

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20000920147

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                    | READ INSTRUCTIONS<br>BEFORE COMPLETING FORM                                              |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------|------------------------------------------------------------------------------------------|
| 1. REPORT NUMBER<br>HDL-TM-82-10                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 2. GOVT ACCESSION NO.<br>ADA121430 | 3. RECIPIENT'S CATALOG NUMBER                                                            |
| 4. TITLE (and Subtitle)<br>Fluerics 42: Some Commonly Used Laminar<br>Fluidic Gain Blocks                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                    | 5. TYPE OF REPORT & PERIOD COVERED<br>Technical Memorandum                               |
| 7. AUTHOR(s)<br>Tadeusz M. Drzewiecki                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                                    | 6. PERFORMING ORG. REPORT NUMBER                                                         |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>U.S. Army Materiel Development and<br>Readiness Command<br>Alexandria VA 22333                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                    | 8. CONTRACT OR GRANT NUMBER(s)<br>PRON: 1F2P0001011FA9                                   |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Harry Diamond Laboratories<br>2800 Powder Mill Road<br>Adelphi, MD 20783                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                    | 10. PROGRAM ELEMENT, PROJECT, TASK<br>AREA & WORK UNIT NUMBERS<br>Program Ele: 6.11.02.A |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                    | 12. REPORT DATE<br>September 1982                                                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                    | 13. NUMBER OF PAGES<br>60                                                                |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                    | 15. SECURITY CLASS. (of this report)<br>UNCLASSIFIED                                     |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                                    | 15a. DECLASSIFICATION/DOWNGRADING<br>SCHEDULE                                            |
| 16. DISTRIBUTION STATEMENT (of this Report)<br><br>Approved for public release; distribution unlimited.                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                    |                                                                                          |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |                                    |                                                                                          |
| 18. SUPPLEMENTARY NOTES<br>HDL Project: A41234<br>DRCMS Code: 611102.H.440011<br>DA: 1L161102AH44                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                                    |                                                                                          |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number)<br>Fluidics Pressure regulators<br>Fluerics Laminar jet angular rate sensor<br>Laminar proportional amplifier Fineblanking<br>Gain blocks Electrodischarge machining<br>Servovalve Photochemical etching                                                                                                                                                                                                                                                                   |                                    |                                                                                          |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>This report presents data and operating experience information on many commonly used laminar gain blocks from two to eight stages. In addition, as an aid to design, a short computer program is presented, suitable for use with a pocket programmable calculator. Outputs from this program are individual stage data including nominal supply pressures and flows and staged gain. Also available is the net gain and the bandwidth at 90 deg of phase shift. Several |                                    |                                                                                          |

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

1 SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Reproduced From  
Best Available Copy

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. Abstract (cont'd)

examples of this program are given to cover multiple-stage gain blocks. As an example of the utility of the program, a step-by-step tradeoff study is presented for the Massachusetts Institute of Technology fluidic servovalve, for which an attempt is made to maximize bandwidth and minimize leakage flow.

UNCLASSIFIED

2 SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

## CONTENTS

|                                                            | <u>Page</u> |
|------------------------------------------------------------|-------------|
| 1. INTRODUCTION.....                                       | 5           |
| 2. SIMPLE STAGING DESIGN PROGRAM.....                      | 6           |
| 3. COMMONLY USED GAIN BLOCKS.....                          | 9           |
| 3.1 Two-Stage Gain Blocks.....                             | 10          |
| 3.1.1 Two-Stage Self-Staged Gain Block.....                | 10          |
| 3.1.2 Two-Stage Moderately Pressure-Staged Gain Block..... | 11          |
| 3.2 Three-Stage Gain Blocks.....                           | 13          |
| 3.2.1 Three-Stage Self-Staged Gain Blocks.....             | 13          |
| 3.2.2 Common Supply Pressure Gain Blocks.....              | 15          |
| 3.2.3 Pressure-Staged Gain Blocks.....                     | 17          |
| 3.2.4 Power- or Flow-Gain Gain Blocks.....                 | 24          |
| 3.3 Four-Stage Gain Blocks.....                            | 25          |
| 3.4 Five-Stage Gain Block for Public Address System.....   | 25          |
| 3.5 Eight-Stage Gain Block.....                            | 26          |
| 4. DISCUSSION AND CONCLUSIONS.....                         | 28          |
| ACKNOWLEDGEMENTS.....                                      | 29          |
| LITERATURE CITED.....                                      | 31          |
| DISTRIBUTION.....                                          | 53          |

## APPENDICES

|                                                    |    |
|----------------------------------------------------|----|
| A.--BASIC PROGRAM AND REPRESENTATIVE EXAMPLES..... | 33 |
| B.--REPRESENTATIVE STACKING ORDERS.....            | 47 |

## FIGURES

|                                                                                                            |    |
|------------------------------------------------------------------------------------------------------------|----|
| 1. Gain as function of bias for standard laminar proportional amplifier of Harry Diamond Laboratories..... | 6  |
| 2. Two-stage self-staged gain block:.....                                                                  | 10 |

FIGURES (Cont'd)

|                                                                                             | <u>Page</u> |
|---------------------------------------------------------------------------------------------|-------------|
| 3. Fluidic capillary pyrometer gain block:.....                                             | 12          |
| 4. Three-stage self-staged gain block:.....                                                 | 14          |
| 5. Three-stage common supply pressure gain block:.....                                      | 16          |
| 6. Three-stage, parallel-element, common supply pressure gain block:.....                   | 17          |
| 7. Three-stage maximum dynamic range gain block:.....                                       | 19          |
| 8. Three-stage high-input-impedance gain block:.....                                        | 19          |
| 9. Three-stage preamplifier for laminar jet angular rate sensors:..                         | 20          |
| 10. Bode plot of flueric servovalve three-stage gain block.....                             | 21          |
| 11. Four-stage pressure regulator gain block:.....                                          | 26          |
| 12. Design program output for Harry Diamond Laboratories flueric public address system..... | 27          |

TABLES

|                                                                                                                   |    |
|-------------------------------------------------------------------------------------------------------------------|----|
| 1. Optimization of Fluidic Servovalve for Leakage Flow, Bandpass, Output-to-Input Resistance Ratio, and Gain..... | 22 |
| 2. Makeup of Eight-Stage Gain Block for M48A5 Gun Stabilization System.....                                       | 28 |

DTIC  
ELECTE  
NOV 16 1982  
B



|                    |                                            |
|--------------------|--------------------------------------------|
| Accession For      |                                            |
| NTIS GRA&I         | <input checked="checked" type="checkbox"/> |
| DTIC TAB           | <input type="checkbox"/>                   |
| Unannounced        | <input type="checkbox"/>                   |
| Justification      |                                            |
| By                 |                                            |
| Distribution/      |                                            |
| Availability Codes |                                            |
| Avail and/or       |                                            |
| Dist               | Special                                    |
| A                  |                                            |

## 1. INTRODUCTION

In developing fluidic systems, it is most often necessary to provide a certain amount of gain. Whether it is to boost sensor outputs to useful levels or to provide high gain feedback, each application requires amplification of differential pressures. Since the gain of a single standard laminar proportional amplifier (LPA) is about 10, it is necessary to stage LPA's if more gain is desired.

Staging LPA's has been dealt with extensively in the literature;<sup>1-6</sup> however, performance of preferred topologies has not in general been discussed. Certain advantages, not specifically obvious, lie with certain specific designs.

The most commonly used gain block is the self-staged gain block. Although one of the most important operational advantages of such a device is that the high single-stage LPA input-to-output resistance ratio is maintained, perhaps the most compelling reason for its use is the ease with which assembly and manifolding of supply pressure occur since only one supply pressure is needed. Other topologies, however, use a single common supply pressure to each amplifier, and most gain blocks use a single supply which is then manifolded down. Therefore, this report presents experimental data for many different gain blocks. Although operational characteristics are stressed, a design rationale where it is not obvious is presented. A simple program, developed for use with a pocket programmable calculator, provides the basis for the design of a gain block and is treated first.

---

<sup>1</sup>F. M. Manion and G. Mon, *Fluerics 33: Design and Staging of Laminar Proportional Amplifiers*, Harry Diamond Laboratories, HDL-TR-1608 (September 1972).

<sup>2</sup>F. M. Manion and T. M. Drzewiecki, *Analytical Design of Laminar Proportional Amplifiers*, *Proceedings of HDL Fluidic State-of-the-Art Symposium*, 1 (October 1974).

<sup>3</sup>T. M. Drzewiecki, D. Wormley, and F. M. Manion, *A Computer-Aided Design Procedure for Laminar Fluidic Systems*, *J. Dyn. Sys. Meas. Control*, 97, Series G, No. 4 (December 1975).

<sup>4</sup>C. Mon, *Flueric Laminar Gain Blocks and an Operational Amplifier Scaler*, Harry Diamond Laboratories, HDL-TR-1730 (December 1975).

<sup>5</sup>T. M. Drzewiecki, *A Fluidic Audio Intercom*, *Proceedings of 20th Anniversary of Fluidics Symposium*, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).

<sup>6</sup>M. Cycon and D. Shaffer, *Design Guide for Laminar Flow Fluidic Amplifiers and Sensors*, contract with Garrett Pneumatic Systems Division, Harry Diamond Laboratories, HDL-CR-82-288-1 (March 1982).

## 2. SIMPLE STAGING DESIGN PROGRAM

The in-stage gain of a standard LPA is determined by the operating bias pressure and the load that the LPA is driving. The sensitivity of gain to bias pressure is given by the relationship<sup>7</sup>

$$G_{\text{biased}}/G_{\text{zero bias}} = 1/[1 + 0.6(P_{\text{bias}}/P_s)] \quad (1)$$

which is shown in figure 1 for some typical amplifiers.

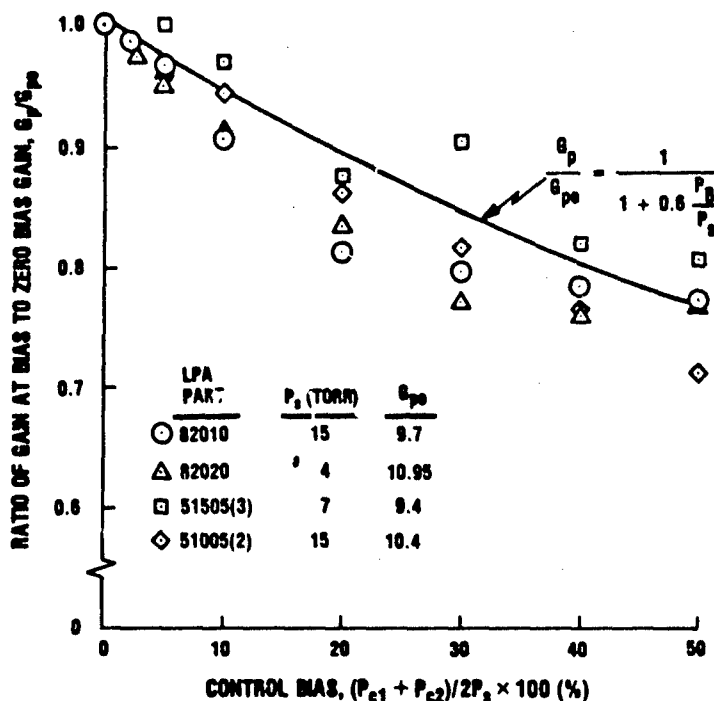


Figure 1. Gain as function of bias for standard laminar proportional amplifier of Harry Diamond Laboratories.

If one assumes that under most loading conditions the recovered pressure of a preceding stage is at least 33 percent (for aspect ratio,  $\sigma > 0.7$ ), then the expression for gain can be approximated in terms of the preceding ( $n - 1$ ) stage supply pressure, so that

$$G_{\text{biased}}/G_{\text{zero bias}} = 1/[1 + 0.2(P_{s(n-1)}/P_{sn})] \quad (2)$$

<sup>7</sup>T. M. Drzewiecki, *Fluerics 38: A Computer-Aided Design Analysis for the Static and Dynamic Port Characteristics of Laminar Proportional Amplifiers*, Harry Diamond Laboratories, HDL-TR-1758 (June 1976).

The gain of an LPA is also determined by the load into which the amplifier is operating so that

$$G_{\text{load}}/G_{\text{blocked}} = 1/[1 + (R_o/R_L)] \quad (3)$$

where  $R_o$  is the LPA output resistance and  $R_L$  is the load resistance. Since the output resistance for almost any case is<sup>5</sup>  $R_{on} = 0.5P_{sn}/Q_{sn}$  and the in-stage load is the input resistance of a succeeding  $(n + 1)$  stage,<sup>5</sup> then

$$R_L = R_{i(n+1)} = 0.75P_{s(n+1)}/Q_{s(n+1)} \quad .$$

In such a manner, equation (3) becomes

$$G_{\text{load}}/G_{\text{blocked}} = 1/[1 + 0.667(P_{sn}/P_{s(n+1)})(Q_{s(n+1)}/Q_{sn})] \quad (4)$$

The phase shift for small phase angles is determined by the signal transport lag in the device. The total gain block phase shift, as a minimum, is the sum of the phase shifts of each stage:

$$\phi_n = 360 \tau f \quad (5)$$

and

$$\phi = \sum_{n=1}^N \phi_n \quad (5a)$$

so that

$$\phi = 360f \sum_{n=1}^N \tau_n \quad (5b)$$

where  $\phi$  is in degrees,  $\tau$  is the signal transport time across an LPA (equal to twice the particle transport time),<sup>5</sup> and  $f$  is the frequency in hertz. The signal transport time is

---

<sup>5</sup>T. M. Drzewiecki, A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).

$$\tau = 2x_{sp}/c_d(2P_s/\rho)^{1/2} . \quad (6)$$

Since in the standard LPA the nozzle-to-splitter distance,  $x_{sp}$ , is eight nozzle widths ( $8b_s$ ),  $\tau$  becomes

$$\tau = 16b_s/c_d(2P_s/\rho)^{1/2} . \quad (7)$$

To determine the frequency at which total phase shift is  $\phi$  degrees, one uses equations (5b) and (7) to get

$$f = (\phi/360)/\left[16 \sum_{n=1}^N b_{sn}/c_d(2P_{sn}/\rho)^{1/2}\right] , \quad (8)$$

where  $c_d$  is the LPA discharge coefficient ( $c_d = 0.7$  for the nominal operating point) and  $\rho$  is the fluid density.

Equations (1), (3), and (8) can be written in a program for  $N$  stages. Just such a program, written in BASIC, is shown in appendix A. The bulk of the program is taken up by setting up the arrays for all the input data. Flow consumption is based on a nominal 0.3 liters/min (LPM) for an LPA with  $b_s = 0.5$  mm at a modified Reynolds number,  $N_R' = 120$ .

$$N_R' = N_R/[2(1 + 1/\sigma)^2]$$

and

$$N_R = b_s(2P_s/\rho)^{1/2}/\nu ,$$

in air,

$$N_R = 1000b_s \text{ (mm)} [P_s \text{ (torr)}]^{1/2} .$$

Sample printouts are shown in appendix A for nine runs.

Verification of the validity of the results of this program is left to the following sections, in which they are used as a design guide.

### 3. COMMONLY USED GAIN BLOCKS

In trying to present the information logically, it is easiest to use the number of stages as the primary delineating factor. What follows, therefore, is a compendium of gain blocks and their performance, starting with two stages and ending with eight. Stacking orders for some of the more commonly used circuits are given for standard Harry Diamond Laboratories (HDL) integrated format parts in appendix B.

As a rule, the nominal gain of a single standard LPA is about 10 at  $\sigma N_R = 1000$ . This value, however, varies depending on the manufacturing process used, the accuracy to which the nominal dimensions are kept, and the aspect ratio. As a result, a normal span of gain variation is from 7 to 12. As the aspect ratio gets below 1, the gain decreases from a nominal 10 to as low as 7 at an aspect ratio of 1/3.

The currently accepted methods for fabrication are photochemical etching, fineblanking, and wire electrodischarge machining.<sup>8,9</sup> These manufacturing methods are designated by numerical prefixes to the four-digit designation numbers as 5, 6, and 8, respectively, forming a five-digit LPA part number. The two digits immediately following the manufacturing prefix correspond to the nozzle width in mils, and the last two digits are the lamination thickness in mils. Alphanumeric suffixes in brackets may designate special dimensions or functions; for example, [R] refers to a rectifier. In this fashion, a fineblanked LPA with  $b_s = 0.5$  mm (0.020 in.) and  $\sigma = 0.75$  is designated as P.N. 62015, and an etched LPA with  $b_s = 0.25$  mm (0.010 in.) and  $\sigma = 0.5$  is designated as P.N. 51005.

In the following sections describing gain blocks, the average value of a single-stage blocked-pressure gain is given to provide a yardstick against which to evaluate possible alternative performances. The reader should remember that net gain is the product of the blocked single-stage gain raised to the power  $N$  (where  $N$  is the number of stages) multiplied by the net losses. The losses generally remain the same, independent of the blocked gain, so that if one is interested in the performance of a gain block made up of LPA's of gain different from those reported here, one merely multiplies by the ratio of new gain to old gain raised to the  $N$ th power. For example, a three-stage gain block is reported here to have a gain of 200 using LPA's with a blocked single-stage gain of 8, but is reproduced by using components with a gain of 10. The new gain block has a gain of  $(10/8)^3$  higher, or 391.

<sup>8</sup>L. Schesr, J. Roundy, and J. Joyce, *Manufacturing Techniques for Producing High Quality Fluidic Laminates in Production Quantities*, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).

<sup>9</sup>R. M. Phillippi, *A Study of Fineblanking for the Manufacture of Fluoric Laminar Proportional Amplifiers*, Harry Diamond Laboratories, HDL-TM-77-8 (May 1977).

### 3.1 Two-Stage Gain Blocks

Several two-stage gain blocks have been implemented at HDI, but two are most common. The first is a self-staged gain block, and the second is a moderately pressure-staged gain block that is extensively used in fluidic capillary pyrometer circuits.<sup>10</sup>

#### 3.1.1 Two-Stage Self-Staged Gain Block

Figure 2 shows a collection of data for various size and aspect ratio two-stage self-staged gain blocks. Representative transfer characteristics are given at the nominal operating point in figure 2(a), and the gain as a function of normalized supply pressure is given in figure 2(b). Also shown in figure 2(b) are the computed values of gain using the program given in appendix A. As may be observed, there is good correlation. A generic stacking order is given in appendix B.

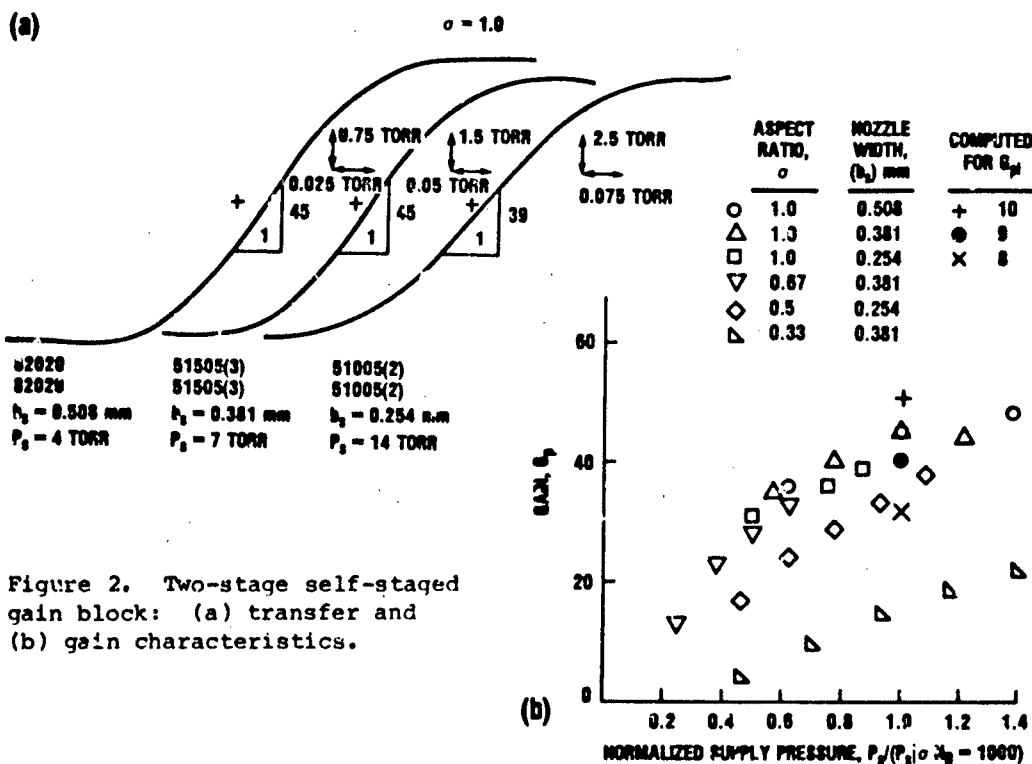


Figure 2. Two-stage self-staged gain block: (a) transfer and (b) gain characteristics.

<sup>10</sup>R. M. Phillippi, T. M. Drzewiecki, T. Negas, and H. S. Parker, Design of a Fluidic Capillary Pyrometer for Contact Duty at Temperatures to 2750°C, Proceedings of 6th International Symposium on Temperature, Washington, DC (15 to 19 March 1982).

### 3.1.2 Two-Stage Moderately Pressure-Staged Gain Block

To get more gain using low-aspect-ratio, small-size devices with high impedance and high output pressure, some slight amount of pressure staging is obtained by cascading a device with an aspect ratio of 0.33 with one of 0.67 for the first stage. These stages operate at different pressures, so to operate the device from the common last-stage pressure, a dropping resistor must be employed.

The computer program generates values for nominal supply pressure and flow so that values of dropping resistors can be estimated by taking the difference between last-stage pressure and desired-stage pressure and dividing by the desired-stage supply flow. In this manner,

$$R_d = (P_N - P_i)/Q_i ,$$

where  $P_N$  is the common supply pressure (pressure to the last stage),  $P_i$  is the pressure to the stage of interest, and  $Q_i$  is the flow to the stage of interest.

For the case at hand,  $P_1 = 16$  torr,  $P_2 = 64$  torr, and  $Q_1 = 0.225$  LPM (see example A-1 in app A). This requires a resistance of about 200 torr/LPM between the common supply and the first-stage supply. Standard available resistances, at a nominal flow rate of 0.05 LPM, are 35, 200, 300, and 500 torr/LPM. These correspond to P.N. 5221a nozzles with  $b_s = 0.51$  mm and  $\sigma = 0.5$ ,  $b_s = 0.56$  mm and  $\sigma = 0.23$ ,  $b_s = 0.51$  mm and  $\sigma = 0.25$ , and  $b_s = 0.51$  mm and  $\sigma = 0.20$ .

The 35 and 300 resistors are available in fineblanked parts, and the 200, 300, and 500 resistors are available etched. For flow rates above 0.05 LPM, the orifice term adds resistance so that a nominal 200-torr resistor at 0.225 LPM has too high a resistance for this job. By using two 300-torr resistors in parallel at a flow rate of 0.112 LPM each, the net 150 torr/LPM is increased so that it is close to 200. (It is good practice always to use dropping resistors in parallel to cut supply noise. Keeping the flow to less than 0.05 LPM per resistor further reduces noise.)

Figure 3(a) shows typical transfer characteristics and figure 3(b) shows the gain versus the supply pressure for this fluidic capillary pyrometer gain block using fineblanked parts of nominal gain just under 9. The computed value of 61, shown in appendix B using a single-stage gain of 8.5, is in good agreement with the value of 62 actually obtained.

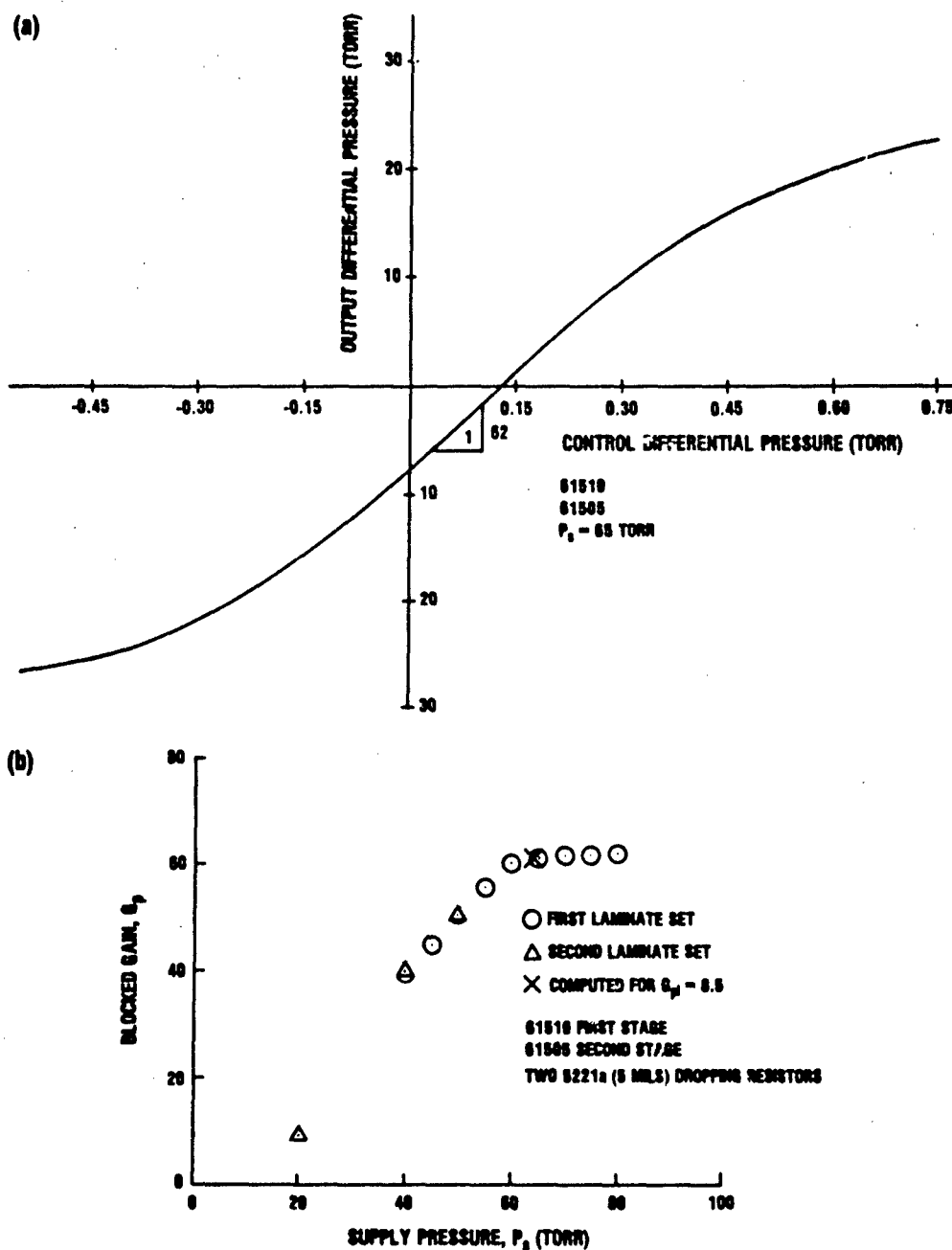


Figure 3. Fluidic capillary pyrometer gain block: (a) transfer and (b) gain characteristics.

22

The stacking order for standard C format assembly is given in appendix B.

### 3.2 Three-Stage Gain Blocks

Perhaps the most commonly used generic gain block is composed of three stages. Gains from 100 to 1000 are readily obtainable with frequency response well past the normal AM radio/telephone range ( $>3$  kHz). Typical use involves reducing the noise floor of commercial pressure transducers or driving of pressure-controlled oscillators. For example, a typical  $\pm 1$  psi ( $\pm 50$  torr) pressure transducer with a signal-to-noise ratio of 2000 can discriminate 0.001 psi (0.05 torr). (This corresponds to 5 mV of noise for a 10-V output.) Typical threshold signals of fluidic sensors are two to three orders of magnitude below 0.05 torr. A no-noise gain block with a gain of 500 boosts the signals above the equivalent electronic noise floor, so that the transducer can effectively discriminate signals of  $2 \times 10^{-6}$  psi ( $10^{-4}$  torr).

As with two-stage devices, the most common device is the self-staged gain block. Other topologies that follow are pressure or flow staged to one extent or another.

#### 3.2.1 Three-Stage Self-Staged Gain Blocks

The reference gain block is composed of three stages of LPA's with  $\sigma = 1$ . Since LPA's come in standard sizes-- $b_g = 0.75, 0.5, 0.375$ , and  $0.25$  mm (corresponding to  $0.03, 0.02, 0.015$ , and  $0.01$  in.)--the performance of the three most commonly used sizes is presented in figure 4a at nominal operating conditions.

Figure 4b shows the variation of gain with supply pressure and computed values from the program. Agreement is good.

The standard components used comprise C format amplifiers 63030, 82020, three stacked 51505's, and two stacked 51005's. The stacking order is similar to that given in appendix B for the two-stage device. There are several guidelines to follow in the assembly of three and more stage gain blocks. The last stage (highest pressure if not self-staged) should be closest to the supply pressure source to minimize high-pressure leaks. The supply flow should be manifolded in such a way that the last stages are fed first with the first stage receiving only that flow which it needs. More succinctly, it is not desirable to have excess flow rushing past the first stage where it can generate noise that can be amplified through the stack. Furthermore, the first stage vents should always be isolated or decoupled from the rest of the stack, if possible, to prevent spurious latter-stage vent flows from producing noise that can be amplified up the stack (example B-1, use of 5022a plate).

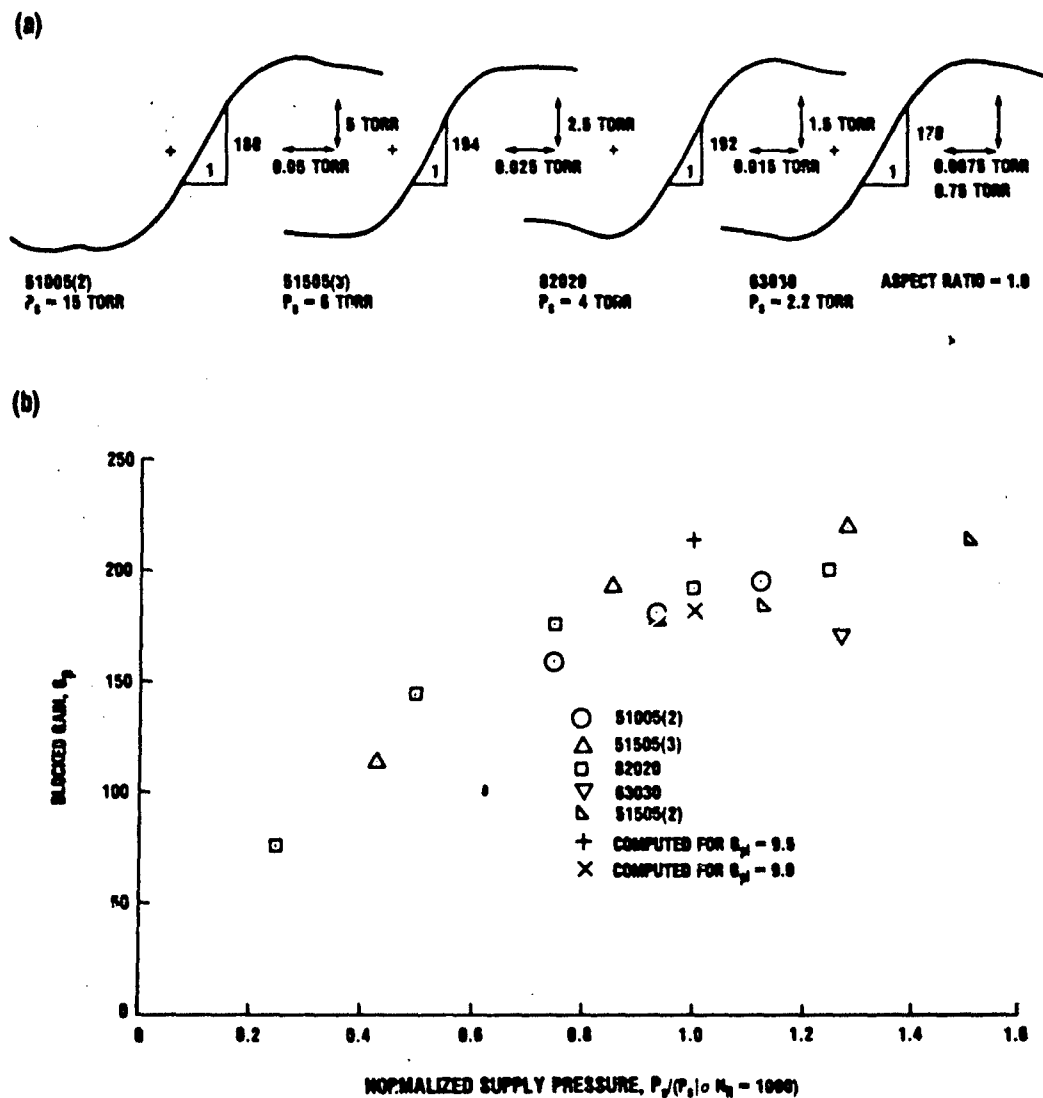


Figure 4. Three-stage self-staged gain block: (a) transfer and (b) gain characteristics.

It is possible to build self-staged gain blocks of different aspect ratios; the gain stays about the same, but the operating pressure changes. For example, a 63020 gain block ( $\sigma = 0.67$ ) has a supply pressure of 2.5 torr and a measured gain of 255 with a single-stage normal gain of 11.1.

### 3.2.2 Common Supply Pressure Gain Blocks

The tremendous advantage of the self-staged gain block is not having to drop supply pressures. This advantage extends to another class of topologies. Since LPA's of the same height, no matter what the nozzle width, operate at the same supply pressure, a moderate increase in staged gain can be achieved by increasing succeeding stage input impedance by decreasing plan view size. In this manner, the four LPA's of standard nozzle width can be staged in various combinations of three or more to get more gain than in the self-staged case. Two such devices are the 63020-62020-51005(4)\* and the 62015-51505(3)-51005(3) gain blocks. Figure 5 shows typical transfer and gain characteristics.

Instead of decreasing size, to increase input impedance at constant supply pressure, one may decrease the number of parallel elements per stage and achieve a similar increase in gain. Although this method has the added advantage of requiring only one plan view size amplifier, the cost is a considerable increase in flow consumption. An easy configuration to examine is a first stage with four parallel elements, the second with two, and the third with only one.<sup>†</sup> In this gain block, the input impedance of each succeeding stage is doubled. Figure 6 shows the gain characteristics of this device.

The gain of these blocks, which varies from 300 to 400, is considerably higher than the nominal 200 to 250 gain that the self-staged block exhibits. However, a penalty must be paid for this gain increase in an increased output-to-input impedance ratio. In increasing the output-to-input impedance ratio by paralleling early stages, an additional penalty in flow is exacted for using amplifiers that are all the same size. However, a side benefit of this scheme may be the dramatic reduction in null offset due to cancellation in the multiple elements of the first stage, especially when an even number of parallel

\*Metal etched laminates usually come in either 0.1-mm (0.004-in.) or 0.125-mm (0.005-in.) thickness. Since the smaller amplifiers are not available in fineblanked single laminates, the number of laminates used is given in parentheses.

†Designation of the number of parallel elements appears as a numerical prefix in brackets to the part number. Hence, four parallel elements of the metal etched parts with  $b_s = 0.254$  mm and  $\sigma = 1$  is designated as [4]51005(2).

stages is employed. Care must be taken to decouple the power supplies in the parallel stages to eliminate power-supply coupling and cross talk that promotes early transition to turbulence. This decoupling moderately increases the manifolding complexity, but still is easier to implement than using dropping resistors.

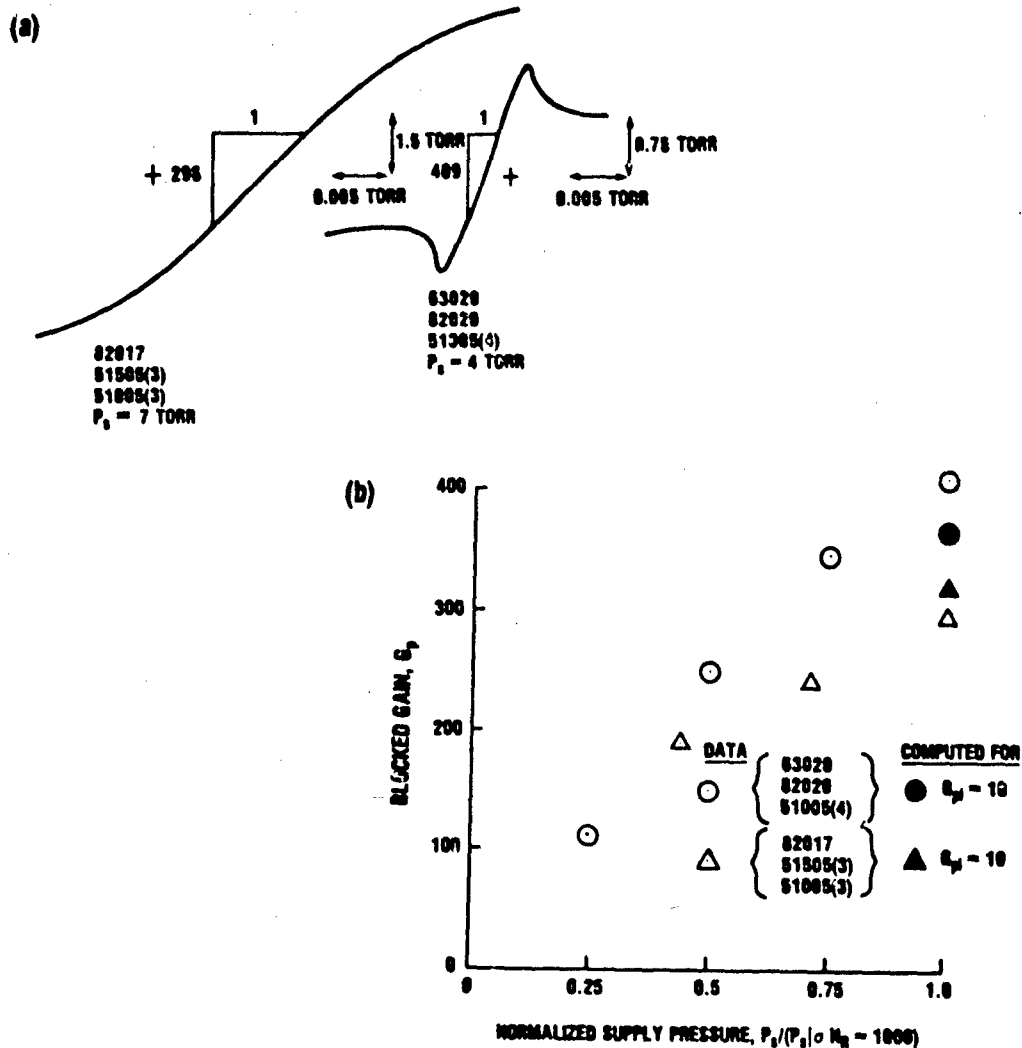


Figure 5. Three-stage common supply pressure gain block: (a) transfer and (b) gain characteristics.

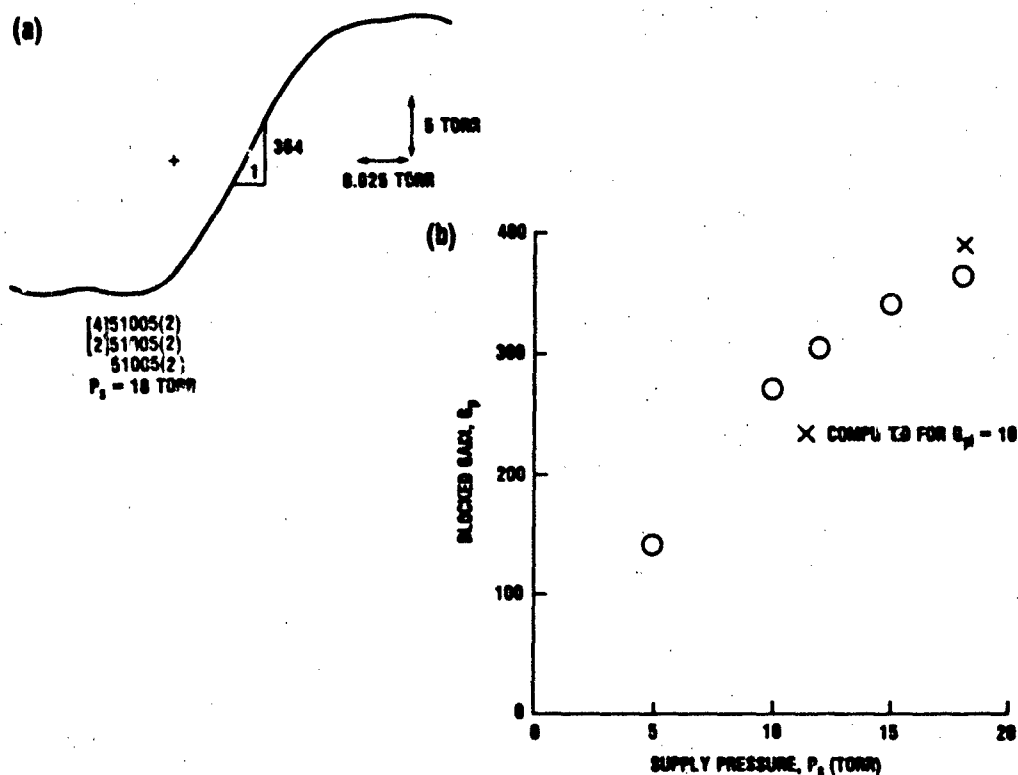


Figure 6. Three-stage, parallel-element, common supply pressure gain block: (a) transfer and (b) gain characteristics.

### 3.2.3 Pressure-Staged Gain Blocks

Drzewiecki<sup>5</sup> derives the staging conditions for maximum staged gain and maximum dynamic range as

$$(\sigma_n/\sigma_{n-1})^2(b_{sn}/b_{sn-1}) = 1/G_{pn(staged)} \quad (9)$$

<sup>5</sup>T. M. Drzewiecki, A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).

Since under optimum loading (almost blocked) the staged gain is nominally 10, then for the same size plan view amplifiers the aspect ratio must decrease by approximately three in each stage to produce maximum gain and dynamic range. When dynamic range is maximized, the jets all deflect the same amount so that the null offset of the gain block is the same percentage as that of the first stage alone. In other words, there is no deflection angle gain in the block. In the self-staged gain block, there is a deflection angle increase; hence, the more stages used, the worse the null offset.

Maximum dynamic range gain block.--By using the lowest aspect ratio to start with for the final stage, one can work backward and determine the aspect ratios for the earlier stages. Normally,  $\sigma = 0.4$  is the lowest available for  $b_g > 0.5$  mm (neglecting single-laminate metal etched parts with  $\sigma = 0.2$  and  $0.25$ ). The next-to-last-stage aspect ratio should then be  $\sigma = 1.2$ , and the one before that should be 3.6. With further increase in  $\sigma$ , operating pressure becomes ridiculously low (such as  $\sigma = 10.8$  and  $P_g = 0.03$  torr). Therefore, the practical limit for a maximally pressure-staged LPA is three stages for a single plan view size. Figure 7 shows the gain characteristics for a three-stage gain block with  $\sigma_1 = 3.6$ ,  $\sigma_2 = 1.2$ , and  $\sigma_3 = 0.4$  with  $b_g = 0.5$  mm. (Appendix A has printouts of nominal predicted and design operation, and appendix B lists stacking orders.)

This high gain unit has an excellent null characteristic, linearity, and gain. However, the first stage operates at a very low supply pressure ( $P_g = 0.3$  torr) and consequently limits the bandpass to approximately 117 Hz. In addition, the output resistance's being considerably higher than the input (40 to 1) makes it difficult to use this device in a feedback configuration.

By compromising in the staging makeup, other configurations are possible. The three following gain blocks illustrate such compromises.

High-input-impedance gain block.--In an effort to increase the input impedance and the bandpass of the gain block, the first- and second-stage aspect ratios can be reduced. Figure 8 shows data taken for a gain block made up of  $\sigma_1 = 0.75$ ,  $\sigma_2 = 0.5$ ,  $\sigma_3 = 0.4$ , and  $b_g = 0.5$  mm. This typical gain block is used as a preamplifier for laminar jet angular rate sensors and sometimes for the photofluidic interface. (The photofluidic interface most commonly uses a second-stage aspect ratio,  $\sigma = 0.6$ , but this use does not materially change the characteristics from the block discussed here.)

Gain is about half of the maximum dynamic range device, but the output-to-input resistance ratio is reduced to about 3.

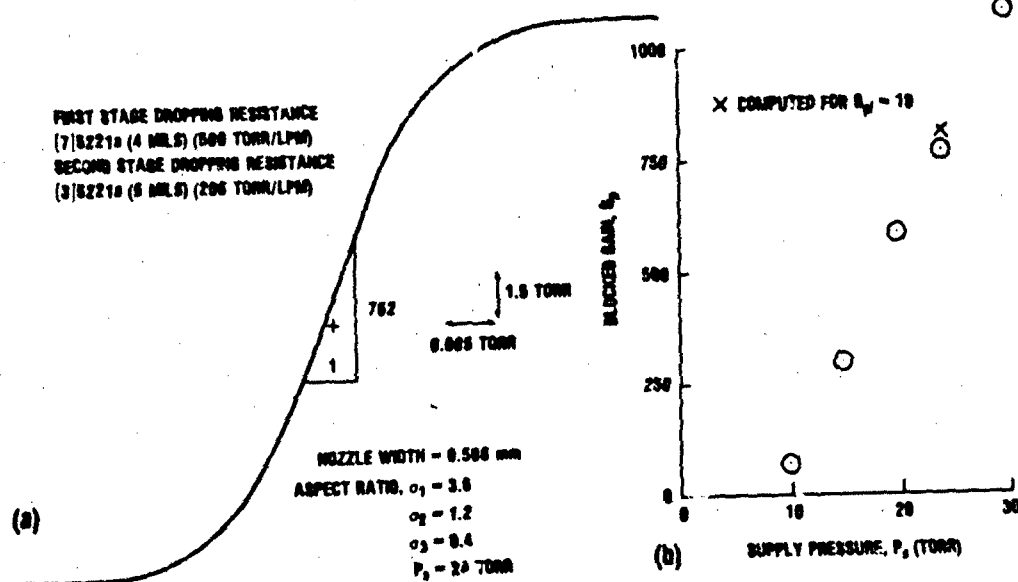


Figure 7. Three-stage maximum dynamic range gain block: (a) transfer and (b) gain characteristics.

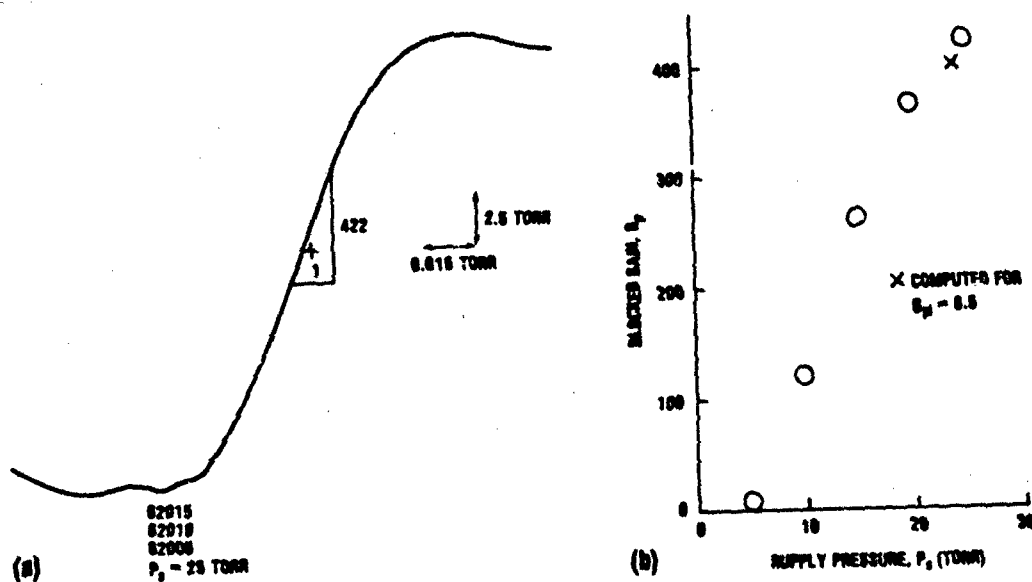


Figure 8. Three-stage high-input-impedance gain block: (a) transfer and (b) gain characteristics.

Change-in-size moderate-pressure staging gain block.--In a modification of the common supply pressure gain block with varying sizes, the gain can be increased by lowering the aspect ratio of the final stage. This device requires only one dropping resistor to supply the common first- and second-stage pressure. (The resistor must now accommodate flow for two stages and must be appropriately sized so that the flow per laminate does not exceed 0.1 LPM.) Shown in figure 9 are the characteristics for a gain block mode up of 63020, 62020, and 81008 LPA's.

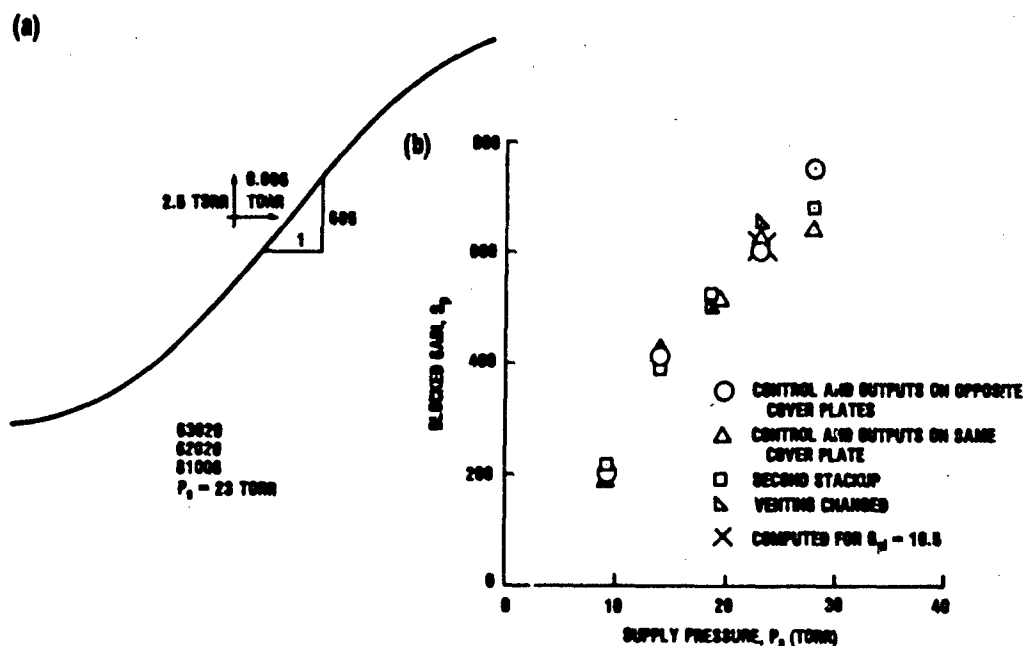


Figure 9. Three-stage preamplifier for laminar jet angular rate sensor: (a) transfer and (b) gain characteristics.

The dropping resistor is required to drop 24 to 4 torr or 20 torr at a flow rate of 0.75 LPM or  $R = 27$  torr/LPM. This drop is readily achieved with eight 200-torr/LPM resistors.

The gain of 605 compares favorably with the design goal of 608 from the program in appendix A at  $G = 10.5$  and is 20 to 25 percent higher than the previous case. However, the input-to-output resistance ratio is worse and the bandwidth is down.

Flueric servovalve amplifier.--The flueric servovalve<sup>11,12</sup> is a three-stage LPA with multiple parallel elements in each stage. As configured in C format, it consists of a first stage containing two 63020 parallel elements, a second stage containing three 62010 parallel elements, and a third stage containing six 61505 parallel elements. The design program predicts a gain of 335, a bandpass of 281 Hz, a leak flow of the first two stages of 1.757 LPM, and an output-to-input resistance ratio of 9.5 (example A-8). Figure 10 shows a Bode plot taken at the Massachusetts Institute of Technology for operation in hydraulic oil. (Note that the volumetric flows in air and oil are the same, the pressures are different, and the dynamics are essentially the same since the kinematic viscosities are similar.) Agreement between the prediction of the design program and the data is good.

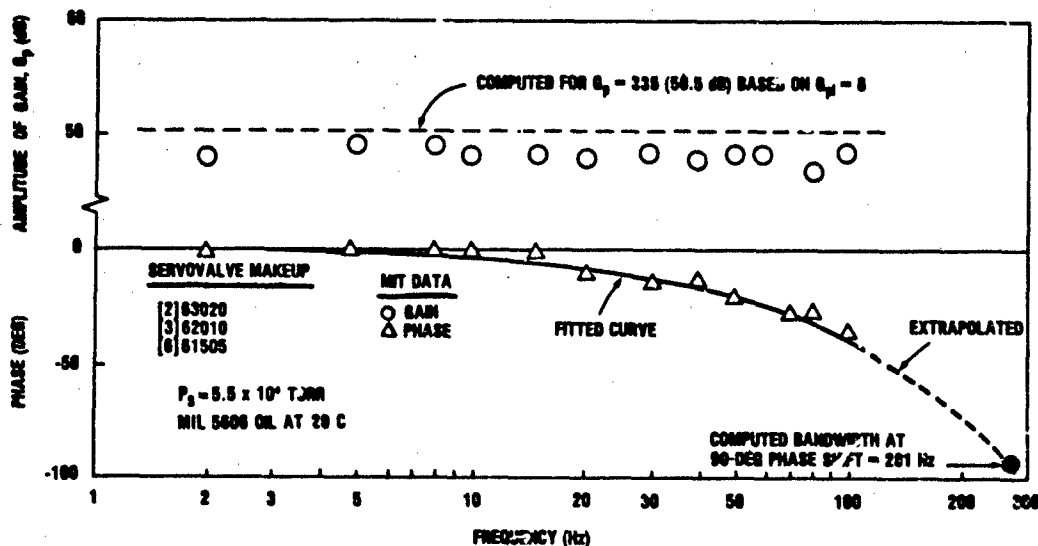


Figure 10. Bode plot of flueric servovalve three-stage gain block.

Five parameters are of interest in the design of a flueric servovalve:

- leakage flow
- input-to-output resistance ratio
- bandpass
- gain
- pressure recovery

<sup>11</sup>D. N. Wormley, D. Lee, and K. M. Lee, Development of a Fluidic, Hydraulic Servovalve, Massachusetts Institute of Technology, contract with Harry Diamond Laboratories, HDL-CR-81-216-1 (February 1981).

<sup>12</sup>D. Lee and D. N. Wormley, A Fluidic Hydraulic Servovalve, J. Dyn. Sys. Meas. Control, 103, No. 4 (December 1981).

Given the plan view of the standard LPA and the sizes available, the thinnest lamination with a reasonable aspect ratio gives rise to either  $\sigma = 0.375$  for  $b_s = 0.375$  mm or  $\sigma = 0.5$  for  $b_s = 0.25$  mm so that operation in air at 64 torr is possible, corresponding to  $5.5 \times 10^4$  torr in oil (1100 psi). Pressure recovery is thus fixed. Pressure recovery can be increased by changing LPA geometry, but that increase is not within the purview of this report. Thus, let us examine the optimization or increase in performance of the other three parameters at the expense, if any, of gain. By using the design program, some changes can be easily tried out. Table 1 shows design parameters as they are affected by various changes.

TABLE 1. OPTIMIZATION OF FLUERIC SERVOVALVE FOR LEAKAGE FLOW, BANDPASS, OUTPUT-TO-INPUT RESISTANCE RATIO, AND GAIN

| Trial | Gain block makeup                 | Geometric changes from previous case                                                                                   | Leakage flow (LPM) | Bandpass (Hz) | Output-to-input resistance ratio | Gain |
|-------|-----------------------------------|------------------------------------------------------------------------------------------------------------------------|--------------------|---------------|----------------------------------|------|
| 1     | [2]63020<br>[3]62010<br>[6]61505  | (Baseline)                                                                                                             | 1.76               | 281           | 9.5                              | 335  |
| 2     | [3]62020<br>[4]62010<br>[10]51005 | $\sigma_1 = 1$<br>$b_{s1} = 0.5$ mm<br>$N_1 = 3$<br>$N_2 = 4$<br>$N_3 = 10$<br>$b_{s3} = 0.254$ mm<br>$\sigma_3 = 0.5$ | 2.07               | 376           | 7.2                              | 320  |
| 3     | [2]62020<br>[3]62010<br>[10]61505 | $N_1 = 2$<br>$N_2 = 3$<br>$b_{s3} = 0.37$ mm                                                                           | 1.49               | 363           | 4.0                              | 285  |
| 4     | [2]62016<br>[2]62010<br>[12]61505 | $\sigma_1 = 0.8$<br>$N_2 = 2$<br>$N_3 = 12$                                                                            | 1.19               | 412           | 2.1                              | 229  |
| 5     | [3]62016<br>[3]62010<br>[8]61505  | $N_1 = 3$<br>$N_2 = 3$<br>$N_3 = 8$                                                                                    | 1.79               | 412           | 4.7                              | 289  |
| 6     | [4]62016<br>[3]62010<br>[6]61505  | $N_1 = 4$<br>$N_3 = 6$                                                                                                 | 2.09               | 412           | 9.5                              | 321  |
| 7     | [2]62020<br>[2]62010<br>[8]61505  | $N_1 = 2$<br>$N_2 = 2$<br>$\sigma_1 = 1$<br>$N_3 = 8$                                                                  | 1.19               | 363           | 5.0                              | 289  |

Notes:  $\sigma$  = aspect ratio,  $b_s$  = supply nozzle width,  $N$  = number of stages.

In trying to follow the rationale for the changes shown in the second column of table 1, the following arguments are set forth.

● First change (trial 2).--Increase the first-stage bandwidth by decreasing LPA size, but keep the input resistance the same by using more elements.<sup>3</sup> Decrease the output resistance by increasing the number of output elements to 10. Keep the gain up by reducing second-stage resistance relative to the third-stage resistance by increasing the number of parallel elements in the second stage and decreasing element size in the third stage.

Result.--The bandpass increases at the expense essentially of leakage flow.

● Second change (trial 3).--Increase the input resistance by reducing the number of elements in the first stage. Decrease the output resistance by increasing the element size back up to baseline. Reduce leakage by reducing the number of elements in the second stage.

Result.--Leakage flow and the output-to-input resistance ratio decrease at the expense of gain.

● Third change (trial 4).--Further increase the input resistance by reducing the first stage aspect ratio to 0.8, thereby also increasing the bandpass. Further decrease leakage flow by reducing the number of elements in the second stage to two. Decrease the output resistance by increasing the number of output elements to 12.

Result.--Leakage flow and the output-to-input resistance ratio decrease and the bandpass increases at the further expense of gain.\*

● Fourth change (trial 5).--Bring the gain back up by reducing the input resistance by adding an element to the first stage, increase the output resistance by decreasing the number of output elements, and increase the second- to third-stage gain by increasing the number of second-stage elements to three.

<sup>3</sup>T. M. Drzewiecki, D. Wormley, and F. M. Manion, A Computer-Aided Design Procedure for Laminar Fluidic Systems, J. Dyn. Sys. Meas. Control, 97, Series G, No. 4 (December 1975).

\*Reduction in gain is not altogether unacceptable when it is noted that in a feedback arrangement the overall performance is dependent somewhat on closed loop gain, which increases with a decreasing output-to-input resistance ratio. Since gain is down 32 percent but the input-to-output resistance ratio is up over 400 percent, this case may be more desirable.

Result.--Leakage flow is back up to baseline, but the bandpass is still high at a slight expense to the input-to-output resistance ratio. The gain is up, but is still down from the baseline.

• Fifth change (trial 6).--Examine the condition in which the output-to-input resistance ratio bandpass is high, by increasing the number of elements in the first stage to four and in the third stage to six.

Result.--The bandpass is high at the expense of leakage flow. The gain is back at the baseline.

• Final change (trial 7).--Decrease leakage flow by reducing the number of elements in the first and second stages to two each. Keep the gain up by increasing the first-stage aspect ratio to one. Decrease the output resistance by increasing the number of output elements to eight.

Result.--Leakage is reduced to 68 percent of the baseline, the bandpass is increased by 29 percent over the baseline, and the output-to-input resistance ratio is halved, with only a 14-percent penalty in gain.

Preliminary tests at the Massachusetts Institute of Technology have verified this capability to increase bandwidth and decrease leakage flow.

#### 3.2.4 Power- or Flow-Gain Gain Blocks

In some applications, pressure gain is not important. However, the ability to deliver flow at a given pressure is important when, for example, a positive displacement actuator must be moved at a given rate. It is clear from the arguments presented above that output impedance can be significantly reduced by employing multiple parallel elements. One gain block that has been tried for driving small actuators involves a common supply pressure arrangement consisting of LPA's with  $b_g = 0.5$  mm and  $\sigma = 0.4$  with a first stage of three parallel elements, a second stage of four, and a third stage of eight. The unit makeup is designated as [3]62008, [4]62008, [8]62008. The measured gain of 75 compares favorably with the 70 computed by using a single change gain of 8.

The output resistance of 5.84 torr/LPM indicates that at the roughly 6-torr maximum power point the unit can deliver about 1 LPM of flow.

### 3.3 Four-Stage Gain Blocks

Gain blocks with more than three stages are not very common in dc applications primarily because as the gain becomes high, even a small initial null offset can be devastating. In ac applications where high-pass filters are commonly used, a dc null offset does not affect operation. One such example is in the fluidic intercom system described by this author.<sup>5</sup> In that case, a four-stage LPA is composed of a three-stage, self-staged preamplifier of  $b_s = 0.25$  mm and  $\sigma = 1.2$  and a power fourth stage composed of two parallel elements with  $b_s = 0.25$  mm and  $\sigma = 0.8$ . The gain of this device is about 60 dB for 1 to 2 kHz.

One dc application in which a four-stage device is used, however, is a pressure regulator.\* Since it is used in a feedback configuration, it is important that the input and output resistances be comparable, that the gain be relatively high, and that it be capable of delivering sufficient flow to a load at, in this case, 6 torr. For these reasons, at least four stages are required. The gain block designed for this application is composed of a first stage of one element of  $b_{s1} = 0.5$  mm and  $\sigma = 0.75$  (62015), a second stage of two elements of  $b_{s2} = 0.375$  mm and  $\sigma_2 = 0.67$  ([2]61510), a third stage of three elements of  $b_{s3} = 0.375$  mm and  $\sigma_3 = 0.67$  ([3]61510), and a fourth stage of six elements of  $b_{s4} = 0.375$  mm and  $\sigma_4 = 0.33$  ([6]61505). The transfer characteristics and the gain as a function of supply pressure to the last stage are shown in figure 11 (p. 26). The very low gain of 61505 LPA's is the reason that the average single-stage gain is 7.5. The gain would be considerably increased by using components with better gain, say, 9 to 10. This use would increase the gain 100 to 200 percent.

### 3.4 Five-Stage Gain Block for Public Address System

The only currently used five-stage gain block is in a flueric public address system at HDL. This device is designed to have high gain and bandpass and very low output impedance in order to drive large exponential horns. To provide good matching between stages, it was decided to operate each stage at the same impedance despite changes in size or supply pressure. The design program was exercised with the result shown in figure 12. As can be seen, three different size LPA's

<sup>5</sup>T. M. Drzewiecki, A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).

\*T. M. Drzewiecki, Some Active Fluidic Compensation Circuits, submitted for American Society of Mechanical Engineers, 1982 Winter Annual Meeting, Phoenix, AZ (November 1982).

are used in an almost perfect impedance matching scheme. The dc gain was not available since the device is high passed between the first and second stages and between the fourth and fifth stages with inductive shunts designed for passing a frequency of 600 Hz. The device works well and with minimum distortion over a 600- to 3000-Hz frequency band.

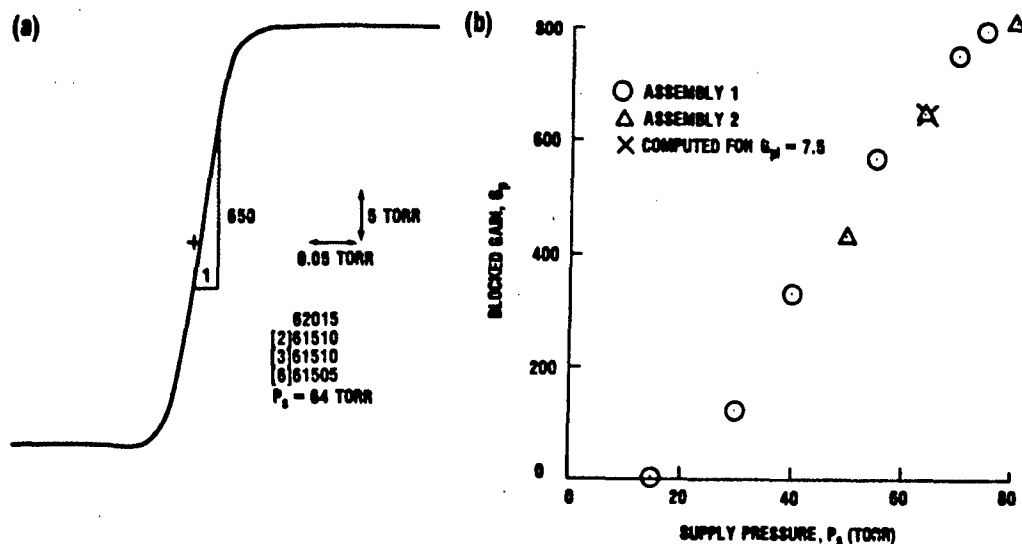


Figure 11. Four-stage pressure regulator gain block: (a) transfer and (b) gain characteristics.

### 3.5 Eight-Stage Gain Block

There are no commonly used gain blocks of six or seven stages. However, there is one device of eight stages that was used in the stabilization system of an M48 tank.<sup>13</sup> This device was designed by Charles Paras (formerly of HDL) and as implemented used some turbulent final stages. Table 2 shows the makeup.

The design program does not allow  $\sigma N_p$  to be any other value than 1000. However, since the individual gains are not greatly different from their nominal values and only the resistances change in the final two stages, it should not give a bad estimate. For an individual

<sup>13</sup>C. L. Abbott, T. B. Tippetts, S. M. Tenney, and C. Paras, A Study of Fluidic Gun Stabilization Systems for Combat Vehicles: Final Report, AiResearch Manufacturing Company of Arizona, contract with Harry Diamond Laboratories, HDL-CR-80-100-1 (April 1980).

IS YOUR LPA GAIN 10 ? YES  
 NUMBER OF STAGES? 5  
 STAGE 1 ASPECT RATIO? .75  
 NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
 STAGE 1 NOZZLE WIDTH IN MM? .508  
 STAGE 1 SUPPLY PRESSURE = 6.888902666694 TORR  
 STAGE 1 SUPPLY FLOW = .3110204081646 LPM  
 STAGE 1 SUPPLY RESISTANCE = 22.14935896762 TORR/LPM  
 STAGE 2 ASPECT RATIO? .5  
 NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 2  
 STAGE 2 NOZZLE WIDTH IN MM? .508  
 STAGE 2 SUPPLY PRESSURE = 15.50003100006 TORR  
 STAGE 2 SUPPLY FLOW = .5644444444422 LPM  
 STAGE 2 SUPPLY RESISTANCE = 27.46068484274 TORR/LPM  
 STAGE 3 ASPECT RATIO? .66667  
 NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 3  
 STAGE 3 NOZZLE WIDTH IN MM? .381  
 STAGE 3 SUPPLY PRESSURE = 15.49987600082 TORR  
 STAGE 3 SUPPLY FLOW = .6858006858039 LPM  
 STAGE 3 SUPPLY RESISTANCE = 22.60113808818 TORR/LPM  
 STAGE 4 ASPECT RATIO? 1  
 NO. OF PARALLEL ELEMENTS IN STAGE 4 ? 4  
 STAGE 4 NOZZLE WIDTH IN MM? .254  
 STAGE 4 SUPPLY PRESSURE = 15.50003100006 TORR  
 STAGE 4 SUPPLY FLOW = .6349999999976 LPM  
 STAGE 4 SUPPLY RESISTANCE = 24.40949763798 TORR/LPM  
 STAGE 5 ASPECT RATIO? .5  
 NO. OF PARALLEL ELEMENTS IN STAGE 5 ? 20  
 STAGE 5 NOZZLE WIDTH IN MM? .254  
 STAGE 5 SUPPLY PRESSURE = 62.00012400025 TORR  
 STAGE 5 SUPPLY FLOW = 2.822222222212 LPM  
 STAGE 5 SUPPLY RESISTANCE = 21.96854787418 TORR/LPM  
 FIRST STAGE BIAS PRESSURE IN TORR? 0  
 ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
 A BLOCKED LOAD IS PUT IN AS AN AR=1 AND RS=0  
 LOAD NO. OF PARALLEL STAGES? 1  
 LOAD ASPECT RATIO? 1  
 LOAD NOZZLE WIDTH(MM)? 0  
 STAGE 1 PRESSURE GAIN = 6.50198537992  
 STAGE 2 PRESSURE GAIN = 5.072692711794  
 STAGE 3 PRESSURE GAIN = 5.151701658716  
 STAGE 4 PRESSURE GAIN = 4.786223675775  
 STAGE 5 PRESSURE GAIN = 9.523809523819  
 PRESSURE GAIN OF THE 5 STAGE GAINBLOCK = 7745.312407647  
 GAINBLOCK INPUT RESISTANCE = 16.61201922572 TORR/LPM  
 GAINBLOCK OUTPUT RESISTANCE = 10.98427393709 TORR/LPM  
 GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 305.1565742289 HERTZ  
 DO YOU WANT TO MAKE ANOTHER CALCULATION? NO

Figures 12. Design program output for Harry Diamond Laboratories  
 fluoric public address system.

nominal gain of 10 per stage, the program computes a value of gain of  $2.72 \times 10^6$  (example A-9). This is in excellent agreement with the measured value of  $3 \times 10^6$ .

This then indicates the power of the design program for estimating off-design points.

TABLE 2. MAKEUP OF EIGHT-STAGE GAIN BLOCK FOR M48A5 GUN STABILIZATION SYSTEM

| Stage | Aspect ratio | Nozzle width (mm) | $ON_R$ |
|-------|--------------|-------------------|--------|
| 1     | 1.07         | 0.76              | 701    |
| 2     | 1.00         | 0.76              | 983    |
| 3     | 0.83         | 0.76              | 884    |
| 4     | 0.67         | 0.76              | 977    |
| 5     | 0.53         | 0.76              | 957    |
| 6     | 0.33         | 0.76              | 1403   |
| 7     | 0.45         | 0.51              | 4000   |
| 8     | 0.30         | 0.76              | 4617   |

Note:  $ON_R$  = aspect ratio times Reynolds number.

#### 4. DISCUSSION AND CONCLUSIONS

This report presents gain and transfer characteristic data for most of the currently used gain blocks. These gain blocks have all been implemented in C format using standard HDL LPA's.

During collection of data, it was discovered that certain LPA's did not conform to the desired characteristics of bias insensitivity as designed<sup>7</sup> in the original HDL model 3.1.1.8. These were specifically the fineblanked devices. Although they operated well and pretty much as predicted in pressure-staged configurations, they operated poorly in self-staged configurations. This behavior extended to metal etched parts manufactured from the same program that made the fineblanking dies. Subsequently, LPA's designed specifically to HDL dimensions were made by electrodischarge machining and metal etching and were found to be as desired. Consequently, no fineblanked parts exist, at this writing, that are suitable for proper high-bias or self-staged operation.

The computer design-guide program has been shown to be an effective tool for gain-block design, optimization, and off-design estimation. Optimization has been specifically demonstrated on the fluoric servo-valve amplifier.

<sup>7</sup>T. M. Drzewiecki, Fluorics 38: A Computer-Aided Design Analysis for the Static and Dynamic Port Characteristics of Laminar Proportional Amplifiers, Harry Diamond Laboratories, HDL-TR-1758 (June 1976).

22

Interestingly, high gain can be implemented with considerably fewer stages if one uses positive feedback. Typically, gains of 150 to 500 can be obtained in two stages at the expense of bandwidth. By using the first amplifier as a buffer or preamplifier and a second stage with feedback, the loss in bandwidth can be minimized. An example of using positive feedback is the three-stage servovalve in which gain is increased from 335 to over 1500.

Finally, design guidelines for amplifier stacking and implementation and a format for stacking orders have been presented.

The reader is encouraged to use the results presented here as a basis for a private library of gain blocks. Other useful devices should be logged, documented, and reported, as soon as practicable.

#### ACKNOWLEDGEMENTS

This report would have been far leaner for data had it not been for the diligence and hard work of our co-op student, Bill O'Brien, who was responsible for generating most of the gain information. The able assistance and encouragement of James Joyce also are greatly appreciated.

LITERATURE CITED

- (1) F. M. Manion and G. Mon, Fluorics 33: Design and Staging of Laminar Proportional Amplifiers, Harry Diamond Laboratories, HDL-TR-1608 (September 1972).
- (2) F. M. Manion and T. M. Drzewiecki, Analytical Design of Laminar Proportional Amplifiers, Proceedings of HDL Fluidic State-of-the-Art Symposium, 1 (October 1974).
- (3) T. M. Drzewiecki, D. Wormley, and F. M. Manion, A Computer-Aided Design Procedure for Laminar Fluidic Systems, J. Dyn. Sys. Meas. Control, 97, Series G, No. 4 (December 1975).
- (4) G. Mon, Fluoric Laminar Gain Blocks and an Operational Amplifier Scaler, Harry Diamond Laboratories, HDL-TR-1730 (December 1975).
- (5) T. M. Drzewiecki, A Fluidic Audio Intercom, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).
- (6) M. Cycon and D. Shaffer, Design Guide for Laminar Flow Fluidic Amplifiers and Sensors, contract with Garrett Pneumatic Systems Division, Harry Diamond Laboratories, HDL-CR-82-288-1 (March 1982).
- (7) T. M. Drzewiecki, Fluorics 38: A Computer-Aided Design Analysis for the Static and Dynamic Port Characteristics of Laminar Proportional Amplifiers, Harry Diamond Laboratories, HDL-TR-1758 (June 1976).
- (8) L. Scheer, J. Roundy, and J. Joyce, Manufacturing Techniques for Producing High Quality Fluidic Laminates in Production Quantities, Proceedings of 20th Anniversary of Fluidics Symposium, American Society of Mechanical Engineers special publication G00177, Chicago, IL (November 1980).
- (9) R. M. Phillippi, A Study of Fineblanking for the Manufacture of Fluoric Laminar Proportional Amplifiers, Harry Diamond Laboratories, HDL-TM-77-8 (May 1977).
- (10) R. M. Phillippi, T. M. Drzewiecki, T. Negas, and H. S. Parker, Design of a Fluidic Capillary Pyrometer for Contact Duty at Temperatures to 2750°C, Proceedings of 6th International Symposium on Temperature, Washington, DC (15 to 19 March 1982).

- (11) D. N. Wormley, D. Lee, and K. M. Lee, Development of a Fluidic, Hydraulic Servovalve, Massachusetts Institute of Technology, contract with Harry Diamond Laboratories, HDL-CR-81-216-1 (February 1981).
- (12) D. Lee and D. N. Wormley, A Fluidic Hydraulic Servovalve, J. Dyn. Sys. Meas. Control, 103, No. 4 (December 1981).
- (13) C. L. Abbott, T. B. Tippetts, S. M. Tenney, and C. Paras, A Study of Fluidic Gun Stabilization Systems for Combat Vehicles: Final Report, AiResearch Manufacturing Company of Arizona, contract with Harry Diamond Laboratories, HDL-CR-80-100-1 (April 1980).

#### APPENDIX A.--BASIC PROGRAM AND REPRESENTATIVE EXAMPLES

This appendix contains the computer program, written in BASIC, that yields design approximations for multistage laminar proportional amplifiers. The program is based on a single-stage block-loaded gain of 10, but allows the user to insert different corresponding gain values where appropriate.

Following a listing of the program, nine different sample runs are presented.

# APPENDIX A

```

10 DIM P(10),Q(10),K(10),A(10),B(10),G(10)
20 GO=10
30 PRINT "*****"
40 PRINT "THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS"
50 PRINT "BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS, BLOCKED"
60 PRINT "SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA*NR=1000 IN AIR."
70 PRINT "FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF PREVIOUS, E.G. FOR BS1=BS2, AR(1)=3 AND AR(2)=1."
80 PRINT "*****"
90 PRINT
100 INPUT "IS YOUR LPA GAIN 10 ",Y$: IF STR(Y$,1,1)="Y" THEN 120
110 INPUT "WHAT IS YOUR GAIN",GO
120 INPUT "NUMBER OF STAGES",N
130 FOR M=1 TO N
140 PRINT "STAGE ";M;" ASPECT RATIO";: INPUT A(M+1)
150 PRINT "NO. OF PARALLEL ELEMENTS IN STAGE ";M;: INPUT K(M+1)
160 PRINT "STAGE ";M;" NOZZLE WIDTH IN MM";: INPUT B(M+1)
170 P(M+1)=1/(A(M+1)*B(M+1))^2
180 PRINT "STAGE ";M;" SUPPLY PRESSURE = ";P(M+1);" TORR"
190 Q(M+1)=2.5*SQR(P(M+1)*B(M+1)^2/(1+1/A(M+1))^2)*K(M+1)
200 PRINT "STAGE ";M;" SUPPLY FLOW = ";Q(M+1);" LPM"
210 PRINT "STAGE ";M;" SUPPLY RESISTANCE = ";P(M+1)/Q(M+1);" TORR/LPM"
220 NEXT M
230 INPUT "FIRST STAGE BIAS PRESSURE IN TORR",P0
240 P(1)=P0^3
250 PRINT "ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA"
260 PRINT "A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0"
270 INPUT "LOAD NO. OF PARALLEL STAGES",K(N+2)
280 INPUT "LOAD ASPECT RATIO",A(N+2)
290 INPUT "LOAD NOZZLE WIDTH(MM)",B(N+2)
300 IF B(N+2)=0 THEN 310:P(N+2)=1/(A(N+2)*B(N+2))^2:Q(N+2)=2.5*SQR(P(N+2)*K(N+2)*B(N+2)^2/(1+1/A(N+2))^2):GOTO 320
310 P(N+2)=1:Q(N+2)=0
320 L=0
330 FOR J=1 TO N
340 G(J)=GO*(1/(1+.20*P(J)/P(J+1)))*(1/(1+.667*P(J+1)*Q(J+2)/P(J+2)/Q(J+1)))
350 PRINT "STAGE ";J;" PRESSURE GAIN = ";G(J)
360 L=L+B(J+1)/SQR(P(J+1))
370 IF J=1 THEN 400
380 G=G(J)*G
390 GOTO 410
400 G=G(J)
410 NEXT J
420 PRINT "PRESSURE GAIN OF THE ";N;" STAGE GAINBLOCK = ";G
430 PRINT "GAINBLOCK INPUT RESISTANCE = ";.75*P(2)/Q(2);" TORR/LPM"
440 PRINT "GAINBLOCK OUTPUT RESISTANCE = ";.5*P(N+1)/Q(N+1);" TORR/LPM"
450 PRINT "GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = ";157.5/L;" HERTZ"
460 INPUT "DO YOU WANT TO MAKE ANOTHER CALCULATION",I$: IF STR(I$,1,1)="Y" THEN 470:GOTO 480
470 PRINT :PRINT :PRINT :GOTO 120
480 STOP :END

```

BASIC PROGRAM

## APPENDIX A

\*\*\*\*\*  
 THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS  
 BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS, BLOCKED  
 SINGLE STAGE GAIN OF 10 OPERATING AT  $\text{SIGMA} \cdot \text{NR} = 1000$  IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND  
 NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF THE  
 PREVIOUS, E.G. FOR  $\text{BS1} = \text{BS2}$ ,  $\text{AR}(1) = 3$  AND  $\text{AR}(2) = 1$ .  
 \*\*\*\*\*

IS YOUR LPA GAIN 10 ? N  
 WHAT IS YOUR GAIN? 8  
 NUMBER OF STAGES? 2  
 STAGE 1 ASPECT RATIO? .667  
 NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
 STAGE 1 NOZZLE WIDTH IN MM? .381  
 STAGE 1 SUPPLY PRESSURE = 15.4845425861 TORR  
 STAGE 1 SUPPLY FLOW = .2286228417162 LPM  
 STAGE 1 SUPPLY RESISTANCE = 67.72963921655 TORR/LPM  
 STAGE 2 ASPECT RATIO? .667  
 NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 1  
 STAGE 2 NOZZLE WIDTH IN MM? .381  
 STAGE 2 SUPPLY PRESSURE = 15.4845425861 TORR  
 STAGE 2 SUPPLY FLOW = .2286228417162 LPM  
 STAGE 2 SUPPLY RESISTANCE = 67.72963921655 TORR/LPM  
 FIRST STAGE BIAS PRESSURE IN TORR? 0  
 ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
 A BLOCKED LOAD IS PUT IN AS AN  $\text{AR} = 1$  AND  $\text{BS} = 0$   
 LOAD NO. OF PARALLEL STAGES? 1  
 LOAD ASPECT RATIO? 1  
 LOAD NOZZLE WIDTH(MM)? 0  
 STAGE 1 PRESSURE GAIN = 4.799040191962  
 STAGE 2 PRESSURE GAIN = 6.666666666666  
 PRESSURE GAIN OF THE 2 STAGE GAINBLOCK = 31.99360127974  
 GAINBLOCK INPUT RESISTANCE = 50.79722941243 TORR/LPM  
 GAINBLOCK OUTPUT RESISTANCE = 33.86481960827 TORR/LPM  
 GAINBLOCK BANDWIDTH AT 90DEC PHASE SHIFT = 813.3449550178 HERTZ  
 DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP

Example A-1. Two-stage, self-staged gain block.

## APPENDIX A

\*\*\*\*\*  
 THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS  
 BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS, BLOCKED  
 SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA\*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND  
 NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF THE  
 PREVIOUS, E.G. FOR BS1=BS2, AR(1)=3 AND AR(2)=1.

\*\*\*\*\*

IS YOUR LPA GAIN 10 ? N  
 WHAT IS YOUR GAIN? 8.5  
 NUMBER OF STAGES? 2  
 STAGE 1 ASPECT RATIO? .66667  
 NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
 STAGE 1 NOZZLE WIDTH IN MM? .381  
 STAGE 1 SUPPLY PRESSURE = 15.49987600082 TORR  
 STAGE 1 SUPPLY FLOW = .2286002286013 LPM  
 STAGE 1 SUPPLY RESISTANCE = 67.80341426453 TORR/LPM  
 STAGE 2 ASPECT RATIO? .333333  
 NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 1  
 STAGE 2 NOZZLE WIDTH IN MM? .381  
 STAGE 2 SUPPLY PRESSURE = 62.00024800074 TORR  
 STAGE 2 SUPPLY FLOW = .1785936607044 LPM  
 STAGE 2 SUPPLY RESISTANCE = 347.1581676315 TORR/LPM  
 FIRST STAGE BIAS PRESSURE IN TORR? 0  
 ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
 A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0  
 LOAD NO. OF PARALLEL STAGES? 1  
 LOAD ASPECT RATIO? 1  
 LOAD NOZZLE WIDTH(MM)? 0  
 STAGE 1 PRESSURE GAIN = 7.520315831375  
 STAGE 2 PRESSURE GAIN = 8.09524272106  
 PRESSURE GAIN OF THE 2 STAGE GAINBLOCK = 60.87878199401  
 GAINBLOCK INPUT RESISTANCE = 50.85256069842 TORR/LPM  
 GAINBLOCK OUTPUT RESISTANCE = 173.5790838157 TORR/LPM  
 GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 1084.998915014 HERTZ  
 DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP

Example A-2. Two-stage gain block of fluidic capillary pyrometer.

# APPENDIX A

\*\*\*\*\*  
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS  
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS, BLOCKED  
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA\*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND  
NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF THE  
PREVIOUS. E.G. FOR BS1=BS2, AR(1)=3 AND AR(2)=1.

\*\*\*\*\*

IS YOUR LPA GAIN 10 ? Y  
NUMBER OF STAGES? 3  
STAGE 1 ASPECT RATIO? 1  
NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
STAGE 1 NOZZLE WIDTH IN MM? .508  
STAGE 1 SUPPLY PRESSURE = 3.875007750016 TORR  
STAGE 1 SUPPLY FLOW = .3174999999988 LPM  
STAGE 1 SUPPLY RESISTANCE = 12.20474881899 TORR/LPM  
STAGE 2 ASPECT RATIO? 1  
NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 1  
STAGE 2 NOZZLE WIDTH IN MM? .508  
STAGE 2 SUPPLY PRESSURE = 3.875007750016 TORR  
STAGE 2 SUPPLY FLOW = .3174999999988 LPM  
STAGE 2 SUPPLY RESISTANCE = 12.20474881899 TORR/LPM  
STAGE 3 ASPECT RATIO? 1  
NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 1  
STAGE 3 NOZZLE WIDTH IN MM? .508  
STAGE 3 SUPPLY PRESSURE = 3.875007750016 TORR  
STAGE 3 SUPPLY FLOW = .3174999999988 LPM  
STAGE 3 SUPPLY RESISTANCE = 12.20474881899 TORR/LPM  
FIRST STAGE BIAS PRESSURE IN TORR? 0  
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0  
LOAD NO. OF PARALLEL STAGES? 1  
LOAD ASPECT RATIO? 1  
LOAD NOZZLE WIDTH(MM)? 0  
STAGE 1 PRESSURE GAIN = 5.998800239952  
STAGE 2 PRESSURE GAIN = 4.99900019996  
STAGE 3 PRESSURE GAIN = 8.33333333333  
PRESSURE GAIN OF THE 3 STAGE GAINBLOCK = 249.900029992  
GAINBLOCK INPUT RESISTANCE = 9.153561614246 TORR/LPM  
GAINBLOCK OUTPUT RESISTANCE = 6.102374409497 TORR/LPM  
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 203.437906875 HERTZ  
DO YOU WANT TO MAKE ANOTHER CALCULATION? Y

Example A-3. Three-stage, self-staged gain block.

# APPENDIX A

NUMBER OF STAGES? 3  
 STAGE 1 ASPECT RATIO? .6667  
 NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
 STAGE 1 NOZZLE WIDTH IN MM? .76  
 STAGE 1 SUPPLY PRESSURE = 3.895039849219 TORR  
 STAGE 1 SUPPLY FLOW = .4560045596449 LPM  
 STAGE 1 SUPPLY RESISTANCE = 8.54166864527 TORR/LPM  
 STAGE 2 ASPECT RATIO? 1  
 NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 1  
 STAGE 2 NOZZLE WIDTH IN MM? .508  
 STAGE 2 SUPPLY PRESSURE = 3.875007750016 TORR  
 STAGE 2 SUPPLY FLOW = .3174999999988 LPM  
 STAGE 2 SUPPLY RESISTANCE = 12.20474881899 TORR/LPM  
 STAGE 3 ASPECT RATIO? 2  
 NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 1  
 STAGE 3 NOZZLE WIDTH IN MM? .254  
 STAGE 3 SUPPLY PRESSURE = 3.875007750016 TORR  
 STAGE 3 SUPPLY FLOW = .1411111111105 LPM  
 STAGE 3 SUPPLY RESISTANCE = 27.46068484275 TORR/LPM  
 FIRST STAGE DIAS PRESSURE IN TORR? 0  
 ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
 A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0  
 LOAD NO. OF PARALLEL STAGES? 1  
 LOAD ASPECT RATIO? 1  
 LOAD NOZZLE WIDTH(MM)? 0  
 STAGE 1 PRESSURE GAIN = 6.817517773483  
 STAGE 2 PRESSURE GAIN = 6.422303400955  
 STAGE 3 PRESSURE GAIN = 8.333333333333  
 PRESSURE GAIN OF THE 3 STAGE GAINBLOCK = 364.8680631895  
 GAINBLOCK INPUT RESISTANCE = 6.406251483952 TORR/LPM  
 GAINBLOCK OUTPUT RESISTANCE = 13.73034242139 TORR/LPM  
 GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 203.9674795827 HERTZ  
 DO YOU WANT TO MAKE ANOTHER CALCULATION? Y

Example A-4. Three-stage, common supply gain block.

# APPENDIX A

\*\*\*\*\*  
 THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS  
 BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-LOSS, BLOCKED  
 SINGLE STAGE GAIN OF 10 OPERATING AT  $\Sigma NR=1000$  IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND  
 NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF THE  
 PREVIOUS, E.G. FOR  $BS1=BS2$ ,  $AR(1)=3$  AND  $AR(2)=1$ .

\*\*\*\*\*

IS YOUR LPA GAIN 10 ? Y  
 NUMBER OF STAGES? 3  
 STAGE 1 ASPECT RATIO? 1  
 NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 4  
 STAGE 1 NOZZLE WIDTH IN MM? .254  
 STAGE 1 SUPPLY PRESSURE = 15.50003100006 TORR  
 STAGE 1 SUPPLY FLOW = .6347999999976 LPM  
 STAGE 1 SUPPLY RESISTANCE = 24.40949763798 TORR/LPM  
 STAGE 2 ASPECT RATIO? 1  
 NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 2  
 STAGE 2 NOZZLE WIDTH IN MM? .254  
 STAGE 2 SUPPLY PRESSURE = 15.50003100006 TORR  
 STAGE 2 SUPPLY FLOW = .3174999999988 LPM  
 STAGE 2 SUPPLY RESISTANCE = 48.81899527596 TORR/LPM  
 STAGE 3 ASPECT RATIO? 1  
 NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 1  
 STAGE 3 NOZZLE WIDTH IN MM? .254  
 STAGE 3 SUPPLY PRESSURE = 15.50003100006 TORR  
 STAGE 3 SUPPLY FLOW = .1587499999994 LPM  
 STAGE 3 SUPPLY RESISTANCE = 97.63799055193 TORR/LPM  
 FIRST STAGE BIAS PRESSURE IN TORR? 0  
 ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
 A BLOCKED LOAD IS PUT IN AS AN  $AR=1$  AND  $BS=0$   
 LOAD NO. OF PARALLEL STAGES? 1  
 LOAD ASPECT RATIO? 1  
 LOAD NOZZLE WIDTH(MM)? 0  
 STAGE 1 PRESSURE GAIN = 7.499062617173  
 STAGE 2 PRESSURE GAIN = 6.249218847644  
 STAGE 3 PRESSURE GAIN = 8.333333333333  
 PRESSURE GAIN OF THE 3 STAGE GAINBLOCK = 390.5273620575  
 GAINBLOCK INPUT RESISTANCE = 18.30712322849 TORR/LPM  
 GAINBLOCK OUTPUT RESISTANCE = 48.81899527596 TORR/LPM  
 GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 813.7516275003 HERTZ  
 DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP

Example A-5. Three-stage, parallel-element, common supply gain block.

## APPENDIX A

\*\*\*\*\*  
 THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS  
 BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS, BLOCKED  
 SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA\*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND  
 NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF THE  
 PREVIOUS, E.G. FOR BS1=BS2, AR(1)=3 AND AR(2)=1.  
 \*\*\*\*\*

IS YOUR LPA GAIN 10 ? Y  
 NUMBER OF STAGES? 3  
 STAGE 1 ASPECT RATIO? 3.6  
 NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
 STAGE 1 NOZZLE WIDTH IN MM? .508  
 STAGE 1 SUPPLY PRESSURE = .2989975115753 TORR  
 STAGE 1 SUPPLY FLOW = .2160680529282 LPM  
 STAGE 1 SUPPLY RESISTANCE = 1.383811755247 TORR/LPM  
 STAGE 2 ASPECT RATIO? 1.2  
 NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 1  
 STAGE 2 NOZZLE WIDTH IN MM? .508  
 STAGE 2 SUPPLY PRESSURE = 2.690977604177 TORR  
 STAGE 2 SUPPLY FLOW = .3148760330576 LPM  
 STAGE 2 SUPPLY RESISTANCE = 8.546149346606 TORR/LPM  
 STAGE 3 ASPECT RATIO? .4  
 NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 1  
 STAGE 3 NOZZLE WIDTH IN MM? .508  
 STAGE 3 SUPPLY PRESSURE = 24.2187984376 TORR  
 STAGE 3 SUPPLY FLOW = .2991836734683 LPM  
 STAGE 3 SUPPLY RESISTANCE = 93.44260814546 TORR/LPM  
 FIRST STAGE BIAS PRESSURE IN TORR? 0  
 ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
 A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0  
 LOAD NO. OF PARALLEL STAGES? 1  
 LOAD ASPECT RATIO? 1  
 LOAD NOZZLE WIDTH(MM)? 0  
 STAGE 1 PRESSURE GAIN = 9.025253305181  
 STAGE 2 PRESSURE GAIN = 9.220151573197  
 STAGE 3 PRESSURE GAIN = 9.782608695654  
 PRESSURE GAIN OF THE 3 STAGE GAINBLOCK = 814.0519903724  
 GAINBLOCK INPUT RESISTANCE = 1.037858816435 TORR/LPM  
 GAINBLOCK OUTPUT RESISTANCE = 46.7213040727 TORR/LPM  
 GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 117.3680231977 HERTZ  
 DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP

Example A-6. Three-stage maximum dynamic range gain block.

# APPENDIX A

\*\*\*\*\*  
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS  
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS, BLOCKED  
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA\*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND  
NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF THE  
PREVIOUS, E.G. FOR BS1=BS2, AR(1)=3 AND AR(2)=1.  
\*\*\*\*\*

IS YOUR LPA GAIN 10 ? Y  
NUMBER OF STAGES? 3  
STAGE 1 ASPECT RATIO? .67  
NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
STAGE 1 NOZZLE WIDTH IN MM? .76  
STAGE 1 SUPPLY PRESSURE = 3.85676529084 TORR  
STAGE 1 SUPPLY FLOW = .4564523647292 LPM  
STAGE 1 SUPPLY RESISTANCE = 8.449436543347 TORR/LPM  
STAGE 2 ASPECT RATIO? 1  
NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 1  
STAGE 2 NOZZLE WIDTH IN MM? .508  
STAGE 2 SUPPLY PRESSURE = 3.875007750016 TORR  
STAGE 2 SUPPLY FLOW = .3174999999988 LPM  
STAGE 2 SUPPLY RESISTANCE = 12.20474881899 TORR/LPM  
STAGE 3 ASPECT RATIO? .8  
NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 1  
STAGE 3 NOZZLE WIDTH IN MM? .254  
STAGE 3 SUPPLY PRESSURE = 24.2187984376 TORR  
STAGE 3 SUPPLY FLOW = .1567901234562 LPM  
STAGE 3 SUPPLY RESISTANCE = 154.4663522404 TORR/LPM  
FIRST STAGE BIAS PRESSURE IN TORR? 0  
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0  
LOAD NO. OF PARALLEL STAGES? 1  
LOAD ASPECT RATIO? 1  
LOAD NOZZLE WIDTH(MM)? 0  
STAGE 1 PRESSURE GAIN = 6.841026366496  
STAGE 2 PRESSURE GAIN = 7.922358876867  
STAGE 3 PRESSURE GAIN = 9.68992248062  
PRESSURE GAIN OF THE 3 STAGE GAINBLOCK = 525.1653678439  
GAINBLOCK INPUT RESISTANCE = 6.33707740751 TORR/LPM  
GAINBLOCK OUTPUT RESISTANCE = 77.2331761202 TORR/LPM  
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 226.0758627341 HERTZ  
DO YOU WANT TO MAKE ANOTHER CALCULATION? NO

STOP

Example A-7. Moderately pressure staged, three-stage gain block with  
change in size.

# APPENDIX A

\*\*\*\*\*  
THIS PROGRAM GIVES DESIGN APPROXIMATIONS FOR MULTISTAGE LPAS  
BASED ON THE STANDARD HDL LPA, ASSUMING A ZERO-BIAS, BLOCKED  
SINGLE STAGE GAIN OF 10 OPERATING AT SIGMA\*NR=1000 IN AIR.

FOR MAXIMUM DYNAMIC RANGE THE PRODUCT OF ASPECT RATIO AND  
NOZZLE WIDTH OF EACH SUCCEEDING STAGE SHOULD BE 1/3RD OF THE  
PREVIOUS, E.G. FOR BS1=BS2, AR(1)=3 AND AR(2)=1.  
\*\*\*\*\*

IS YOUR LPA GAIN 10 ? N  
WHAT IS YOUR GAIN? 8  
NUMBER OF STAGES? 3  
STAGE 1 ASPECT RATIO? .66667  
NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 2  
STAGE 1 NOZZLE WIDTH IN MM? .76  
STAGE 1 SUPPLY PRESSURE = 3.895390408859 TORR  
STAGE 1 SUPPLY FLOW = .9120009119738 LPM  
STAGE 1 SUPPLY RESISTANCE = 4.271257142088 TORR/LPM  
STAGE 2 ASPECT RATIO? .5  
NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 3  
STAGE 2 NOZZLE WIDTH IN MM? .508  
STAGE 2 SUPPLY PRESSURE = 15.50003100006 TORR  
STAGE 2 SUPPLY FLOW = .8466666666633 LPM  
STAGE 2 SUPPLY RESISTANCE = 18.30712322845 TORR/LPM  
STAGE 3 ASPECT RATIO? .3333  
NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 6  
STAGE 3 NOZZLE WIDTH IN MM? .375  
STAGE 3 SUPPLY PRESSURE = 64.01280192128 TORR  
STAGE 3 SUPPLY FLOW = 1.054634762344 LPM  
STAGE 3 SUPPLY RESISTANCE = 60.69665462099 TORR/LPM  
FIRST STAGE BIAS PRESSURE IN TORR? 0  
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0  
LOAD NO. OF PARALLEL STAGES? 1  
LOAD ASPECT RATIO? 1  
LOAD NOZZLE WIDTH(MM)? 0  
STAGE 1 PRESSURE GAIN = 6.922699358662  
STAGE 2 PRESSURE GAIN = 6.341389575126  
STAGE 3 PRESSURE GAIN = 7.630472181181  
PRESSURE GAIN OF THE 3 STAGE GAINBLOCK = 334.97416948  
GAINBLOCK INPUT RESISTANCE = 3.203442856566 TORR/LPM  
GAINBLOCK OUTPUT RESISTANCE = 30.34832731049 TORR/LPM  
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 280.7632244981 HERTZ  
DO YOU WANT TO MAKE ANOTHER CALCULATION? N

STOP

Example A-8. Flueric servovalve gain block.

# APPENDIX A

NUMBER OF STAGES? 8  
 STAGE 1 ASPECT RATIO? 1.07  
 NO. OF PARALLEL ELEMENTS IN STAGE 1 ? 1  
 STAGE 1 NOZZLE WIDTH IN MM? .76  
 STAGE 1 SUPPLY PRESSURE = 1.512186163908 TORR  
 STAGE 1 SUPPLY FLOW = .4744568134623 LPM  
 STAGE 1 SUPPLY RESISTANCE = 3.187194536997 TORR/LPM  
 STAGE 2 ASPECT RATIO? 1  
 NO. OF PARALLEL ELEMENTS IN STAGE 2 ? 1  
 STAGE 2 NOZZLE WIDTH IN MM? .76  
 STAGE 2 SUPPLY PRESSURE = 1.731301939058 TORR  
 STAGE 2 SUPPLY FLOW = .4750000000058 LPM  
 STAGE 2 SUPPLY RESISTANCE = 3.644846187446 TORR/LPM  
 STAGE 3 ASPECT RATIO? .833  
 NO. OF PARALLEL ELEMENTS IN STAGE 3 ? 1  
 STAGE 3 NOZZLE WIDTH IN MM? .76  
 STAGE 3 SUPPLY PRESSURE = 2.495070449392 TORR  
 STAGE 3 SUPPLY FLOW = .4710572283805 LPM  
 STAGE 3 SUPPLY RESISTANCE = 5.296745913379 TORR/LPM  
 STAGE 4 ASPECT RATIO? .66667  
 NO. OF PARALLEL ELEMENTS IN STAGE 4 ? 1  
 STAGE 4 NOZZLE WIDTH IN MM? .76  
 STAGE 4 SUPPLY PRESSURE = 3.895390408859 TORR  
 STAGE 4 SUPPLY FLOW = .4560004559869 LPM  
 STAGE 4 SUPPLY RESISTANCE = 8.542514284176 TORR/LPM  
 STAGE 5 ASPECT RATIO? .5333  
 NO. OF PARALLEL ELEMENTS IN STAGE 5 ? 1  
 STAGE 5 NOZZLE WIDTH IN MM? .76  
 STAGE 5 SUPPLY PRESSURE = 6.08736927703 TORR  
 STAGE 5 SUPPLY FLOW = .4307936914142 LPM  
 STAGE 5 SUPPLY RESISTANCE = 14.12403336359 TORR/LPM  
 STAGE 6 ASPECT RATIO? .333  
 NO. OF PARALLEL ELEMENTS IN STAGE 6 ? 1  
 STAGE 6 NOZZLE WIDTH IN MM? .76  
 STAGE 6 SUPPLY PRESSURE = 15.61292769398 TORR  
 STAGE 6 SUPPLY FLOW = .356071763629 LPM  
 STAGE 6 SUPPLY RESISTANCE = 43.84769950545 TORR/LPM  
 STAGE 7 ASPECT RATIO? .45  
 NO. OF PARALLEL ELEMENTS IN STAGE 7 ? 1  
 STAGE 7 NOZZLE WIDTH IN MM? .508  
 STAGE 7 SUPPLY PRESSURE = 19.13584074082 TORR  
 STAGE 7 SUPPLY FLOW = .271819262763 LPM  
 STAGE 7 SUPPLY RESISTANCE = 70.39913413901 TORR/LPM  
 STAGE 8 ASPECT RATIO? .3  
 NO. OF PARALLEL ELEMENTS IN STAGE 8 ? 1  
 STAGE 8 NOZZLE WIDTH IN MM? .76  
 STAGE 8 SUPPLY PRESSURE = 19.23668821176 TORR  
 STAGE 8 SUPPLY FLOW = .3372781065064 LPM  
 STAGE 8 SUPPLY RESISTANCE = 57.0350931195 TORR/LPM

Example A-9. Eight-stage M48A5 gun stabilization system gain block  
 (cont'd).

APPENDIX A

FIRST STAGE BIAS PRESSURE IN TORR? 0  
ENTER OUTPUT LOAD IN TERMS OF AN EQUIVALENT LPA  
A BLOCKED LOAD IS PUT IN AS AN AR=1 AND BS=0  
LOAD NO. OF PARALLEL STAGES? 1  
LOAD ASPECT RATIO? 1  
LOAD NOZZLE WIDTH(MM)? 0  
STAGE 1 PRESSURE GAIN = 6.316119474231  
STAGE 2 PRESSURE GAIN = 5.834821179151  
STAGE 3 PRESSURE GAIN = 6.212174122533  
STAGE 4 PRESSURE GAIN = 6.316327274507  
STAGE 5 PRESSURE GAIN = 7.297506173708  
STAGE 6 PRESSURE GAIN = 6.553892007645  
STAGE 7 PRESSURE GAIN = 4.715178897435  
STAGE 8 PRESSURE GAIN = 8.340620888182  
PRESSURE GAIN OF THE 8 STAGE GAINBLOCK = 2719921.938609  
GAINBLOCK INPUT RESISTANCE = 2.390395902748 TORR/LPM  
GAINBLOCK OUTPUT RESISTANCE = 28.51754655975 TORR/LPM  
GAINBLOCK BANDWIDTH AT 90DEG PHASE SHIFT = 55.2316647611 HERTZ  
DO YOU WANT TO MAKE ANOTHER CALCULATION? NO

STOP

Example A-9. Eight-stage M48A5 gun stabilization system gain block  
(cont'd).

22

APPENDIX B.--REPRESENTATIVE STACKING ORDERS

## APPENDIX B

This appendix presents the detailed stacking orders for three specific gain block configurations.

### EXAMPLE B-1. STACKING ORDER FOR TWO-STAGE, SELF-STAGED GAIN BLOCK

| Part             | Orientation | Notes                                         |
|------------------|-------------|-----------------------------------------------|
| 5035             | A           | Transfer control signal to outer holes        |
| 5018a            | H           | Blocks control signal from second stage       |
| Vent             | H           | 5011a or 5239, depending on $b_s$             |
| Kidney           | A           | 5215a, 5237a, 5242a, or 5340a                 |
| Butterfly        | A           | 5137a, 5236a, 5241a, or 5339a                 |
| LPA <sup>a</sup> | A           | 630xx, 620xx, 615xx, or other                 |
| Butterfly        | A           | --                                            |
| Kidney           | A           | --                                            |
| Vent             | H           | --                                            |
| 5022a            | D           | Keeps vents from communicating                |
| 5018a            | A           | Blocks first-stage controls from second stage |
| Vent             | H           | --                                            |
| Kidney           | H           | --                                            |
| Butterfly        | H           | --                                            |
| LPA              | H           | --                                            |
| Butterfly        | H           | --                                            |
| Kidney           | H           | --                                            |
| Vent             | H           | --                                            |
| 5040a            | A           | --                                            |
| 5117             | H           | Transfer control signal to first-stage inputs |
| 5040a            | A           | Paralleled supply transfer for quietness.     |
| 5011a            | E           |                                               |
| 5040a            | A           |                                               |
| 5011a            | E           |                                               |
| Cover plate      | --          | --                                            |

<sup>a</sup>LPA: laminar proportional amplifier

# APPENDIX B

## EXAMPLE B-2. GAIN BLOCK OF FLUIDIC CAPILLARY PYROMETER

| Part  | Orientation | Notes                                              |
|-------|-------------|----------------------------------------------------|
| 5043  | --          | Not needed when base is "0" ringed                 |
| 5005  | --          | Not needed with good filtration                    |
| 5109  | F           | --                                                 |
| 5116  | H           | --                                                 |
| 5111  | G           | --                                                 |
| 5221a | A           | 5 mils thick                                       |
| 5018a | A           | --                                                 |
| 5221a | A           | --                                                 |
| 5018a | A           | Second-stage LPA, <sup>a</sup> aspect ratio = 0.33 |
| 5011a | A           |                                                    |
| 5339a | C           |                                                    |
| 61505 | C           |                                                    |
| 5339a | C           |                                                    |
| 5011a | A           | First-stage LPA, aspect ratio = 0.67               |
| 5018a | H           |                                                    |
| 5011a | A           |                                                    |
| 5339a | F           |                                                    |
| 61510 | A           |                                                    |
| 5339a | F           | First-stage LPA, aspect ratio = 0.67               |
| 5011a | A           |                                                    |
| 5018a | A           |                                                    |
| 5118a | A           |                                                    |
| 5018A | H           |                                                    |
| 5114  | H           | --                                                 |
| 5039  | F           | --                                                 |
| 5112  | B           | --                                                 |

<sup>a</sup>LPA: laminar proportional amplifier

APPENDIX B

EXAMPLE B-3. THREE-STAGE MAXIMUM DYNAMIC RANGE GAIN BLOCK

| Part           | Orientation | Notes                                                                         |
|----------------|-------------|-------------------------------------------------------------------------------|
| 5239a(2)       | A           | Exhaust                                                                       |
| 5215a          | C           | Vent collector                                                                |
| 5137a          | C           | Vent plate                                                                    |
| 62012(6)       | C           | First-stage laminar proportional amplifier, aspect ratio = 3.6                |
| 5137a          | C           | --                                                                            |
| 5215a          | C           | --                                                                            |
| 5239a(2)       | A           | --                                                                            |
| 5022a          | B           | Isolate first-stage venting                                                   |
| 5188a(3)       | C           | Transfer input signal into first stage                                        |
| 5018a          | A           | } Three pairs, first-stage supply transfer                                    |
| 5011a          | D           |                                                                               |
| 5021a          | A           | Block main pressure from first stage                                          |
| 5221a (4 mils) | A           | } Four pairs, first-stage dropping resistor                                   |
| 5018a          | A           |                                                                               |
| 5221a (4 mils) | A           | --                                                                            |
| 5021a          | C           | Block second-stage pressure from first stage                                  |
| 5239a          | A           | --                                                                            |
| 5215a          | A           | --                                                                            |
| 5137a          | A           | --                                                                            |
| 62012(2)       | A           | Second-stage laminar proportional amplifier, aspect ratio = 1.2               |
| 5137a          | A           | --                                                                            |
| 5215a          | A           | --                                                                            |
| 5018a          | C           | Block second stage controls, transfer to third stage                          |
| 5239a          | A           | --                                                                            |
| 5215a          | C           | --                                                                            |
| 5137a          | C           | --                                                                            |
| 62008          | C           | --                                                                            |
| 5137a          | C           | --                                                                            |
| 5215a          | C           | --                                                                            |
| 5239a          | A           | --                                                                            |
| 5018a          | A           | } Five pairs, second-stage dropping resistor and third-stage control blockage |
| 5221a (5 mils) | A           |                                                                               |
| 5118a(3)       | C           | Transfer input signal to outer holes to transfer to first stage               |

# DISTRIBUTION

ADMINISTRATOR  
DEFENSE TECHNICAL INFORMATION CENTER  
ATTN DTIC-DDA (12 COPIES)  
CAMERON STATION, BUILDING 5  
ALEXANDRIA, VA 22314

COMMANDER  
US ARMY RSCH & STD GP (EUR)  
ATTN CHIEF, PHYSICS & MATH BRANCH  
FPO NEW YORK 09510

COMMANDER  
US ARMY MATERIEL DEVELOPMENT &  
READINESS COMMAND  
ATTN DRCLDC, JAMES BENDER  
5001 EISENHOWER AVENUE  
ALEXANDRIA, VA 22333

COMMANDER  
US ARMY ARMAMENT MATERIEL  
READINESS COMMAND  
ATTN DRSAR-ASF, FUZE &  
MUNITIONS SUPPORT DIV  
ATTN DRSAR-RDP, SYS DEV DIV-FUZES  
ATTN DRSAR-RDG-T, R. SPENCER  
ATTN DRSAR-ASF  
ATTN DRSAR-LEP-L, TECH LIBRARY  
ROCK ISLAND, IL 61299

COMMANDER  
US ARMY MISSILE & MUNITIONS  
CENTER & SCHOOL  
ATTN ATSK-CTD-F  
REDSTONE ARSENAL, AL 35809

DIRECTOR  
US ARMY MATERIEL SYSTEMS  
ANALYSIS ACTIVITY  
ATTN DRXSY-MP  
ABERDEEN PROVING GROUND, MD 21005

DIRECTOR  
US ARMY BALLISTIC RESEARCH LABORATORY  
ATTN DRDAR-TSB-S (STINFO)  
ABERDEEN PROVING GROUND, MD 21005

US ARMY ELECTRONICS TECHNOLOGY  
& DEVICES LABORATORY  
ATTN DELET-DD  
FT MONMOUTH, NJ 07703

HQ, USAF/SAMI  
WASHINGTON, DC 20330

TELEDYNE BROWN ENGINEERING  
CUMMINGS RESEARCH PARK  
ATTN MELVIN L. PRICE, MS-44  
HUNTSVILLE, AL 35807

ENGINEERING SOCIETIES LIBRARY  
ATTN ACQUISITIONS DEPARTMENT  
345 EAST 47TH STREET  
NEW YORK, NY 10017

COMMANDER IDDR&E  
PENTAGON, ROOM 3D 1089  
ATTN G. KOPCSAK  
WASHINGTON, DC 20310

OFFICE OF THE DEPUTY CHIEF OF STAFF FOR  
RESEARCH, DEVELOPMENT & ACQUISITION  
DEPARTMENT OF THE ARMY  
ATTN DAMA-ARP-P  
ATTN DAMA-CSS-N  
WASHINGTON, DC 20310

US ARMY R&D GROUP (EUROPE)  
BOX 15  
ATTN CHIEF, AERONAUTICS BRANCH  
ATTN CHIEF, ENGINEERING SCIENCES  
FPO NEW YORK 09510

US ARMY RESEARCH OFFICE  
PO BOX 12211  
ATTN R. SINGLETON  
RESEARCH TRIANGLE PARK, NC 27709

BMD ADVANCED TECHNOLOGY CENTER  
PO BOX 1500  
ATTN J. PAPADOPOULOS  
HUNTSVILLE, AL 35807

COMMANDER  
US ARMY FOREIGN SCIENCE  
& TECHNOLOGY CENTER  
FEDERAL OFFICE BUILDING  
ATTN DRXST-SD1  
ATTN DRXST-IS3, C. R. MOORE  
220 7TH STREET, NE  
CHARLOTTESVILLE, VA 22901

DIRECTOR  
APPLIED TECHNOLOGY LABORATORY  
ATTN GEORGE W. FOSDICK, DAVDL-ATL-ASA  
FT EUSTIS, VA 23604

COMMANDER  
US ARMY MATERIEL AND MECHANICS  
RESEARCH CENTER  
ATTN R. KATZ  
WATERTOWN, MA 02172

COMMANDER  
USA MISSILE COMMAND  
ATTN REDSTONE SCIENTIFIC INFORMATION  
CENTER, DRSMI-RBD  
ATTN DRDMI-TCC, WILLIAM GRIFFITH

12

DISTRIBUTION (Cont'd)

USA MISSILE COMMAND (Cont'd)  
ATTN DRDMI-TGC, T. C. DUNAWAY  
ATTN DRCPM-TOE, FRED J. CHEPLEN  
REDSTONE ARSENAL, AL 35898

COMMANDER  
US ARMY MOBILITY EQUIPMENT R&D CENTER  
ATTN TECHNICAL LIBRARY (VAULT)  
ATTN DRDME-EM, R. N. WARE  
FT BELVOIR, VA 22060

COMMANDER  
EDGEWOOD ARSENAL  
ATTN SAREA-MT-T, D. PATTON  
ABERDEEN PROVING GROUND, MD 21010

COMMANDER  
US ARMY ARRADCOM  
ATTN SARPA-TS-S #59  
ATTN DRDAR-LCN-C, A. E. SCHMIDLIN  
ATTN DRDAR-LCW-E, J. CONNORS  
ATTN DRDAR-SCF-IC, V. BAUMCARTH  
ATTN PBM-DPM (TAGLAIRINO)  
ATTN PBM-MG (A. WILLIAMS)  
DOVER, NJ 07801

COMMANDER  
WATERVLIET ARSENAL  
ATTN SARWV-RDT-L  
ATTN DRDAR-LCB-RA, R. RACICOT  
WATERVLIET ARSENAL, NY 12189

COMMANDER  
US ARMY TANK AUTOMOTIVE RES &  
DEV COMMAND  
ARMOR & COMP DIV, DRDTA-RKT  
BLDG. 215  
ATTN M. WHITMORE  
WARREN, MI 48090

COMMANDER  
ATTN STEWS-AD-L, TECHNICAL LIBRARY  
WHITE SANDS MISSILE RANGE, NM 88002

COMMANDER/DIRECTOR  
ATMOSPHERIC SCIENCES LABORATORY  
USA ERADCOM  
ATTN DELAS-AS (HOLT)  
ATTN DELAS-AS-T (R. RUBIO)  
WHITE SANDS MISSILE RANGE, NM 88002

OFFICE OF NAVAL RESEARCH  
DEPARTMENT OF THE NAVY  
ATTN STANLEY W. DOROFF, CODE 438  
ATTN D. S. SIEGEL, CODE 211  
ARLINGTON, VA 22217

DEPARTMENT OF THE NAVY  
R&D PLANS DIVISION  
ROOM 5D760, PENTAGON  
ATTN BENJ R. PETRIE, JR.  
OP-987P4  
WASHINGTON, DC 20350

COMMANDANT  
US NAVAL POSTGRADUATE SCHOOL  
DEPARTMENT OF MECHANICAL ENGINEERING  
ATTN CODE 69 Nn(NUNN)  
MONTEREY, CA 93940

COMMANDER  
NAVAL AIR DEVELOPMENT CENTER  
ATTN R. MCGIBONEY, 60134  
ATTN CODE 8134, LOIS GUISE  
ATTN D. KEYSER, 60134  
WARMINSTER, PA 18974

COMMANDER OFFICER  
NAVAL AIR ENGINEERING CENTER  
ATTN ESSD, CODE 9314, HAROLD OTT  
LAKEHURST, NY 08733

NAVAL AIR SYSTEMS COMMAND  
DEPARTMENT OF THE NAVY  
ATTN CODE AIR-5162C1, J. BURNS  
ATTN CODE AIR-5143J, D. HOUCK  
WASHINGTON, DC 20361

COMMANDER  
PACIFIC MISSILE TEST CENTER  
ATTN CODE 3123, ABE J. GARRETT  
ATTN CODE 1243, A. ANDERSON  
POINT MUGU, CA 93042

COMMANDER  
NAVAL SHIP ENGINEERING CENTER  
PHILADELPHIA DIVISION  
ATTN CODE 6772  
PHILADELPHIA, PA 19112

COMMANDER  
NAVAL SURFACE WEAPONS CENTER  
ATTN CODE 413, CLAYTON MCKINDRA  
WHITE OAK, MD 20910

COMMANDER  
NAVAL ORDNANCE STATION  
ATTN CODE 5123C, K. ENGLANDER  
INDIANHEAD, MD 20640

NAVAL SHIP RES & DEV CENTER  
CODE 1619, K. READER  
BETHESDA, MD 20084

NAVAL RESEARCH LABORATORY  
ATTN S. SEARLES, 117 BG A68  
WASHINGTON, DC 20375

DISTRIBUTION (Cont'd)

NAVAL SEA SYSTEMS COMMAND  
SEA05R11  
ATTN J. H. HARRISON  
WASHINGTON, DC 20362

COMMANDER  
NAVAL WEAPONS CENTER  
ATTN CODE 533, LIBRARY DIVISION  
ATTN CODE 3636, C. BURMEISTER  
CHINA LAKE, CA 93555

COMMANDER  
AF AERO PROPULSION LABORATORY, AFSC  
ATTN LESTER SMALL, AFWL/POTC  
WRIGHT-PATTERSON AFB, OH 45433

COMMANDER  
AIR FORCE AVIONICS LABORATORY  
ATTN AARA-2, RICHARD JACOBS  
WRIGHT-PATTERSON AFB, OH 45433

DIRECTOR  
AF OFFICE OF SCIENTIFIC RESEARCH  
ATTN NE  
BOLLING AFB, DC 20332

COMMANDER  
AIR FORCE FLIGHT DYNAMICS LABORATORY  
ATTN AFFDL/FGL, H. SNOWBALL  
ATTN AFFDL/FER, R. J. DOBBEK  
WRIGHT-PATTERSON AFB, OH 45433

COMMANDER  
AF WEAPONS LABORATORY, AFSC  
ATTN SUL, TECHNICAL LIBRARY  
KIRTLAND AFB, NM 87117

COMMANDER  
ARMAMENT DEVELOPMENT AND TEST CENTER  
ATTN ADTC (DLOSL), TECH LIBRARY  
ATTN DLMA, DAVID T. WILLIAMS  
EGLIN AIR FORCE BASE, FL 32542

AIR FORCE FLIGHT TEST CENTER  
6510 ABG/SSD  
ATTN TECHNICAL LIBRARY  
EDWARDS AFB, CA 93523

AF INSTITUTE OF TECHNOLOGY, AU  
ATTN LIBRARY AFIT (LD),  
BLDG 640, AREA B  
ATTN AFIT (ENM), MILTON E. FRANKE  
WRIGHT-PATTERSON AFB, OH 45433

HQ, AF SYSTEMS COMMAND  
ATTN SGB, CPT GEORGE JAMES  
ANDREWS AFB, DC 20334

ARGONNE NATIONAL LABORATORY  
APPLIED PHYSICS DIV, BLDG 316  
ATTN N. M. O'FALLON  
9700 S. CASS AVE  
ARGONNE, IL 60439

OAK RIDGE NATIONAL LABORATORY  
CENTRAL RES LIBRARY, BLDG 4500N, RM 175  
PO BOX X  
ATTN E. HOWARD  
ATTN C. A. MOSSMAN  
ATTN R. E. HARPER  
OAK RIDGE, TN 37830

DEPARTMENT OF COMMERCE  
NATIONAL BUREAU OF STANDARDS  
ATTN JAMES SCHOOLEY, CHIEF,  
TEMPERATURE SECTION  
ATTN T. NEGAS, SOLID STATE  
CHEMISTRY DIVISION  
ATTN RAY DILS, RM B-254, BLDG 221  
ATTN GEORGE BURNS, RM B-222, BLDG 221  
WASHINGTON, DC 20234

DEPARTMENT OF COMMERCE  
BUREAU OF EAST-WEST TRADE  
OFFICE OF EXPORT ADMINISTRATION  
ATTN WALTER J. RUSNACK  
WASHINGTON, DC 20230

DEPARTMENT OF ENERGY  
C-156, GTN (OART)  
ATTN ROBERT ROBERTS  
ATTN SANDY DAPKUNAS  
WASHINGTON, DC 20545

DEPARTMENT OF ENERGY  
FE-22  
ATTN T. K. LAU  
WASHINGTON, DC 20545

DEPARTMENT OF ENERGY  
F-317, GTN (COAL GASIFICATION)  
ATTN JIM CARR  
WASHINGTON, DC 20545

FEDERAL BUREAU OF INVESTIGATION  
J. EDGAR HOOVER BLDG  
ATTN ROBERT WILLIS  
WASHINGTON, DC 20535

DEPARTMENT OF JUSTICE  
IMMIGRATION AND NATURALIZATION SERVICE  
425 "I" STREET, NW  
ATTN NEILL MCKAY  
WASHINGTON, DC 20536

DISTRIBUTION (Cont'd)

SCIENTIFIC LIBRARY  
US PATENT OFFICE  
ATTN MRS. CURETON  
WASHINGTON, DC 20231

NASA AMES RESEARCH CENTER  
ATTN MS 244-13, DEAN CHISEL  
MOFFETT FIELD, CA 94035

NASA LANGLEY RESEARCH CENTER  
ATTN MS 494, H. D. GARNER  
ATTN MS 494, R. R. HELLBAUM  
ATTN MS 185, TECHNICAL LIBRARY  
HAMPTON, VA 23665

NASA SCIENTIFIC & TECH INFO FACILITY  
PO BOX 8657  
ATTN ACQUISITIONS BRANCH  
BALTIMORE/WASHINGTON INTERNATIONAL  
AIRPORT, MD 21240

UNIVERSITY OF ALABAMA  
CIVIL & MINERAL ENGINEERING DEPT  
PO BOX 1468  
ATTN HAROLD R. HENRY  
UNIVERSITY, AL 35486

UNIVERSITY OF ARKANSAS  
TECHNOLOGY CAMPUS  
PO BOX 3017  
ATTN PAUL C. MCLEOD  
LITTLE ROCK, AR 72203

UNIVERSITY OF ARKANSAS  
MECHANICAL ENGINEERING  
ATTN JACK H. COLE, ASSOC. PROF.  
FAYETTEVILLE, AR 72701

CARNEGIE-MELLON UNIVERSITY  
SCHENLEY PARK  
ATTN PROF. W. T. ROULEAU,  
MECH ENGR DEPT  
PITTSBURGH, PA 15213

CASE WESTERN RESERVE UNIVERSITY  
ATTN PROF. P. A. ORNER  
ATTN PROF. B. HORTON  
UNIVERSITY CIRCLE  
CLEVELAND, OH 44106

THE CITY COLLEGE OF THE CITY  
UNIVERSITY OF NY  
DEPT OF MECH ENGR  
ATTN PROF. L. JIJI  
ATTN PROF. G. LOWEN  
139TH ST. AT CONVENT AVE  
NEW YORK, NY 10031

CLEVELAND STATE UNIVERSITY  
FENN COLLEGE OF ENGINEERING  
ATTN PROF. R. COMPARIN  
CLEVELAND, OH 44115

DUKE UNIVERSITY  
COLLEGE OF ENGINEERING  
ATTN C. M. HARMAN  
DURHAM, NC 27706

ENGINEERING SOCIETIES LIBRARY  
ATTN HOWARD GORDON  
ATTN ACQUISITIONS DEPARTMENT  
345 EAST 47TH STREET  
NEW YORK, NY 10017

FRANKLIN INSTITUTE OF THE STATE  
OF PENNSYLVANIA  
ATTN KA-CHEUNG TSUI, ELEC ENGR DIV  
ATTN C. A. BELSTERLING  
20TH STREET & PARKWAY  
PHILADELPHIA, PA 19103

HUGHES HELICOPTERS  
DIVISION OF SUMMA CORPORATION  
CENTINELA & TEALE STREETS  
ATTN LIBRARY 2/T2124  
CULVER CITY, CA 90230

IIT RESEARCH INSTITUTE  
ATTN K. E. MCKEE  
10 WEST 35TH STREET  
CHICAGO, IL 60616

JET PROPULSION LABORATORY  
ATTN JOHN V. WALSH, MS 125-138  
4800 OAK GROVE DRIVE  
PASADENA, CA 91103

JOHNS HOPKINS UNIVERSITY  
APPLIED PHYSICS LABORATORIES  
ATTN MAYNARD HILL  
ATTN THOMAS RANKIN  
ATTN JOSEPH WALL  
LAUREL, MD 20810

LEHIGH UNIVERSITY  
DEPARTMENT OF MECHANICAL ENGINEERING  
ATTN PROF. FORBES T. BROWN  
BETHLEHEM, PA 18015

LINDA HALL LIBRARY  
ATTN DOCUMENTS DIVISION  
5109 CHERRY STREET  
KANSAS CITY, MO 64110

LOS ALAMOS SCIENTIFIC LAB  
PO BOX 1663  
ATTN FRANK FINCH, MS 178  
LOS ALAMOS, NM 87545

DISTRIBUTION (Cont'd)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
ATTN ENGINEERING TECHNICAL REPORTS,  
RM 10-408  
ATTN DAVID WORMLEY, MECH ENGR DEPT,  
RM 3-146  
77 MASSACHUSETTS AVENUE  
CAMBRIDGE, MA 02139

MICHIGAN TECHNOLOGICAL UNIVERSITY  
LIBRARY, DOCUMENTS DIVISION  
ATTN J. HAWTHORNE  
HOUGHTON, MI 49931

UNIVERSITY OF MISSISSIPPI  
ATTN JOHN A. FOX  
201 CARRIER HALL, DEPT OF MECH ENGR  
UNIVERSITY, MS 38677

MISSISSIPPI STATE UNIVERSITY  
DRAWER ME  
ATTN C. J. BELL, MECH ENG DEPT  
STATE COLLEGE, MS 39762

MISSISSIPPI STATE UNIVERSITY  
DEPT OF AEROSPACE ENGINEERING  
ATTN DAVID MURPHREE  
MISSISSIPPI STATE, MS 39762  
UNIVERSITY OF NEBRASKA LIBRARIES  
ACQUISITIONS DEPT, SERIALS SECTIONS  
ATTN ALAN GOULD  
LINCOLN, NE 68508

UNIVERSITY OF NEW HAMPSHIRE  
MECH ENGR DEPT, KINGSBURY HALL  
ATTN PROF. CHARLES TAFT  
ATTN PROF. DAVID LIMBERT  
DURHAM, NH 03824

UNIVERSITY OF N CAROLINA  
INSTITUTE OF MARINE BIOMEDICAL RESEARCH  
ATTN MICHAEL E. SHEEHAN  
WILMINGTON, NC 28401

NEW JERSEY INSTITUTE OF TECHNOLOGY  
DEPARTMENT OF MECHANICAL ENGINEERING  
ATTN R. Y. CHEN  
323 HIGH STREET  
NEWARK, NJ 07102

OHIO STATE UNIVERSITY LIBRARIES  
SERIAL DIVISION, MAIN LIBRARY  
1858 NEIL AVENUE  
COLUMBUS, OH 43210

OKLAHOMA STATE UNIVERSITY  
SCHOOL OF MECH & AEROSPACE ENGR  
ATTN PROF. KARL N. REID  
STILLWATER, OK 74074

MIAMI UNIVERSITY  
DEPT OF ENG TECH  
SCHOOL OF APPLIED SCIENCE  
ATTN PROF. S. B. FRIEDMAN  
OXFORD, OH 45056

PENNSYLVANIA STATE UNIVERSITY  
ATTN J. L. SHEARER  
215 MECHANICAL ENGINEERING BUILDING  
UNIVERSITY PARK, PA 16802

PENNSYLVANIA STATE UNIVERSITY  
ENGINEERING LIBRARY  
ATTN M. BENNETT, ENGINEERING LIBRARIAN  
201 HAMMOND BLDG  
UNIVERSITY PARK, PA 16802

PORTLAND STATE UNIVERSITY  
DEPT OF ENGINEERING AND  
APPLIED SCIENCE  
PO BOX 751  
ATTN PROF. P. I. CHEN  
PORTLAND, OR 97207

PURDUE UNIVERSITY  
SCHOOL OF MECHANICAL ENGINEERING  
ATTN PROF.. VICTOR W. GOLDSCHMIDT  
ATTN PROF.. ALAN T. McDONALD  
LAFAYETTE, IN 47907

ROCK VALLEY COLLEGE  
ATTN KEN BURTON  
3301 N. MULFORD ROAD  
ROCKFORD, IL 61101

RUTGERS UNIVERSITY  
LIBRARY OF SCIENCE & MEDICINE  
ATTN GOVERNMENT DOCUMENTS DEPT  
SANDRA R. LIVINGSTON  
NEW BRUNSWICK, NJ 08903  
SYRACUSE UNIVERSITY  
DEPT OF MECH & AEROSPACE ENGINEERING  
ATTN PROFESSOR D. S. DOSANJH  
139 E. A. LINK HALL  
SYRACUSE, NY 13210

UNIVERSITY OF TENNESSEE  
DEPT OF MECHANICAL ENGINEERING  
ATTN PROF. G. V. SMITH  
KNOXVILLE, TN 37916

UNIVERSITY OF TENNESSEE SPACE INST  
ENERGY CONVERSION DIVISION  
ATTN MARY ANN SCOTT  
TULLAHOMA, TN 37388

UNIVERSITY OF TEXAS AT AUSTIN  
DEPT OF MECHANICAL ENGINEERING  
ATTN A. J. HEALEY  
AUSTIN, TX 78712

DISTRIBUTION (Cont'd)

THE UNIVERSITY OF TEXAS AT ARLINGTON  
MECHANICAL ENGINEERING DEPARTMENT  
ATTN ROBERT L. WOODS  
ARLINGTON, TX 76019

TULANE UNIVERSITY  
DEPT OF MECHANICAL ENGINEERING  
ATTN H. F. HRUBECKY  
NEW ORLEANS, LA 70118

UNION COLLEGE  
MECHANICAL ENGINEERING  
ATTN ASSOC. PROF. W. C. AUBREY  
MECH ENGR DEPT, STEINMETZ HALL  
SCHENECTADY, NY 12308

UNIVERSITY OF VIRGINIA  
DEPT OF MECH & AEROSPACE ENGR  
ATTN DAVID LEWIS  
CHARLOTTESVILLE, VA 22090

VIRGINIA POLYTECHNIC INSTITUTE  
OF STATE UNIV  
MECHANICAL ENGINEERING DEPARTMENT  
ATTN PROF. H. MOSES  
BLACKSBURG, VA 24061

WASHINGTON UNIVERSITY  
SCHOOL OF ENGINEERING  
PO BOX 1185  
ATTN W. M. SWANSON  
ST LOUIS, MO 63130

WEST VIRGINIA UNIVERSITY  
MECHANICAL ENGINEERING DEPARTMENT  
ATTN RICHARD A. BAJURA  
MORGANTOWN, WV 26505

WICHITA STATE UNIVERSITY  
ATTN DEPT AERO ENGR, E. J. RODGERS  
WICHITA, KS 67208

UNIVERSITY OF WISCONSIN  
MECHANICAL ENGINEERING DEPARTMENT  
ATTN FEDERAL REPORTS CENTER  
ATTN NORMAN H. BEACHLEY, DIR,  
DESIGN ENGINEERING LABORATORIES  
1513 UNIVERSITY AVENUE  
MADISON, WI 53706

WORCESTER POLYTECHNIC INSTITUTE  
ATTN GEORGE C. GORDON LIBRARY (TR)  
ATTN TECHNICAL REPORTS  
WORCESTER, MA 01609

AVCO SYSTEMS DIVISION  
ATTN W. K. CLARK  
201 LOWELL STREET  
WILMINGTON, MA 01887

BARNES ENGINEERING CO  
ATTN FRED SWEIBAUM  
30 COMMERCE ROAD  
STANFORD, CT 06904

BELL HELICOPTER COMPANY  
PO BOX 482  
ATTN R. D. YEARY  
FORTWORTH, TX 76101

BENDIX CORPORATION  
ELECTRODYNAMICS DIVISION  
ATTN D. COOPER  
11600 SHERMAN WAY  
N. HOLLYWOOD, CA 90605

BENDIX CORPORATION  
RESEARCH LABORATORIES DIV  
BENDIX CENTER  
ATTN C. J. AHERN  
ATTN LAEL TAPLIN  
SOUTHFIELD, MI 48075

BOEING COMPANY, THE  
PO BOX 3707  
ATTN HENRIK STRAUB  
SEATTLE, WA 98124

BOWLES FLUIDICS CORPORATION  
ATTN VICE PRES/ENGR  
9347 FRASER AVENUE  
SILVER SPRING, MD 20910

RONALD BOWLES  
2105 SONDRAL COURT  
SILVER SPRING, MD 20904

CHAMBERLAIN MANUFACTURING CORP  
EAST 4TH & ESTHER STS  
PO BOX 2545  
WATERLOO, IA 50705

CONTINENTAL CAN COMPANY  
TECH CENTER  
ATTN P. A. BAUER  
1350 W. 76TH STREET  
CHICAGO, IL 60620

CORDIS CORPORATION  
PO BOX 428  
ATTN STEPHEN F. VADAS, K-2  
MIAMI, FL 33137

CORNING GLASS WORKS  
FLUIDIC PRODUCTS  
ATTN R. H. BELLMAN  
HOUGHTON PARK, B-2  
CORNING, NY 14830

DISTRIBUTION (Cont'd)

CHRYSLER CORPORATION  
PO BOX 118  
CIMS-418-33-22  
ATTN L. GAU  
DETROIT, MI 48231

JOHN DEERE PRODUCT ENGINEERING CENTER  
ATTN V. S. KUMAR  
WATERLOO, IA 50704

ELECTRIC POWER RESEARCH INSTITUTE  
PO BOX 10412  
ATTN MS. M. ANGWIN,  
P. M. GEOTHERMAL ENERGY  
3412 HILLVIEW AVE  
PALO ALTO, CA 94303

FLUIDICS QUARTERLY  
PO BOX 2989  
ATTN D. H. TARUMOTO  
STANFORD, CA 94305

FOXBORO CO  
CORPORATE RESEARCH DIV  
ATTN JAMES VIGNOS  
ATTN J. DECARLO  
ATTN JOHN CHANG  
38 NEPONSET AVE  
FOXBORO, MA 02035

GARRETT PNEUMATIC SYSTEMS DIVISION  
PO BOX 5217  
ATTN GARY FREDERICK  
ATTN TREVOR SUTTON  
ATTN TOM TIPPETTS  
ATTN C. ABBOTT  
111 SOUTH 34TH STREET  
PHOENIX, AZ 85010

GENERAL ELECTRIC COMPANY  
SPACE/RESO DIVISIONS  
PO BOX 8555  
ATTN MGR LIBRARIES, LARRY CHASEN  
PHILADELPHIA, PA 19101

GENERAL ELECTRIC COMPANY  
KNOLLS ATOMIC POWER LABORATORY  
ATTN D. KROMMENHOEK  
SCHENECTADY, NY 12301

GENERAL MOTORS CORPORATION  
DELCO ELECTRONICS DIV  
MANFRED G. WRIGHT  
NEW COMMERCIAL PRODUCTS  
PO BOX 1104  
ATTN R. E. SPARKS  
KOKOMO, IN 46901

GRUMMAN AEROSPACE CORPORATION  
TECHNICAL INFORMATION CENTER  
ATTN C. W. TURNER, DOCUMENTS  
LIBRARIAN  
ATTN TED SORENSEN, MS B1535  
ATTN JACK LEONARD, MS B1535  
SOUTH OYSTER BAY ROAD  
BETHPAGE, L. I., NY 11714

HAMILTON STANDARD  
DIVISION OF UNITED AIRCRAFT CORPORATION  
ATTN PHILIP BARNES  
WINDSOR LOCKS, CT 06096

HONEYWELL, INC  
ATTN J. HEDEEN  
ATTN W. POSINGIES  
1625 ZARTHAN AVE  
MINNEAPOLIS, MN 55413

HONEYWELL, INC  
ATTN RICHARD STEWART, MS 200  
1100 VIRGINIA DRIVE  
FT WASHINGTON, PA 19034

JOHNSON CONTROLS, INC  
ATTN WARREN A. LEDERMAN  
ATTN GEORGE JANU  
507 E. MICHIGAN  
MILWAUKEE, WI 53201

LEEDS & NORTHRUP CO  
ATTN ERNEST VAN VALKENBURG  
DICKERSON ORAD  
NORTH WALES, PA 19454

MOORE PRODUCTS COMPANY  
ATTN R. ADAMS  
SPRING HOUSE, PA 19477

MARTIN MARIETTA CORPORATION  
AEROSPACE DIVISION  
ATTN R. K. BRODERSON, MP 326  
PO BOX 5837  
ORLANDO, FL 32805

MCDONNELL AIRCRAFT COMPANY  
GUIDANCE AND CONTROL MECHANICS DIVISION  
ATTN LOYAL GUENTHER  
ST LOUIS, MO 63166

MCDONNELL DOUGLAS ASTRONAUTICS CO  
PROPULSION DEPARTMENT  
ATTN V. E. HALOULAKOS (A3-226)  
ATTN J. D. SCHWEIKLE (A3-226)  
5301 BOLSA AVENUE  
HUNTINGTON BEACH, CA 92647

DISTRIBUTION (Cont'd)

NATIONAL FLUID POWER ASSOC.  
ATTN JOHN R. LUEKE  
DIR OF TECH SERVICES  
3333 NORTH MAYFAIR ROAD  
MILWAUKEE, WI 53122

NEOS, INC  
3711 AIR PARK RD  
ATTN A. J. OSTDIEK  
LINCOLN, NE 68524

NORTHROP CORP, ELECTRONICS DIV  
ATTN DESMOND NELSON,  
SENIOR ENGINEER  
ORGN C3133, W/C  
2301 W. 120TH ST  
HAWTHORNE, CA 90250

PATSCENTER INTERNATIONAL  
707 ALEXANDER ROAD  
ATTN MR. JOHN CLINE  
PRINCETON, NJ 08540

PLESSEY AEROSPACE LTD  
ATTN A. ROSENBERG  
1700 OLD MEADOW ROAD  
MCLEAN, VA 22102

PROCON, INC  
ATTN HERB MARCH  
OUP PLAZA  
DES PLAINES, IL 60016

PROPULSION DYNAMICS  
ATTN T. HOULIHAN  
2200 SOMERVILLE R  
ANNAPOLIS, MD 21401

RICHARD WHITE & ASSOC.  
ELECTRO/MECHANICAL ENGINEERS  
ATTN RICHARD P. WHITE  
77 PELHAM ISLE ROAD  
SUDBURY, MA 01776

ROCKWELL INTERNATIONAL CORPORATION  
COLUMBUS AIRCRAFT DIVISION,  
PO BOX 1259  
ATTN MARVIN SCHWEIGER  
ATTN LOUIS BIAFORE  
4300 E. 5TH AVENUE  
COLUMBUS, OH 43216

SANDIA LABORATORIES  
ATTN WILLIAM R. LEUENBERGER, DIV 2323  
ATTN JERRY HOOD  
ATTN NED KELTNER  
ATTN ANTHONY VENERUSO, DIV 4742  
ALBUQUERQUE, NM 87185

SCIENCE APPLICATIONS, INC  
ATTN J. ISEMAN  
8400 WESTPARK DR  
MCLEAN, VA 22102

SIKORSKY AIRCRAFT  
ATTN J. R. SOEHNLEIN  
NORTH MAIN STREET  
STRATFORD, CT 06602

STEIN ENGINEERING SERVICES, INC  
5602 E. MONTEROSA  
PHOENIX, AZ 85018

TRANS-TECH, INC  
ATTN L. DOMINGUES  
12 MEEM AVE  
GAITHERSBURG, MD 20760

TRITEC, INC  
ATTN L. SIERACKI  
PO BOX 56  
COLUMBIA, MD 21045

UNITED TECHNOLOGIES RESEARCH CENTER  
ATTN R. E. OLSON, MGR FLUID  
DYNAMICS LABORATORY  
400 MAIN STREET  
E. HARTFORD, CT 06108

VOUGHT CORPORATION  
PO BOX 225907  
ATTN KELLEY FLING  
DALLAS, TX 75265

US ARMY ELECTRONICS RESEARCH  
& DEVELOPMENT COMMAND  
ATTN TECHNICAL DIRECTOR, DRDEL-CT

HARRY DIAMOND LABORATORIES  
ATTN CO/TD/TSO/DIVISION DIRECTORS  
ATTN RECORD COPY, 81200  
ATTN HDL LIBRARY, (2 COPIES), 81100  
ATTN HDL LIBRARY, (WOODBIDGE), 81100  
ATTN TECHNICAL REPORTS BRANCH, 81300  
ATTN LEGAL OFFICE, 97000  
ATTN CHAIRMAN, EDITORIAL COMMITTEE  
ATTN CORRIGAN, J., 20240  
ATTN CHIEF, 13000  
ATTN CHIEF, 13400 (20 COPIES)

END

DATE  
FILMED

12-82

DTIC