890	R,S
SF_6/air	5.11	11860	R,S
SF_6/He	37.0	3960	R,S

FIGURE CAPTIONS

Figure 1. The experimental configuration for real-time Rayleigh light scattering "point" measurements of concentration in binary gas mixtures is shown schematically. The flow system consists of a 6.35 mm diameter pipe with a sharpened edge enclosed within a 100 X 100 cm^2 square cylinder.

Figure 2. The quality of the data which can be acquired utilizing the Rayleigh light scattering technique for concentration is demonstrated. Radial profiles of concentration (in both mole and mass fraction terms) are plotted for a turbulent CH_4 jet flowing into a slow coflow of air. The downstream distance is $z/r_o = 35$ and the Reynolds number is 3950.

Figure 3. Partial time-resolved data records recorded during a simultaneous Rayleigh light scattering and hot-film anemometry experiment are reproduced for a propane jet (Re = 3960) flowing into a slow coflow of air. The observation volume is located on the jet centerline at $z/r_o = 31.5$. The light scattering signals have been calibrated and are plotted in terms of mole fraction of propane. The raw data for the anemometer output is plotted along with the velocity calculated utilizing the calibrations of film response to changes in velocity and gas composition.

Figure 4. The correlation is shown for the heat transfer from a hot-wire as a function of flow velocity for nine different gases. Experimental measurements are nondimensionalized by the use of the Nusselt number and Reynolds number. Corrections have been included for heat losses to the prongs of the hot-wire and thermal slip and accommodation effects at the surface of the probe. $(K_B)_x$ and $(K_A)_x$ are coefficients which are necessary to compensate for variations in molecular properties from gas to gas.

Figure 5. The camera which has been developed for recording real-time Rayleigh light scattering intensity along a line is shown. The top portion indicates the major components and their configuration. The actual appearance of the camera is shown below.

Figure 6. The overall experimental configuration for real-time measurements of concentration along a line in turbulent flows is represented. Rayleigh light scattering is induced along a line in the flow field by the Ar^+ ion laser. Light scattering at 90° is recorded by the digital line camera system consisting of the line camera shown in figure 5, suitable interfaces, and a data acquisition minicomputer.

Figure 7. An example of time-resolved line measurements of propane mole fraction across a turbulent jet of propane (Re = 3960) flowing into a coflow of air is reproduced. Propane mole fraction is represented by a seven level gray scale. The downstream position is 5 diameters and the line read out rate is 830 Hz.

Figure 8. Time-averaged radial profiles of propane mole fraction are shown for five downstream positions in the development region of a propane (Re = 3960) jet flowing into a slow coflow of air. The growth of the boundary layers on either side of the potential core with increasing z and decrease of centerline concentration at the end of the potential core can be clearly observed. It is interesting to note that the data displayed represents 164,000 individual concentration measurements which were recorded during 1.54 s of actual acquisition time.

Figure 9. The apparatus for recording time-resolved shadowgraphs is represented schematically. The light pulse generated by the chopper has a temporal profile which is triangular in shape and has a total duration of 310 μs.

Figure 10. Three time-resolved shadowgraphs are shown for a SF_6 jet (Re = 3950) flowing into a slow coflow of air. Three different downstream positions recorded at different times are represented. Note particularly the formation of a fountain by the SF_6 at a downstream position of $\approx 37.5\ r_o$.

Figure 11. Shadowgraphs are reproduced for jets of SF_6 (Re = 7890 and 11,860) entering slow coflows of air. For each jet four views of the flow recorded at different times and positions in the jet are superimposed. Note that the fine scale turbulence becomes more pronounced with increasing Re, but that the overall spreading rate of the jet does not appear to be affected.

Figure 12. Five sets of superimposed shadowgraphs are shown for jets of one gas flowing into a second gas. With the exception of the SF_6 flow, the Reynolds numbers are roughly the same. The effects of variations in the global density ratio appear as changes in the development region of the flow and modifications in the eddy structure at downstream positions where the flows are close to fully-developed.

Figure 13. Superimposed shadowgraphs are reproduced for propane jets at three Re entering into slow coflows of air. The development of finer turbulent scales with increasing Re can be clearly seen. It is also evident that increasing the Re results in a shortening of the distance required for the development of vortical structures near the nozzle. The overall spreading behavior of the jets is independent of Re supporting the supposition that entrainment is determined by large scale turbulent structures.

Figure 14. Values of $Y_o/\overline{Y}_m$ ($\overline{Y}_c = \overline{Y}_m$ is the centerline concentration at z/r_o and Y_o is the mass fraction of jet fluid at the jet exit) are plotted as a function of z/r_o for six different jet/coflow gas combinations. The solid lines are linear least squares fits of the results. Note the decreasing slopes and upstream movement of the virtual origins (z where $Y_o/\overline{Y}_c \to 0$) which occur as the jet/coflow density ratio is increased.

Figure 15. Predicted values of inverse centerline mass fraction (denoted as $1/\bar{C}_m$) based on the analysis of Thring and Newby [35] are plotted as functions of z/r_o for the six jet/coflow gas pairs which have been experimentally investigated. Comparison of figures 14 and 15 shows that there is good agreement between prediction and experiment.

Figure 16. Values of centerline unmixedness are plotted as a function of z/r_o for the six jet/coflow gas pairs listed. Values of $Y_m'/\bar{Y}_m$ for each jet approach a common asymptote of ≈ 0.23, but the flow distance required increases dramatically as the jet/coflow density ratio increases.

Figure 17. The centerline unmixedness values shown in figure 16 are replotted as a function of z/r_ϵ. The collapse of the data onto a single curve suggests that r_ϵ is the proper scaling parameter for correlating the growth of unmixedness in these variable density flows.

Figure 18. Centerline unmixedness values for three different Re jets of propane entering slow coflows of air are plotted as functions of z/r_o. Flows at higher Re require longer flow distances in order to achieve the asymptotic value of unmixedness even though the value of the asymptote does not change.

Figure 19. The concentration contour corresponding to that for which the laminar flame speed of an ethylene/air mixture is a maximum (Y_1 = 0.073) is plotted as functions of z/r_o and r/r_o. The virtual origin for the plot is assumed to be at z = 0. Two representations are shown. On the right the radial and axial axes have the same scaling, while on the left the radial scale is expanded by a factor of 5.

Figure 20. Experimental values [47] of lift-off height (h) are plotted against jet exit velocity for turbulent jet flames of methane, ethylene, and propane. These measured values are compared with values (solid lines) predicted using eq. (5) and the known velocity and mixing behaviors of the jets. The agreement is excellent.

Figure 21. Experimental [53] (symbols) and calculated values (lines) of blow out velocity are plotted as a function of jet radius for axisymmetric turbulent jet flames of five organic fuels. Calculated values are derived by using eqs. (6) and (7). The agreement of the predicted values with experiment is very good.

Figure 22. Approximate radial density profiles for three nondimensional downstream distances are shown for turbulent jet diffusion flames of hydrogen and a typical organic fuel (methane). These curves are based on measurements reported by several different authors [63,67].

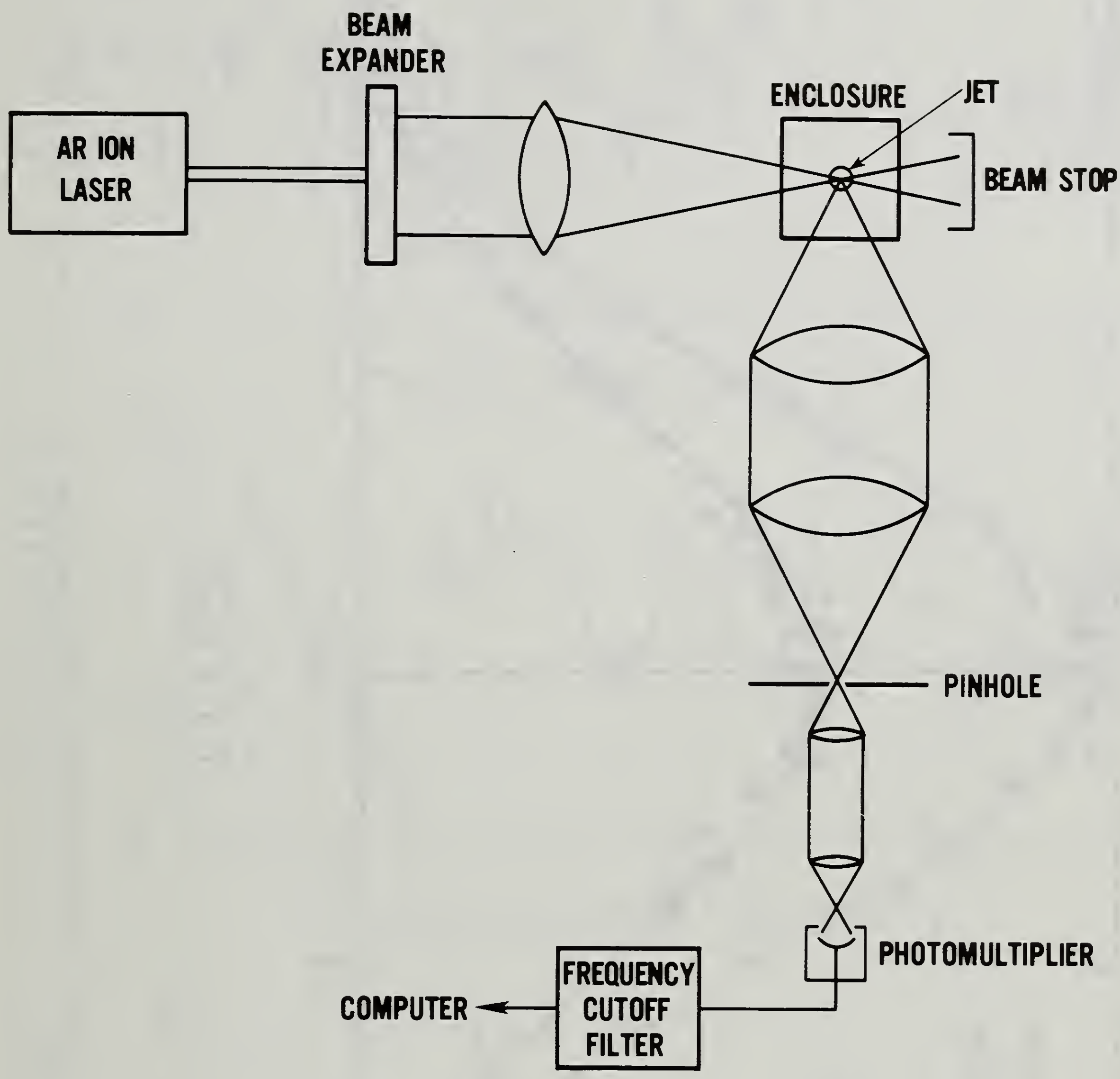


Figure 1. The experimental configuration for real-time Rayleigh light scattering measurements of concentration.

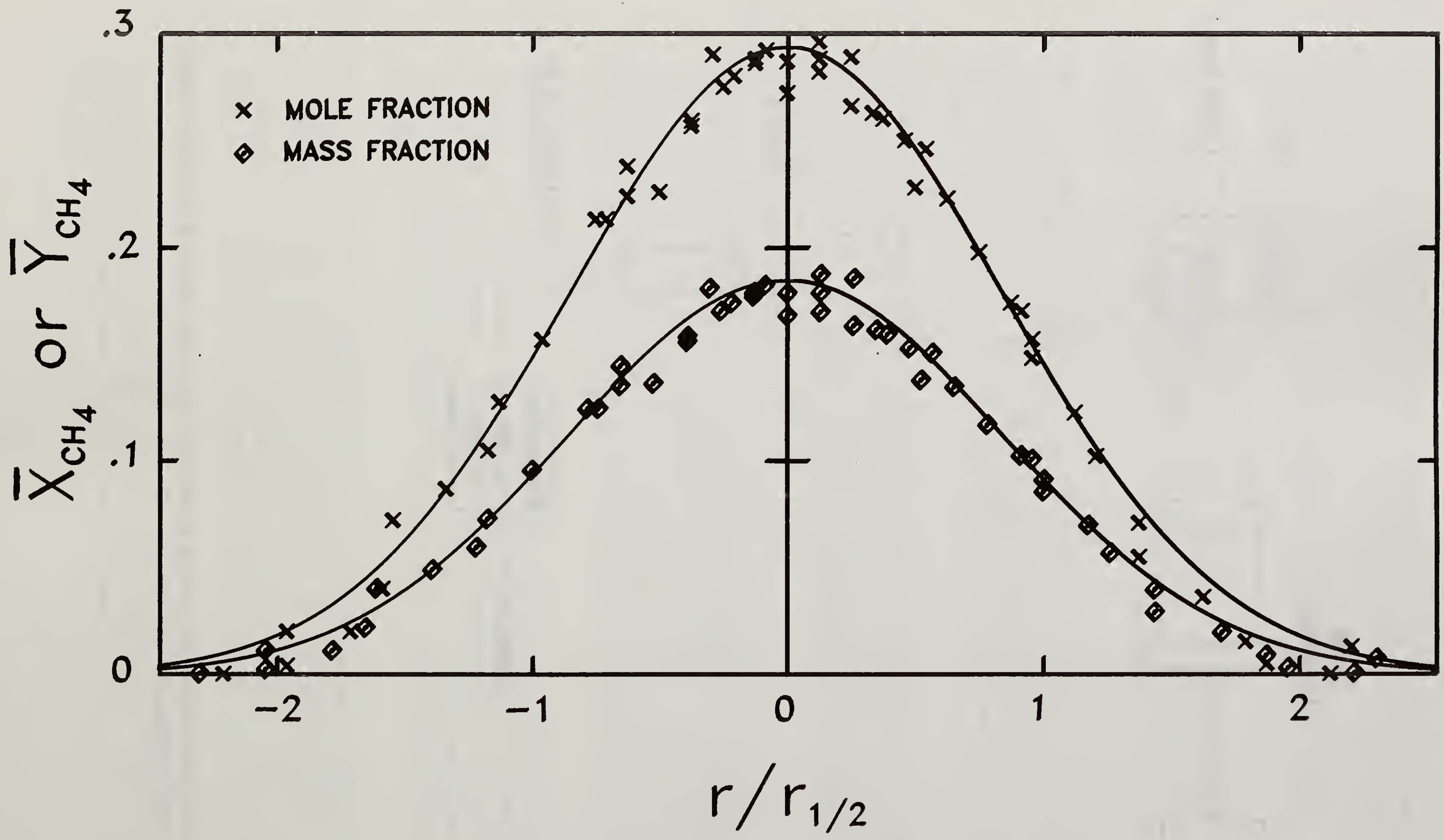


Figure 2. Radial profiles of concentration are plotted for a turbulent CH_4 jet flowing into a slow coflow of air.

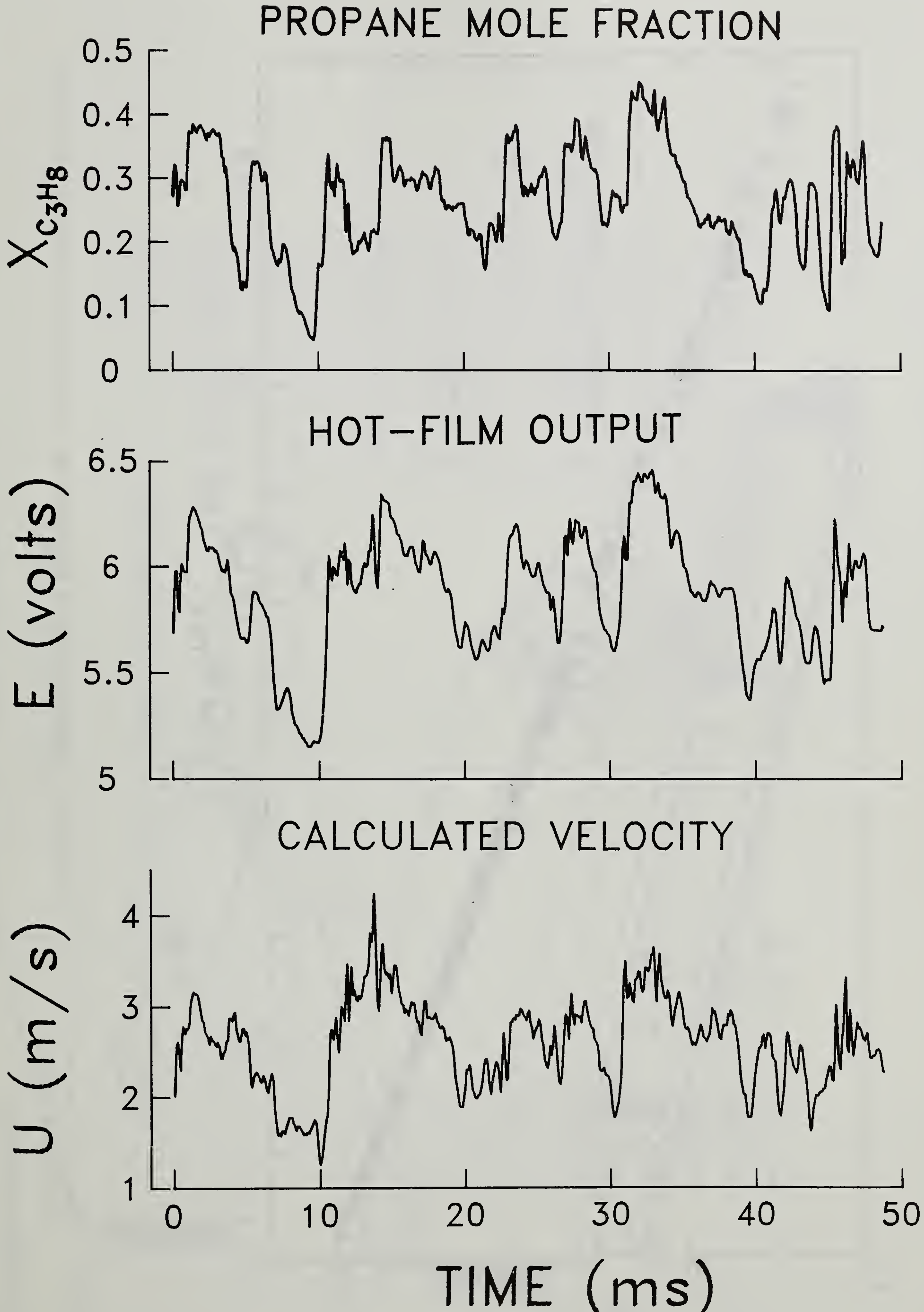


Figure 3. Partial time-resolved data records recorded during a simultaneous Rayleigh light scattering and hot-film anemometry experiment.

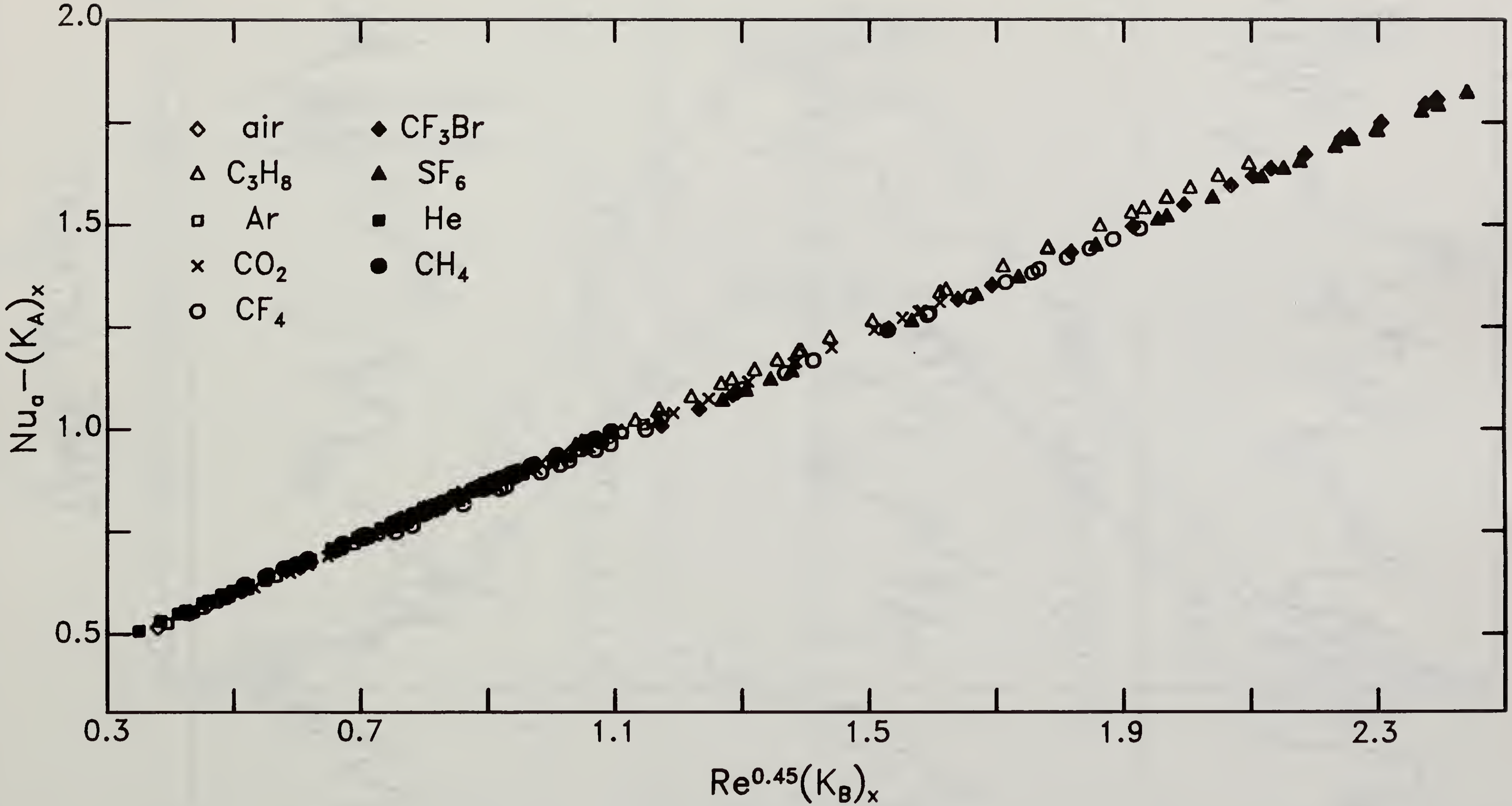


Figure 4. The correlation is shown for the heat transfer from a hot-wire as a function of velocity for nine different gases.

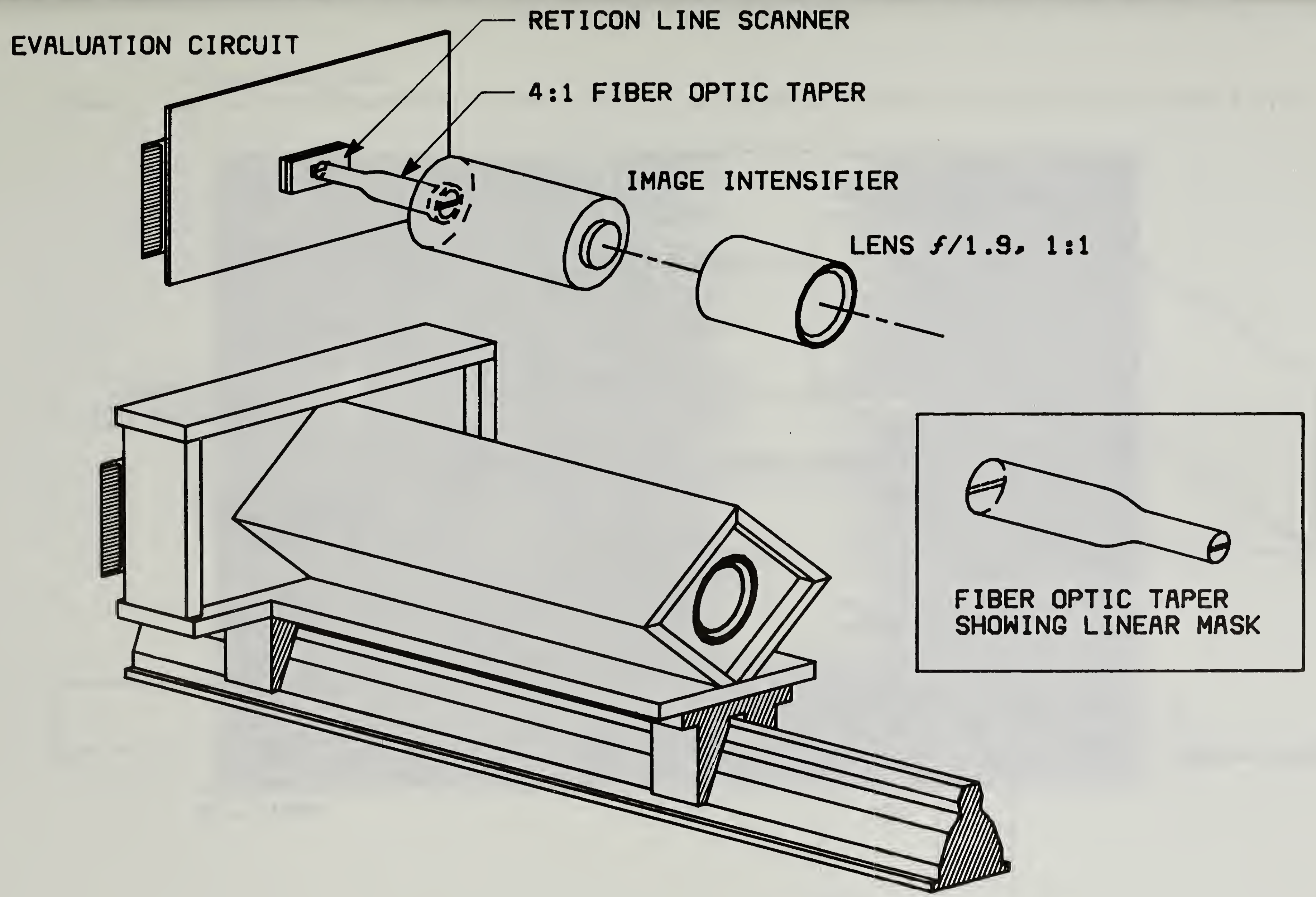


Figure 5. The camera for recording real-time Rayleigh light scattering intensity along a line is shown.

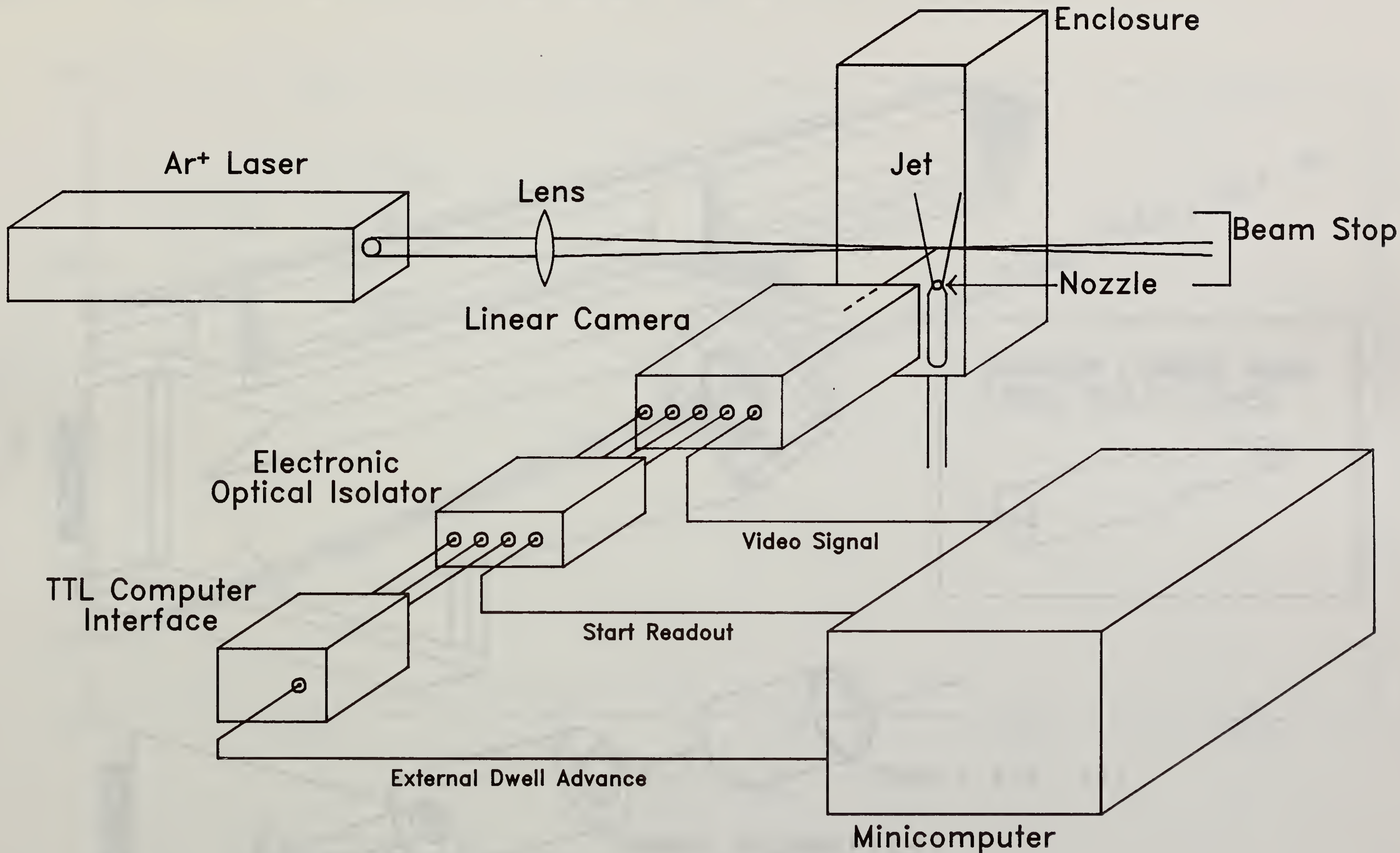


Figure 6. The overall experimental configuration for real-time measurements of concentration along a line in turbulent flows.

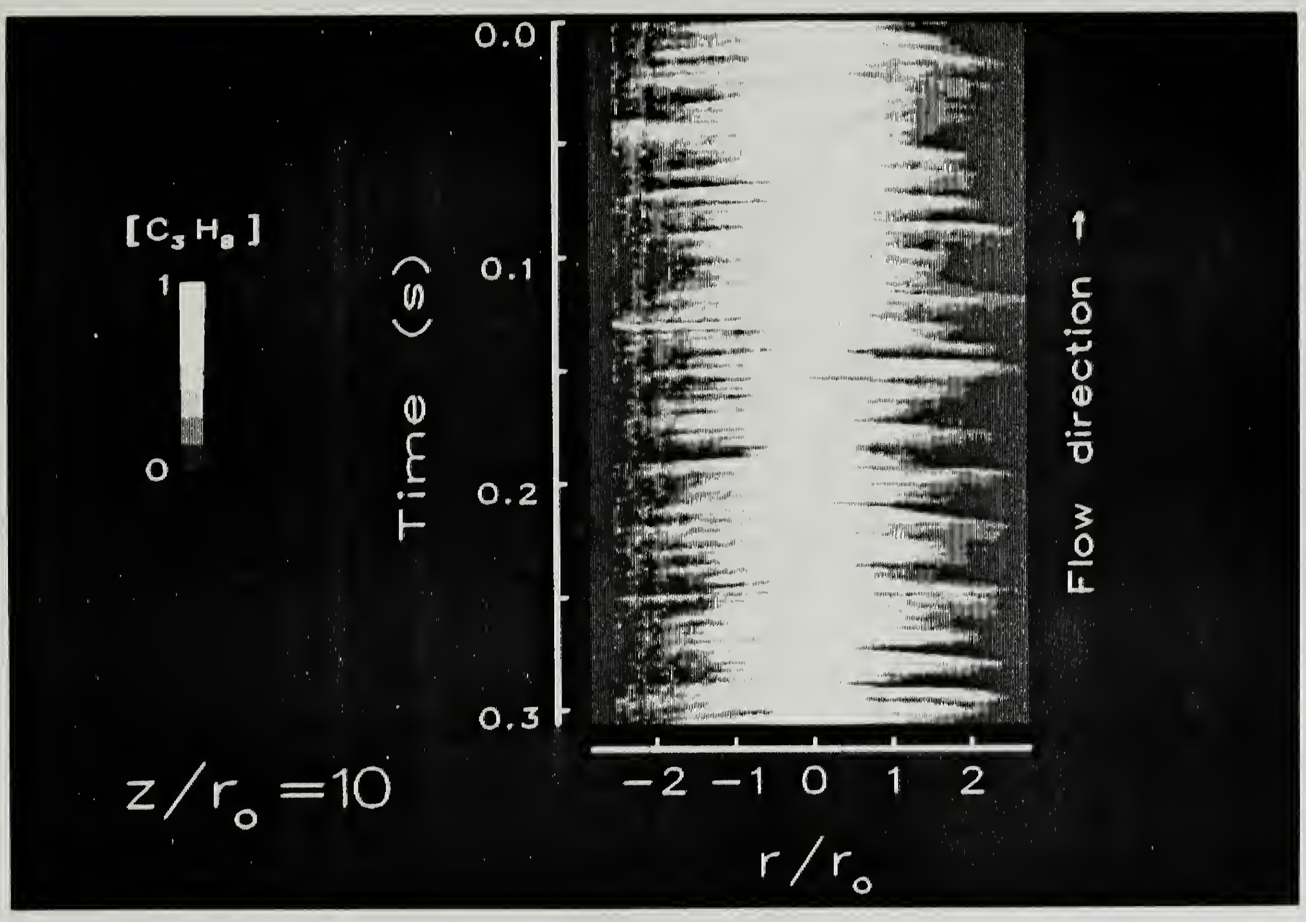


Figure 7. An example of time-resolved line measurements of mole fraction across a turbulent jet of C_3H_8.

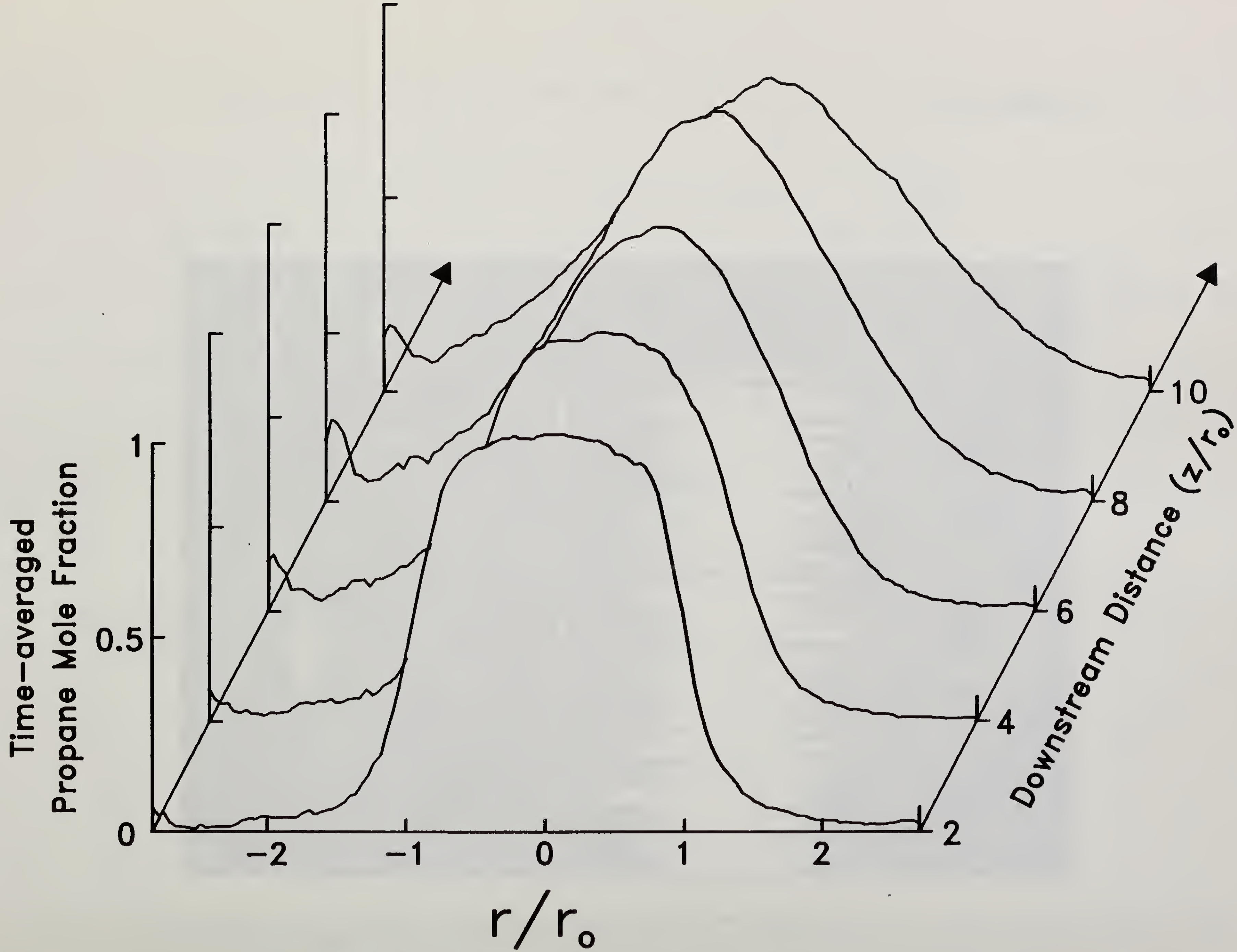


Figure 8. Time-averaged radial profiles of mole fraction are shown for a propane jet flowing into air.

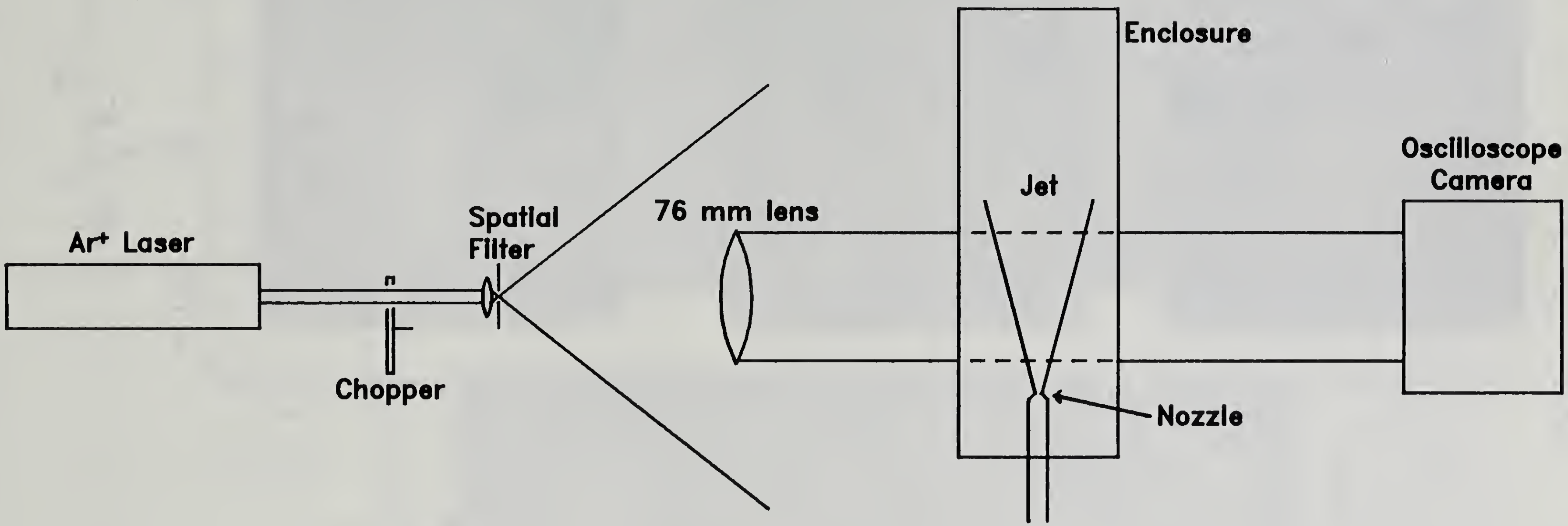


Figure 9. The apparatus for recording time-resolved shadowgraphs is represented schematically.

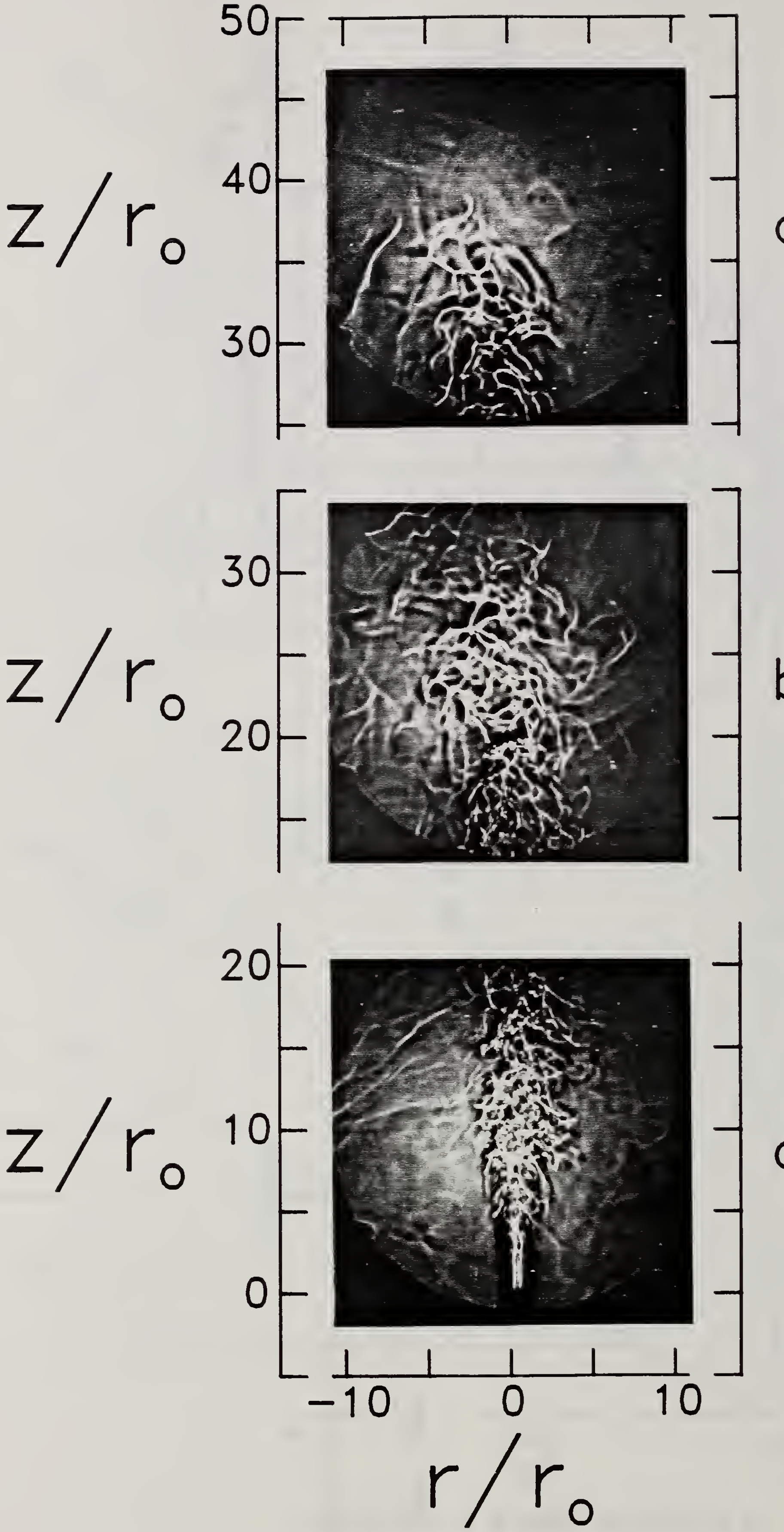


Figure 10. Three time-resolved shadowgraphs are shown for a SF_6 jet (Re = 3950) flowing into a slow coflow of air.

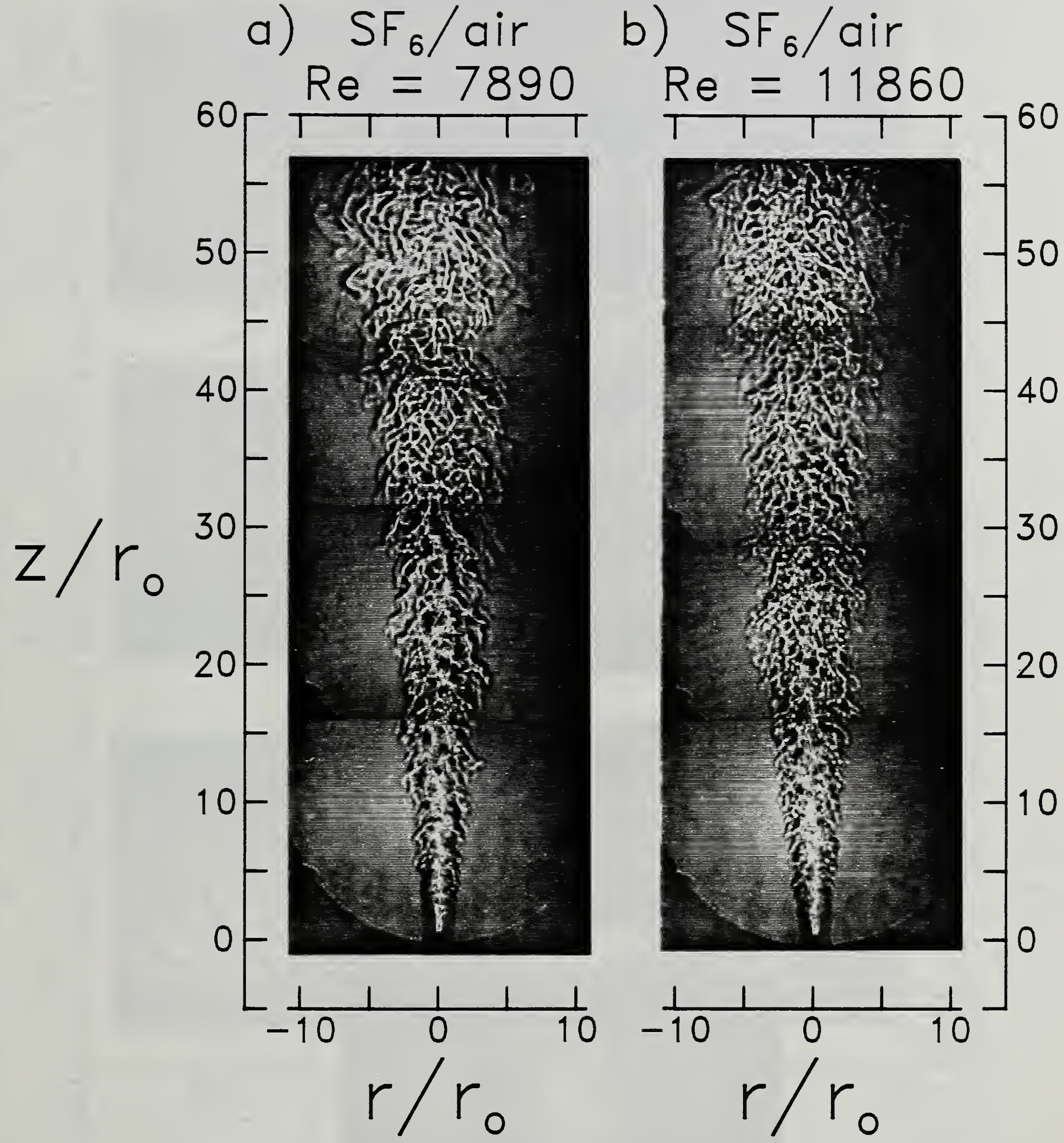


Figure 11. Shadowgraphs are reproduced for jets of SF_6 entering slow coflows of air.

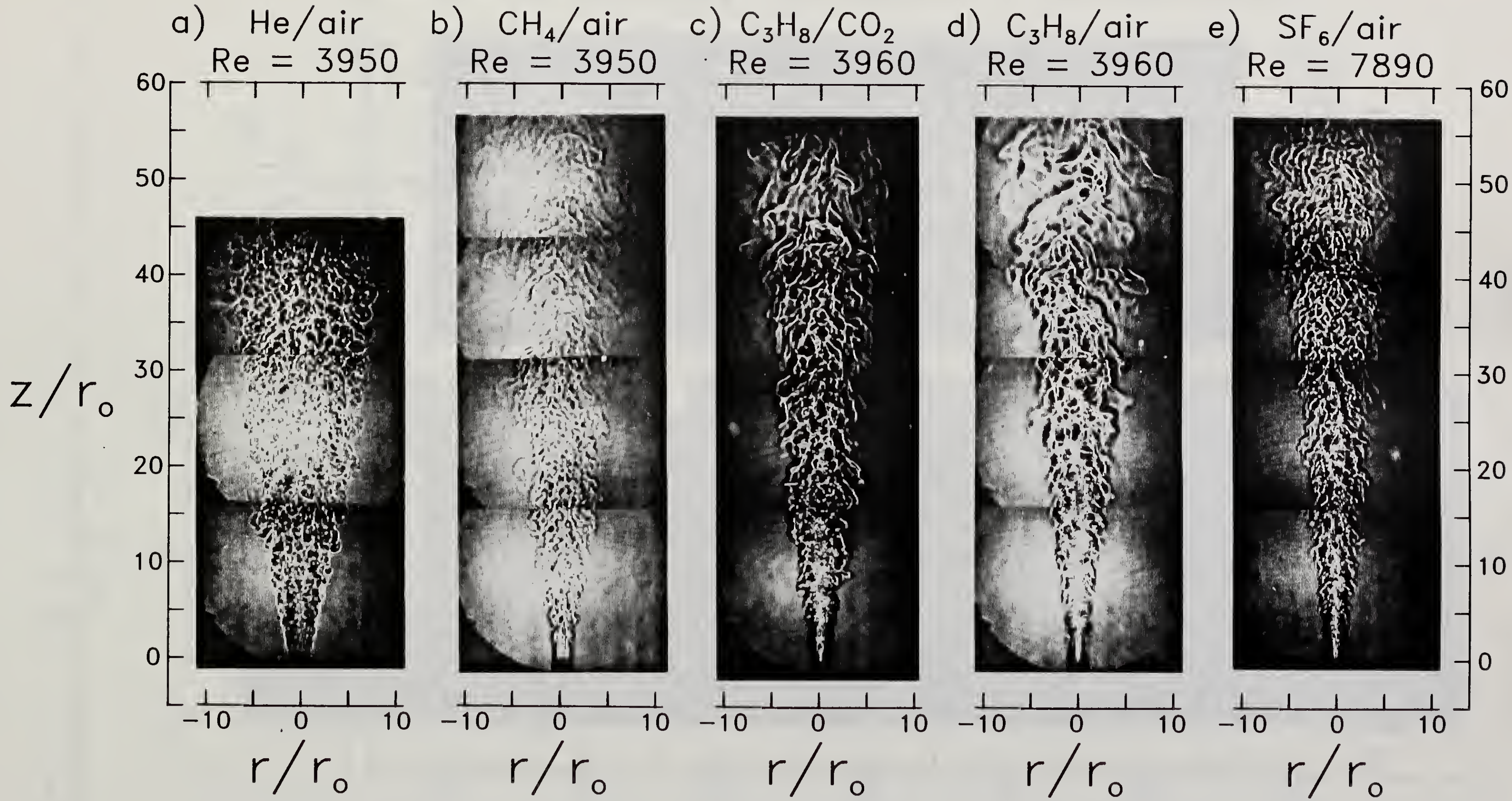


Figure 12. Superimposed shadowgraphs are shown for jets of one gas flowing into a second gas.

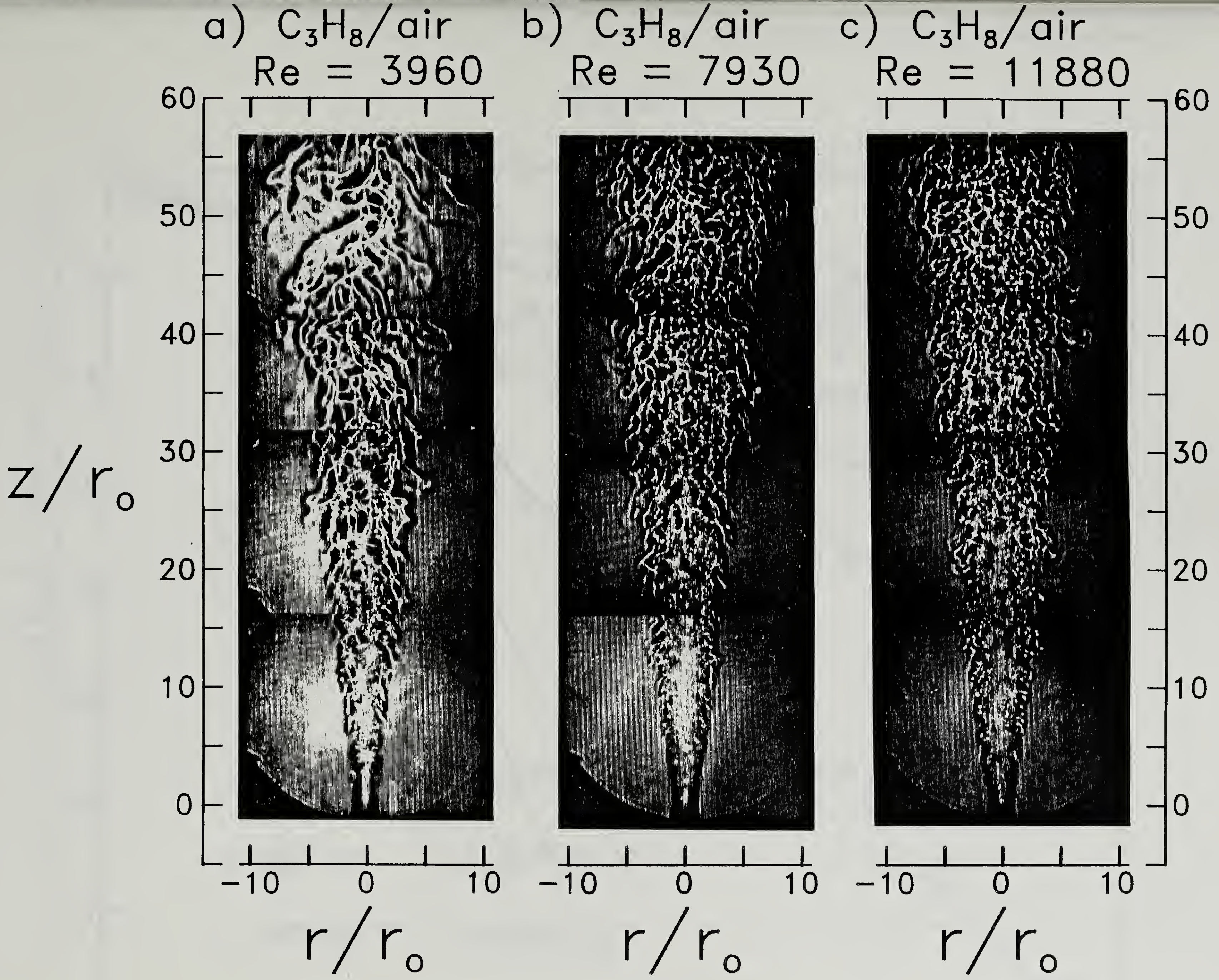


Figure 13. Superimposed shadowgraphs for propane jet at three Re entering slow coflows of air.

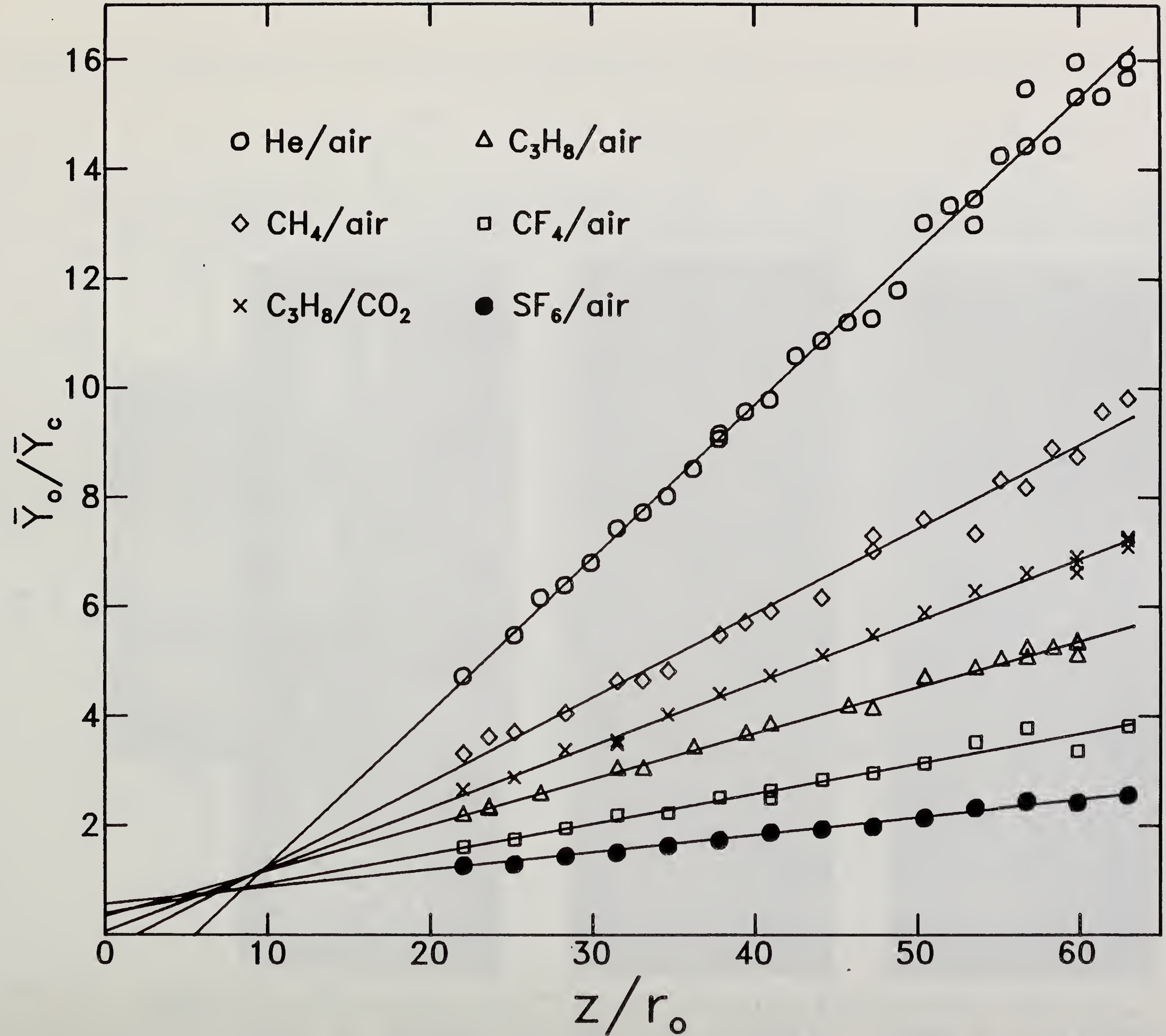


Figure 14. Values of $Y_o/\bar{Y}_m$ are plotted as a function of z/r_o for six different jet/coflow gas combinations.

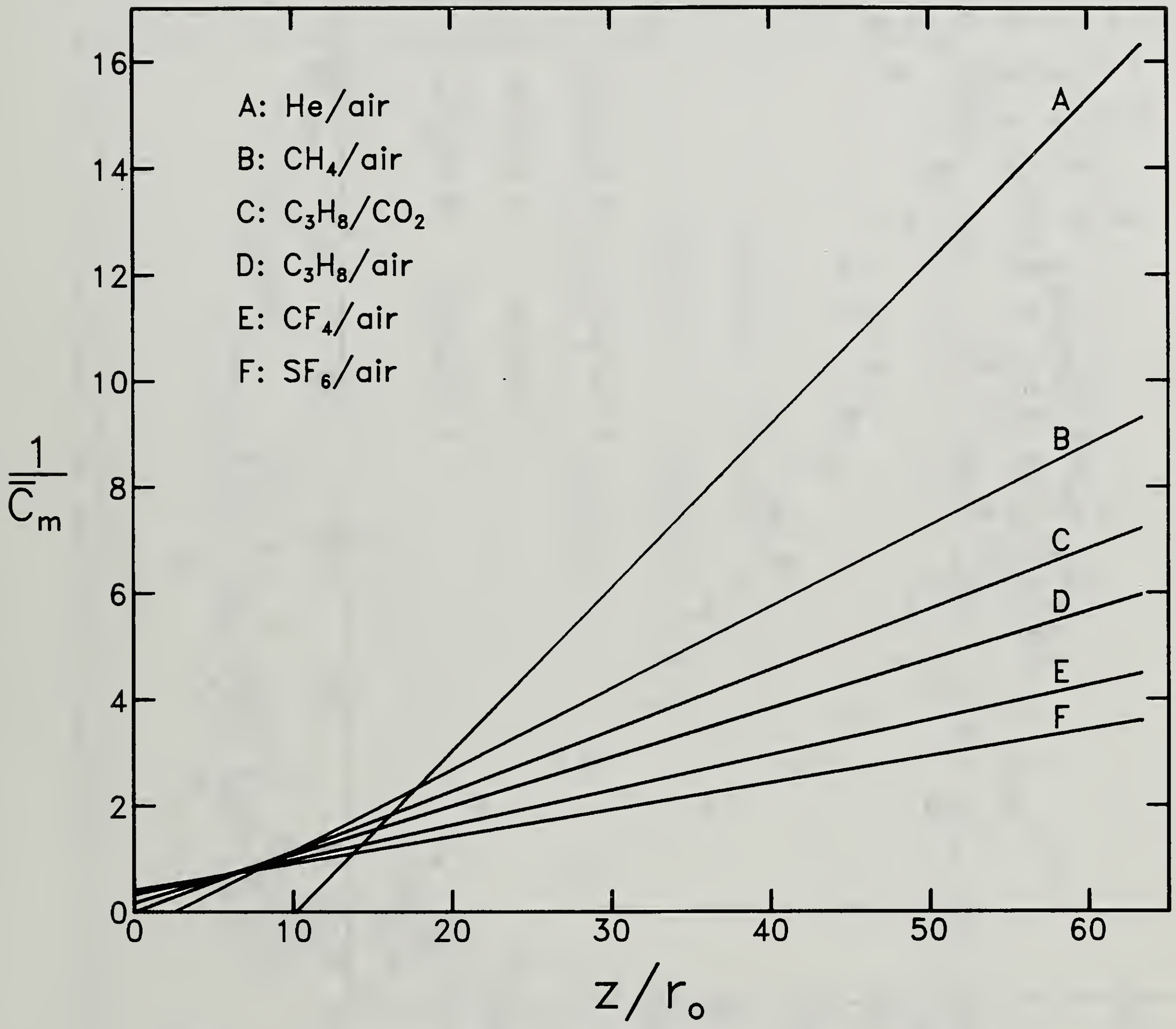


Figure 15. Predicted values of inverse centerline mass fraction based on the analysis of Thring and Newby.

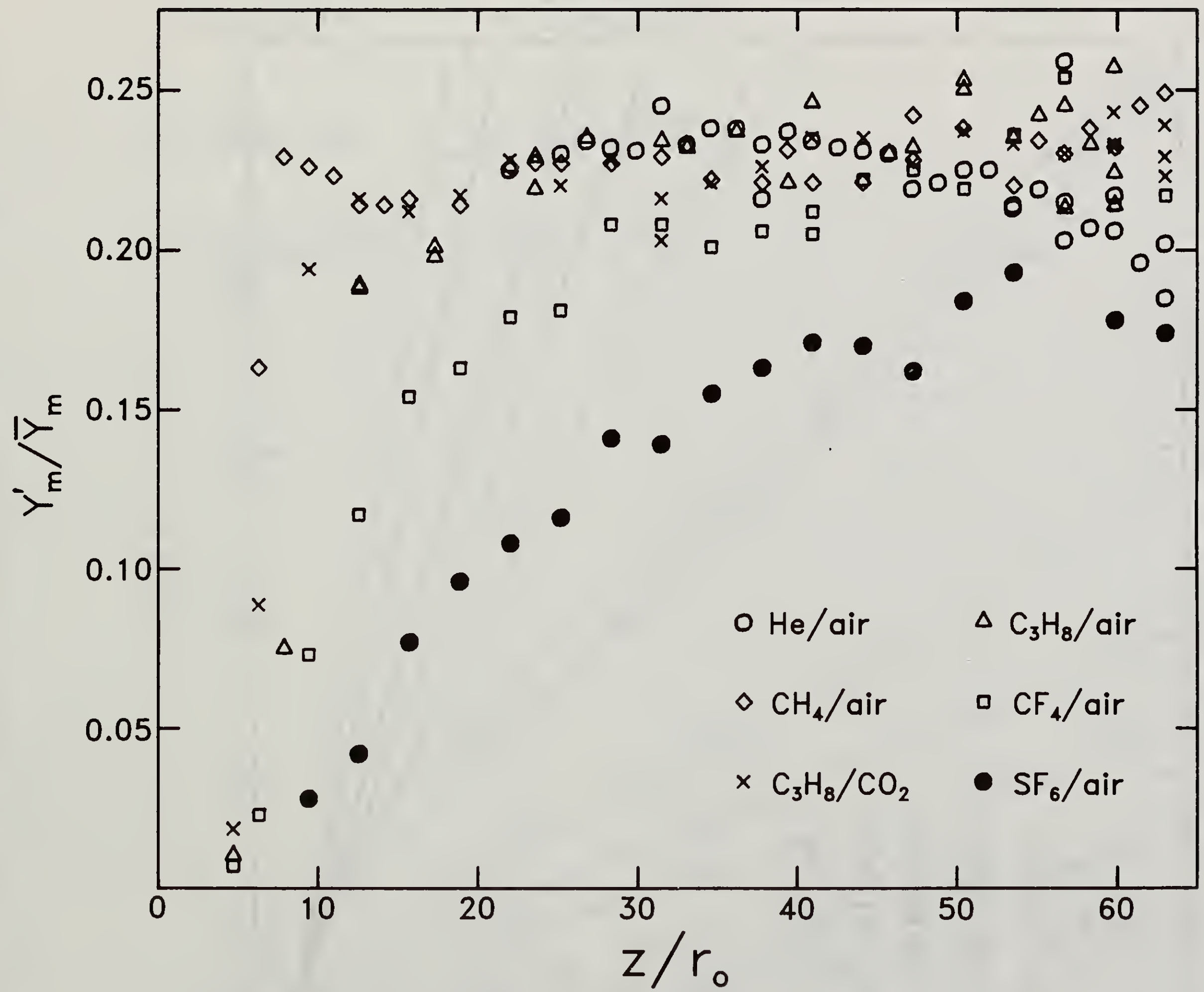


Figure 16. Values of centerline unmixedness are plotted as a function of z/r_o for the jet/coflow pairs listed.

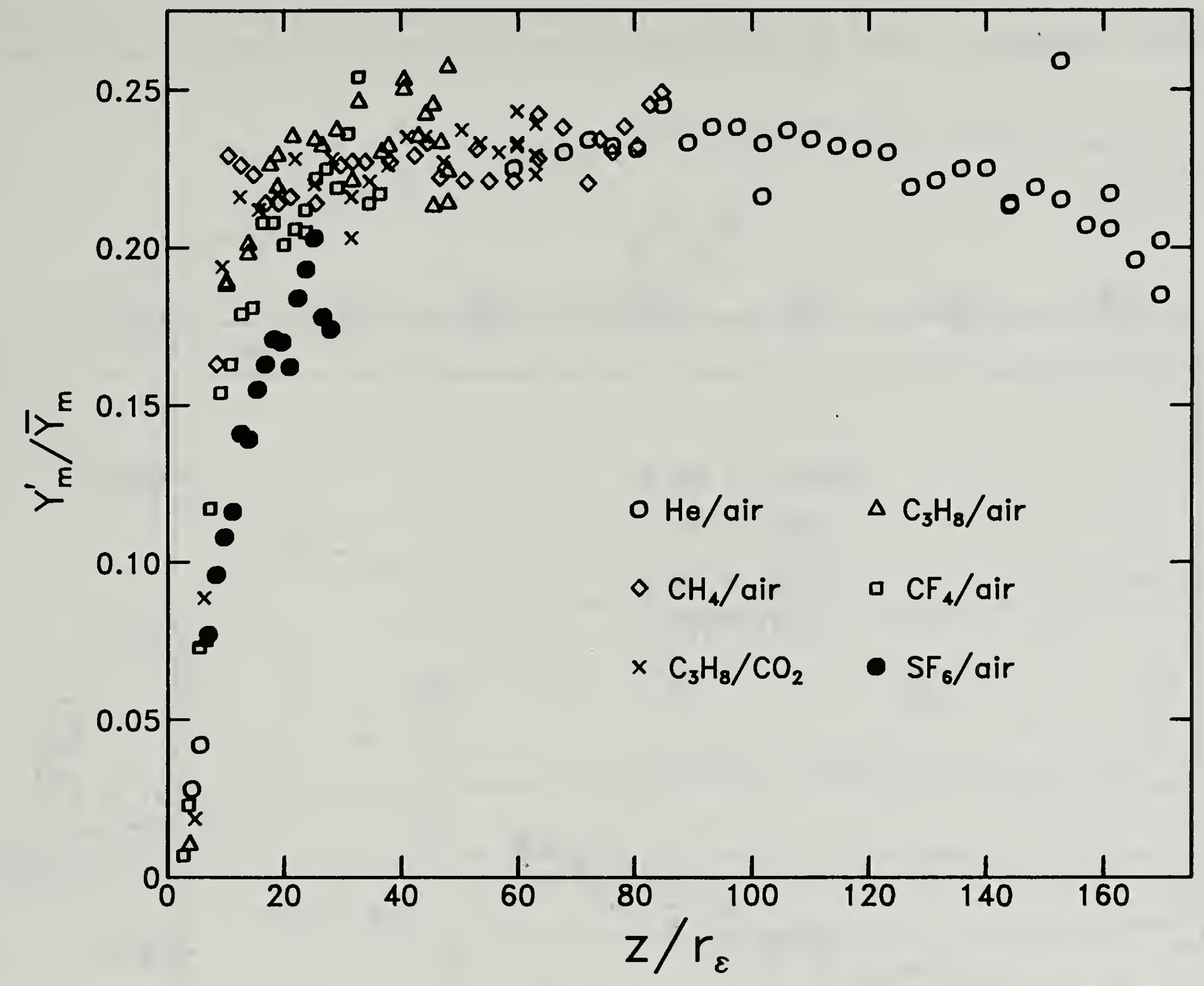


Figure 17. The centerline unmixedness values shown in figure 16 are replotted as a function of z/r_ϵ.

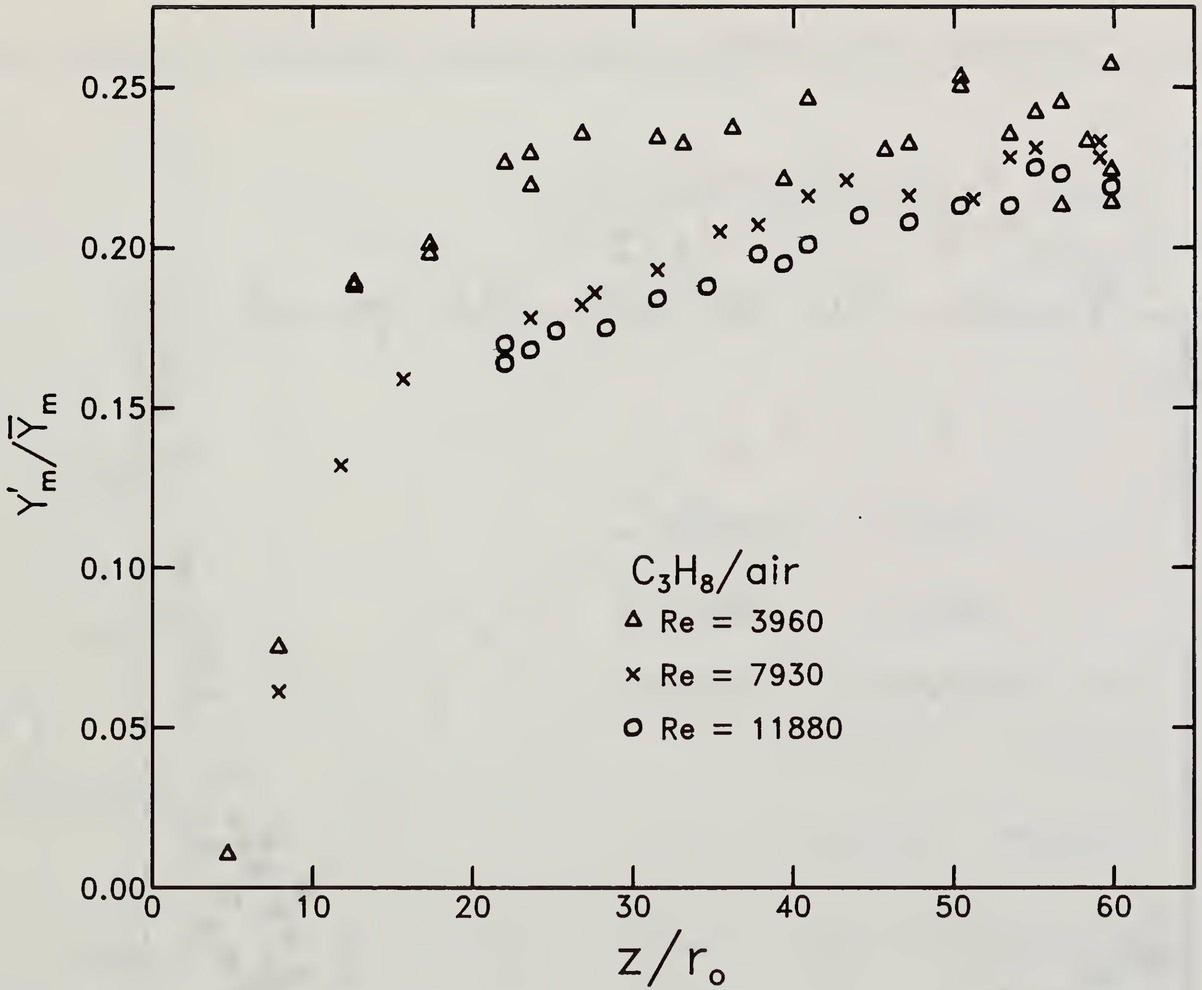


Figure 18. Centerline unmixedness values for three different Re jets of propane entering slow coflows of air are plotted as functions of z/r_o.

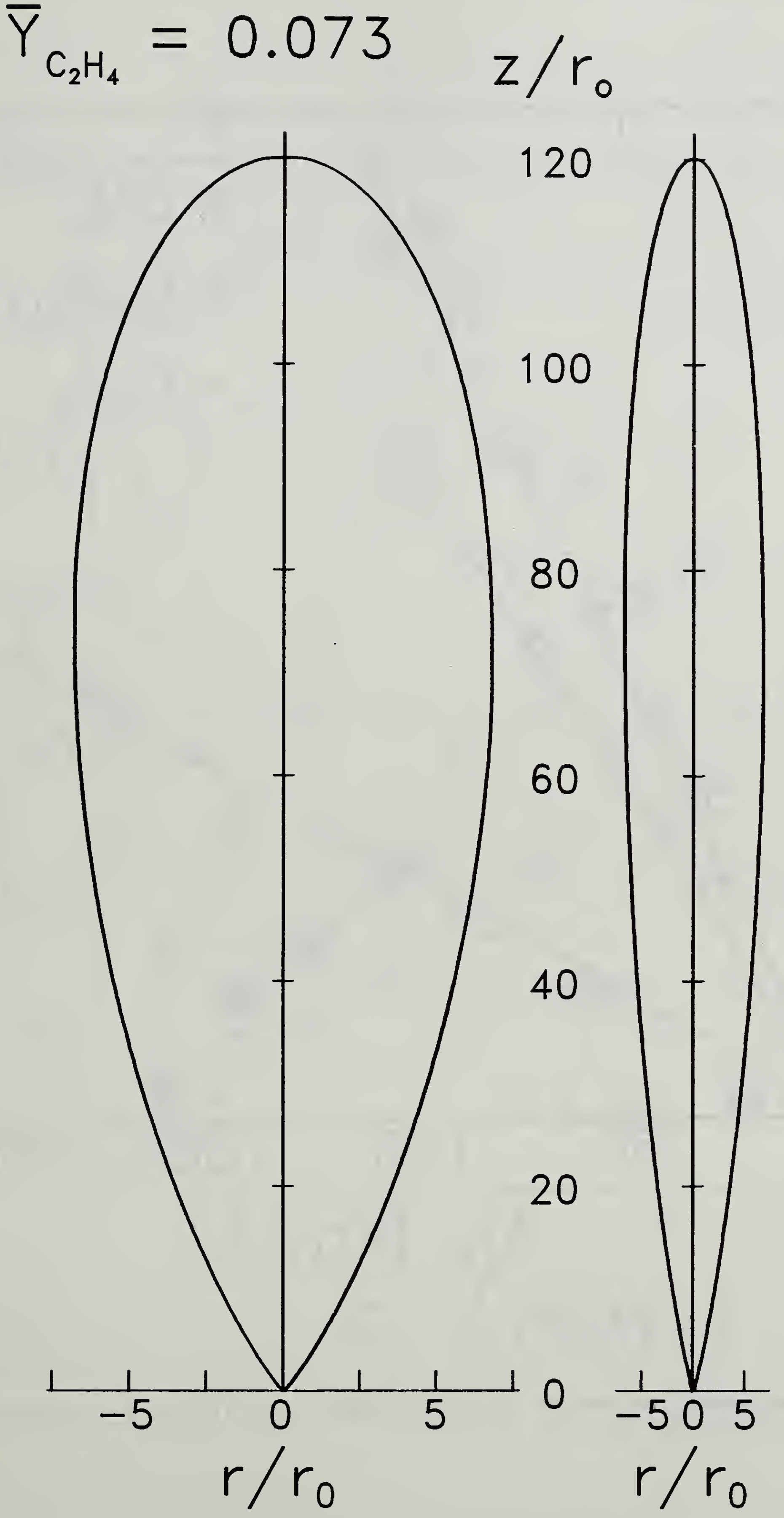


Figure 19. The concentration contour for which the laminar flame speed of an ethylene/air mixture is a maximum.

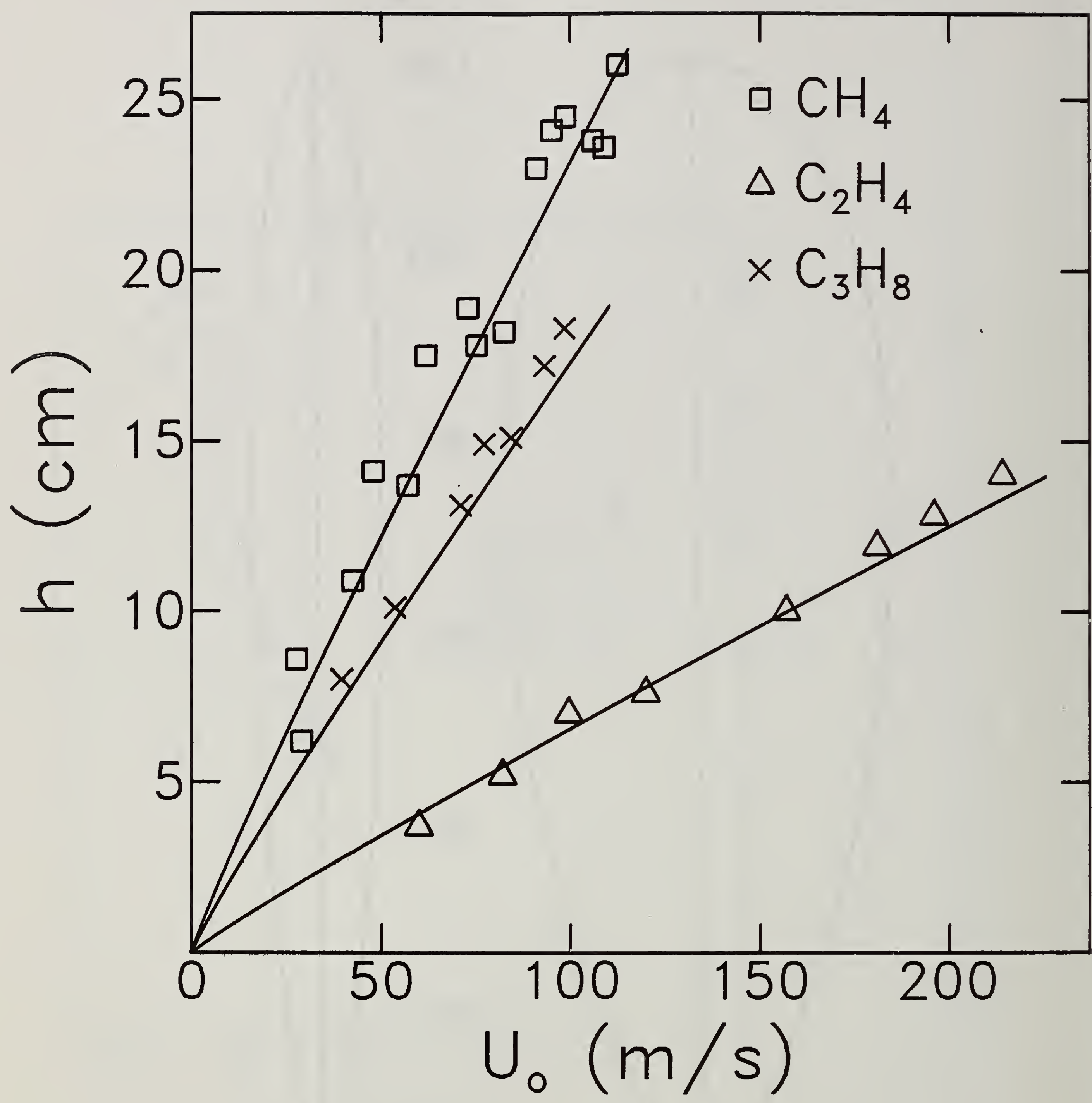


Figure 20. Experimental values of lift-off height (h) are plotted against jet exit velocity.

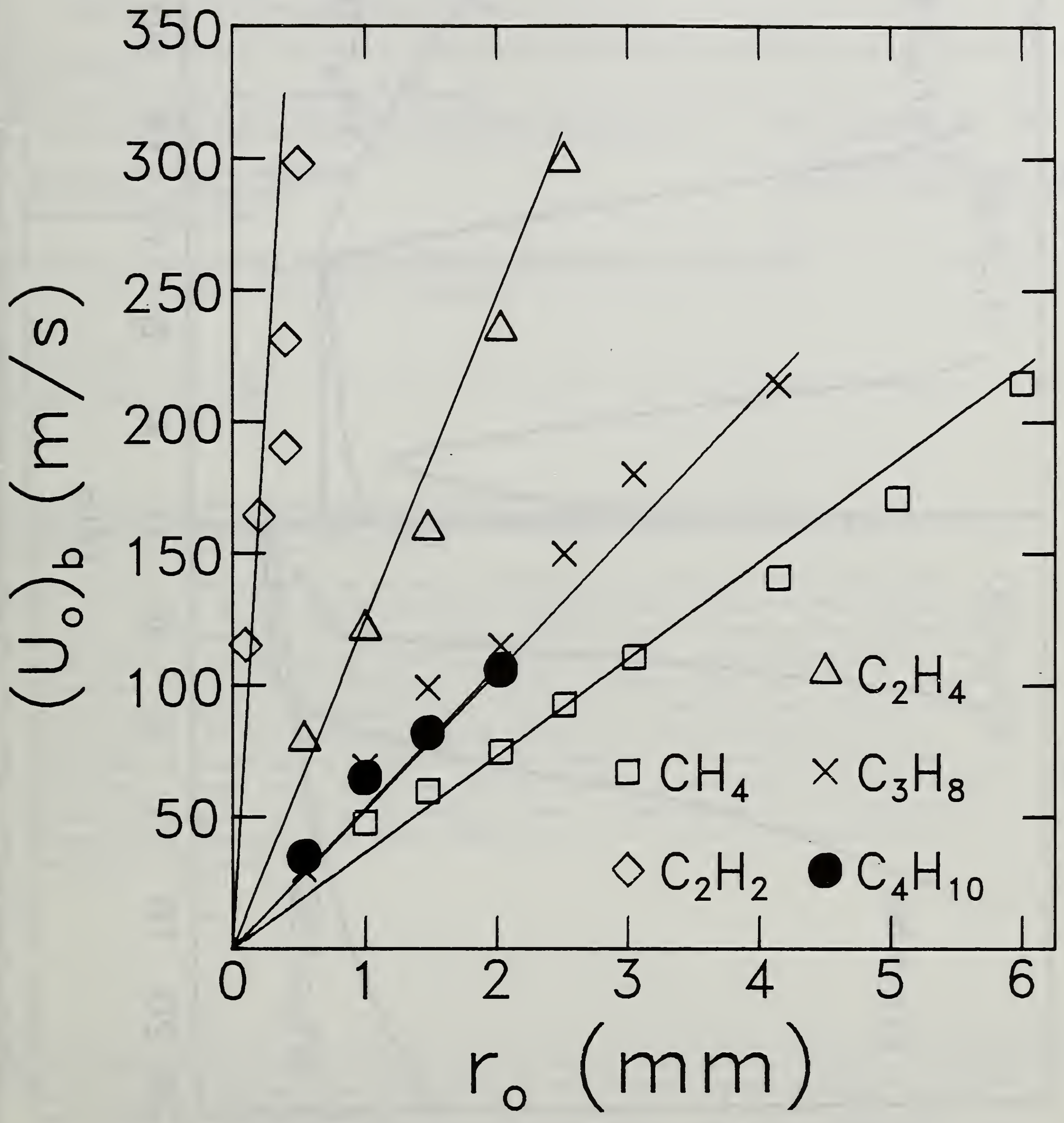


Figure 21. Experimental [53] (symbols) and calculated values (lines) of blow out velocity are plotted.

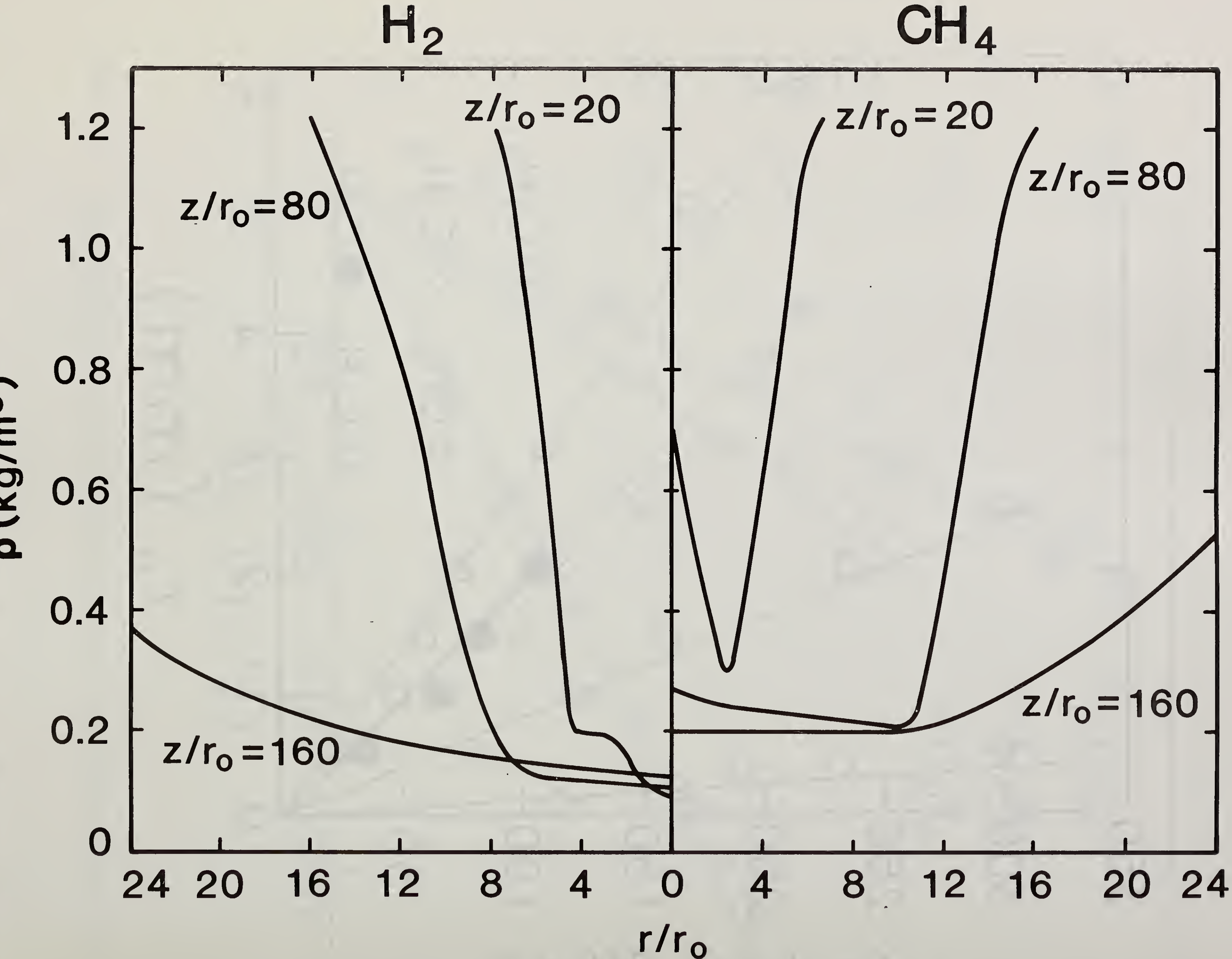


Figure 22. Approximate radial profiles for three nondimensional downstream distances are shown for turbulent jet diffusion flames of hydrogen and a typical organic fuel (methane).

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** *(See instructions)*	1. PUBLICATION OR REPORT NO. NBSIR-87/3550	2. Performing Organ. Report No.	3. Publication Date JUNE 1987

4. TITLE AND SUBTITLE

Mixing in Variable Density, Isothermal Turbulent Flow and Implications for Chemically Reacting Turbulent Flows

5. AUTHOR(S)

William M. Pitts and Takashi Kashiwagi

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No. ISSA-86-00008

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Air Force Office of Scientific Research
Bolling AFB
Building 410
Washington, DC 20332

10. SUPPLEMENTARY NOTES

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

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

This report summarizes the research findings of a project which has been jointly funded by the Air Force Office of Scientific Research and the National Bureau of Standards. The goal of the research was to improve the fundamental understanding of chemically reacting turbulent flow. The approach which was taken was to investigate mixing in variable density flows in order to better understand the role of local density fluctuations (which result from chemical heat release) on the turbulent mixing behavior. The development of new experimental diagnostics having excellent spatial and temporal resolution is described. These techniques have been utilized to investigate a wide range of mixing properties in variable density flows. These results are summarized along with a discussion of their importance to an improved understanding of chemically reacting flow.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

concentration fluctuations; concentration measurement; density effects; digital line camer; flow visualization; hot wire anemometry; jet flames; Rayleigh light scattering; Reynolds number; turbulent flames; velocity measurement

13. AVAILABILITY

[X] Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
[X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES 73

15. Price $13.95

USCOMM-DC 6043-P80