

AFML-TR-67-327  
Volume II

# DEVELOPMENT OF THE MANUFACTURING CAPABILITIES OF THE HYDROSTATIC EXTRUSION PROCESS

## Volume II

R. J. Fiorentino  
J. C. Gerdeen  
B. D. Richardson  
A. M. Sabroff  
F. W. Boulger

**BATTELLE MEMORIAL INSTITUTE  
COLUMBUS LABORATORIES**

TECHNICAL REPORT AFML-TR-67-327, VOLUME II  
October, 1967

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Manufacturing Technology Division of the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433.



METALLURGICAL PROCESSING BRANCH  
MANUFACTURING TECHNOLOGY DIVISION  
AIR FORCE MATERIALS LABORATORY  
RESEARCH AND TECHNOLOGY DIVISION  
AIR FORCE SYSTEMS COMMAND  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

## NOTICES

When U. S. Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

DDC RELEASE TO OTS NOT AUTHORIZED.

This document may not be reproduced in any form in whole or in part without prior approval of the Research and Technology Division. However, DDC is authorized to reproduce the document for "U. S. Governmental purposes".

Qualified requesters may obtain copies of this report from DDC, Defense Document Service Center, Cameron Station, Alexandria, Virginia, 22134. Orders will be expedited if placed through the librarian or other person designated to request documents from DDC.

Copies of this report should not be returned to the Research Technology Division unless return is required by security considerations, contractual obligations, or notice on a specific document.

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval to the Manufacturing Technology Division.

DEVELOPMENT OF THE MANUFACTURING CAPABILITIES  
OF THE HYDROSTATIC EXTRUSION PROCESS

VOLUME II

R. J. Fiorentino  
J. C. Gerdeen  
B. D. Richardson  
A. M. Sabroff  
F. W. Boulger

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Manufacturing Technology Division

## FOREWORD

This final technical report in two volumes covers the work performed under Contract AF 33(615)-3190 from 1 December 1964 through 8 July 1967. Volume I covers the results of the experimental work in hydrostatic extrusion and Volume II contains the work relative to design and construction of high-pressure hydrostatic extrusion containers. The manuscript was released by the authors on 29 September 1967 for publication as an AFML technical report.

This contract with Battelle Memorial Institute of Columbus, Ohio, was initiated under Manufacturing Methods Project No. 8-198, "Development of the Manufacturing Capabilities of the Hydrostatic-Extrusion Process". It was administered under the technical direction of Mr. Charles S. Cook until September 1965 and then by Mr. Gerald A. Gegel of the Metallurgical Processing Branch (MATB), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The program was conducted at Battelle with the prime responsibility assigned to the Metalworking Research Division and with Mr. R. J. Fiorentino, Associate Chief, as Project Engineer. Others contributing to the program were Mr. B. D. Richardson, Research Metallurgical Engineer, Mr. G. E. Meyer, Research Metallurgical Engineer, Mr. F. W. Fawn, Technician, Mr. A. M. Sabroff, Division Chief, and Mr. F. W. Boulger, Senior Technical Advisor. The late Mr. W. R. Hansen, Research Metallurgist, made a significant contribution to the program up to the time of his death in August, 1966. Mr. R. L. Jentgen, Associate Chief in the Structural Physics Division, assisted in the fluid and lubrication studies of the program. Dr. J. C. Gerdeen, Senior Research Mechanical Engineer in the Advanced Solid Mechanics Division, conducted the stress analysis for the high-pressure-container-design study. Mr. E. C. Rodabaugh, Mr. M. Vagins, Senior Mechanical Engineers, and Mr. T. J. Atterbury, Chief of the Applied Solid Mechanics Division, also assisted in this study. Mr. R. E. Mesloh, Research Mechanical Engineer of the Applied Solid Mechanics Division, designed an instrument for measuring fluid pressure at elevated temperatures. Data from which this report has been prepared are contained in Battelle Laboratory Record Books Nos. 21799, 21990, 23065, 23287, 23585, 23791, 23836, and 24446.

This project has been accomplished as a part of the Air Force Manufacturing Methods program, the primary object of which is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of USAF materials and components. The program encompasses the following technical areas:

- Metallurgy - Rolling, Forging, Extruding, Casting, Fiber, Powder.
- Chemical - Propellant, Coating, Ceramic, Graphite, Nonmetallics.
- Fabrication - Forming, Material Removal, Joining, Components.
- Electronics - Solid State, Materials and Special Techniques, Thermionics.

Suggestions concerning additional Manufacturing Methods development required on this or other subjects will be appreciated.

*H. A. Johnson*

H. A. JOHNSON, Chief  
Metallurgical Processing Branch  
Manufacturing Technology Division

## ABSTRACT

The purpose of the program was to develop the manufacturing capabilities of the hydrostatic-extrusion process. Specific applications studied were fabrication of wire, tubing, and shapes from relatively difficult-to-work materials such as refractory-metal alloys, high-strength steels, aluminum alloys, titanium alloys, beryllium, and other selected materials. Phase I was concerned with process optimization and Phase II with direct process application.

As part of Phase I, the effects of critical process variables on pressure requirements and product quality were studied for wrought and powder materials ranging from relatively high-strength easy to work materials such as aluminum alloys and steels to the relatively more difficult-to-work materials such as Ti-6Al-4V titanium alloy and superalloys. With these materials, fluids and lubricants tended to be the factor controlling pressure requirements and product quality. With almost every material extruded the limit in extrusion ratio was set by the design pressure capacity of the container except for the aluminum alloys where the limit was set more by the efficiency of the lubrication system.

In the hydrostatic extrusion of brittle materials, die design proved to be the most significant factor controlling the production of sound, good quality extrusions. New die-design concepts have opened up new fields for the application of hydrostatic extrusion to brittle materials.

Except for the aluminum alloys, the hydrostatic extrudability of the above range of materials was also investigated at 400 and 500 F. Again, fluids and lubricants were developed to enable the production of good quality extrusions. Of particular interest here was the wide range of lubricants that operated successfully at this temperature level.

As part of Phase II of the program, tubing, mill shapes and wire were produced from a variety of materials. For tubing, the floating-mandrel arrangement enabled higher extrusion-ratio capabilities than those for solid rounds. An analysis of the beneficial effects of the floating-mandrel arrangement is given.

T-sections were extruded from round billets and were re-extruded into smaller T-sections. Materials evaluated here were 7075-0 aluminum, AISI 4340 steel, Ti-6Al-4V alloy and Cb752 columbium alloy. The problem of sealing against leaks between the T-billet and die in the re-extrusion of shapes was overcome to some extent following the evaluation of several methods of sealing.

In the reduction of T-sections and wire, a technique of hydrostatic-extrusion drawing developed at Battelle was used. This method, called the HYDRAW technique, was used to reduce wire of Ti-6Al-4V alloy, beryllium, and TZM molybdenum alloy wire at single pass reductions of up to 60 percent. That reduction appeared to be by no means the limit of single-pass reduction achievable with these materials.

During the experimental program, a study of high-pressure container designs was made. Several design concepts that were analyzed are presented in detail in this report. The most promising concept for containing fluid pressures up to 450,000 psi in large-bore containers was that of using pressurized-fluid support as in the ring-fluid-ring design. This and other designs were analyzed on the basis of fatigue-strength criterion, which is believed to be a new and more sound basis for the design of high-pressure containers.

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Manufacturing Technology Division

VOLUME II

TABLE OF CONTENTS

	<u>Page</u>
LIST OF SYMBOLS SECTION 3 . . . . .	xi
XXI. INTRODUCTION . . . . .	149
XXII. SUMMARY OF VOLUME II . . . . .	151
SECTION 3	
ANALYSIS OF SEVERAL HIGH-PRESSURE CONTAINER DESIGN CONCEPTS	
XXIII. SUMMARY FOR SECTION 3 . . . . .	153
XXIV. SCOPE OF ANALYSIS . . . . .	156
XXV. BASIS AND METHOD OF ANALYSIS . . . . .	161
XXVI. METHOD OF PARAMETER NOTATION . . . . .	162
XXVII. FATIGUE CRITERIA . . . . .	163
Fatigue Criterion for Ductile Outer Cylinders . . . . .	163
Fatigue Criterion for High-Strength Liner . . . . .	164
XXVIII. ELASTICITY SOLUTIONS . . . . .	169
Elasticity Solutions for a Cylinder . . . . .	169
Elasticity Solutions for Segmented Components . . . . .	169
Ring Segment . . . . .	170
Pin Segment . . . . .	171
XXIX. NONDIMENSIONAL PARAMETER ANALYSIS . . . . .	173
Multiring Container . . . . .	173
Static Shear Strength Analysis . . . . .	173
Fatigue Shear Strength Analysis . . . . .	175
High-Strength Liner Analysis . . . . .	176
Ring-Segment Container . . . . .	182
Ring-Fluid-Segment Container . . . . .	184
Pin-Segment Container . . . . .	189
Strip-Wound Container . . . . .	194
Controlled Fluid-Fill, Multiring Container . . . . .	194
XXX. ANALYSIS OF RING FLUID RING CONTAINERS FOR HIGH PRESSURE . . . . .	197
Generalized Fatigue Criteria . . . . .	197

TABLE OF CONTENTS  
(Continued)

	<u>Page</u>
General Analysis of Multiring Containers . . . . .	200
Shear-Strength Analysis of a Multiring Container . . . . .	201
Comparison of the Shear and Tensile-Fatigue Criteria . . . . .	202
Example Designs of Containers . . . . .	204
Example Design 1 . . . . .	204
Example Design 2 . . . . .	206
Conclusions and Recommendations . . . . .	207
 XXXI. DESIGN REQUIREMENTS AND LIMITATIONS FOR HIGH-PRESSURE CONTAINERS . . . . .	       208
Possible Manufacturing and Assembling Limitations . . . . .	208
Residual Stress Limitations . . . . .	211
Other Possible Material Limitations . . . . .	215
 SECTION 4  HYDROSTATIC EXTRUSION CONTAINERS DESIGNED AND CONSTRUCTED IN THE PROGRAM  	
XXXII. SUMMARY OF SECTION 4 . . . . .	217
XXXIII. ANALYSIS OF THREE CONTAINERS DESIGN . . . . .	218
Container I . . . . .	218
Selection of Failure Criterion . . . . .	218
Stress Analysis of Container Assembly . . . . .	221
Operational Capabilities Predicted by Theory . . . . .	225
Container II . . . . .	229
Revised Container-Assembly Design . . . . .	229
Stress Analysis . . . . .	231
Component Ring Materials . . . . .	235
Operational Capabilities . . . . .	235
Container III . . . . .	236
The Design of Container III . . . . .	236
Container Assembly . . . . .	238
 APPENDIX I. ELASTICITY SOLUTION FOR A RING SEGMENT . . . . .	   240
ELASTICITY SOLUTION FOR A PIN SEGMENT . . . . .	242
SOLUTION FOR SHEAR STRESSES IN PINS . . . . .	248
 APPENDIX II. DERIVATIONS OF FORMULAS FOR ASSEMBLY INTERFERENCES . . . . .	   253
APPENDIX III. COMPUTER PROGRAMS . . . . .	255
REFERENCES FOR VOLUME II . . . . .	256



LIST OF ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
39. Schematic of High-Pressure-Container Design Concepts Analyzed in the Present Study . . . . .	157
40. Ring-Fluid-Ring Container for High Pressure . . . . .	158
41. Notations Used for Analysis of Container-Design Concepts . . . . .	160
42. Fatigue Diagram for $10^4$ - $10^5$ Cycles Life for High-Strength Steels at Temperatures of 75 F to 1000 F . . . . .	165
43. Maximum Pressure-to-Strength Ratio, $p/2S$ , in Multiring Container Designed on Basis of Static Shear Strength . . . . .	177
44. Maximum Pressure-to-Strength Ratio, $p/\sigma$ , in Multiring Container Designed on Basis of Fatigue Shear Strength . . . . .	177
45. Maximum Pressure-to-Strength Ratio, $p/\sigma_1$ , in Multiring Container With High-Strength Liner Based on the Fatigue Tensile Strength of Liner . . . . .	179
46. Limit to Maximum Pressure-to-Strength Ratio, $p/\sigma$ , in Multiring Container With High-Strength Liner Based on Shear Fatigue Strength of the Outer Rings . . . . .	179
47. Influence of Number of Rings on Maximum Pressure-to-Strength Ratio, $p/\sigma$ , in Multiring Container With High-Strength Liner . . . . .	180
48. Influence of Liner Size on Maximum Pressure-to-Strength Ratio, $p/\sigma$ , in Multiring Container With High-Strength Liner . . . . .	180
49. Comparison of Multiring Container With Ring-Segment Container for Various $k_1$ . . . . .	185
50. Comparison of Multiring Container With Ring-Segment Container for Various Segment Wall Ratios . . . . .	185
51. Effect of Elastic Modulus of Segments on Pressure-to-Strength Ratio, $p/\sigma_1$ , for the Ring-Segment Container . . . . .	186
52. Effect of Liner Size on Pressure-to-Strength Ratio, $p/\sigma$ , for Ring-Segment Container . . . . .	186
53. Effect of Segment Size on the Pressure-to-Strength Ratio, $p/\sigma_1$ , for the Ring-Fluid-Segment Container . . . . .	188
54. Effect of Segment Size on the Pressure-to-Strength Ratio, $p/\sigma_3$ , for the Ring-Fluid-Segment Container . . . . .	188

LIST OF ILLUSTRATIONS  
(Continued)

<u>Figure</u>		<u>Page</u>
55.	Effect of Segment Size on the Pressure-to-Strength Ratio, $p/\sigma_1$ , for the Ring-Fluid-Segment Container . . . . .	190
56.	Effect of Segment Size on the Pressure-to-Strength Ratio, $p/\sigma_3$ , for the Ring-Fluid-Segment Container . . . . .	190
57.	Effect of Support Pressure, $p_3$ , on Bore Pressure, $p$ , Capability for the Ring-Fluid-Segment Container . . . . .	192
58.	Maximum Pressure-to-Strength Ratio, $p/\sigma_1$ , for the Pin-Segment Container . . . . .	192
59.	Ratio of Interface Pressure Between Segments and Liner to Bore Pressure for the Pin-Segment Container . . . . .	193
60.	Controlled Fluid-Fill Cylindrical-Layered Container [Reference (42)] . . . . .	195
61.	Generalized Fatigue Relation in Terms of Shear Stresses . . . . .	198
62.	Shear-Yield- and Shear-Fatigue-Strength Relations . . . . .	198
63.	Influence of Pressures $p_N$ , $q_N$ and $q_0$ on the Pressure Capability $p_0$ . . . . .	202
64.	Pressure-to-Strength Ratios for Single-Ring Container for $10^6$ - $10^7$ Cycles Life . . . . .	203
65.	Comparison of Theory and Experiment for Single-Ring Containers . . . . .	203
66.	Cross-Sectional View of Hydrostatic-Extrusion Tooling . . . . .	219
67.	Cross-Sectional View of Container I . . . . .	222
68.	Stress Pattern in Container I at Room Temperature . . . . .	223
69.	Stress Pattern in Container I at 500 F . . . . .	224
70.	Fractograph of Fractured Surface of Liner of Container I . . . . .	228
71.	Electron Microscopic Fractograph Showing Fine Fatigue Striations in Liner of Container I . . . . .	230
72.	Electron Microscopic Fractograph Showing Cleavage Fracture of Undissolved Carbides in Liner of Container I . . . . .	230
73.	Cross-Sectional View of Container II. . . . .	232
74.	Stress Pattern in Container II at Room Temperature . . . . .	233

LIST OF ILLUSTRATIONS  
(Continued)

<u>Figure</u>		<u>Page</u>
75.	Stress Pattern in Container II at 500 F . . . . .	234
76.	Design Stress Pattern in Container III at Room Temperature . . . . .	237
77.	Geometry of Ring Segment . . . . .	240
78.	Bending Deformation of Ring Segments . . . . .	244
79.	Geometry of Pin Segment . . . . .	244
80.	Loading of Pin Segment . . . . .	244
81.	Loading of Pins . . . . .	245

LIST OF TABLES

<u>Table</u>		
XLI.	Torsional and Triaxial Fatigue Data on Vibrac Steel . . . . .	164
XLII.	Fatigue Strengths of High-Strength Steels From Room-Temperature Rotating-Beam Tests, $\alpha_m = 0$ . . . . .	166
XLIII.	Fatigue Strengths of High-Strength Steels From Room-Temperature Push-Pull Tests, $\alpha_m = \alpha_r$ . . . . .	166
XLIV.	Fatigue Strengths of High-Strength Steels From Push-Pull Tests at Elevated Temperatures . . . . .	167
XLV.	Results of Computer Code MULTIR for Example Design 1 . . . . .	206
XLVI.	Elevated-Temperature Data for 18 Percent Nickel Maraging Steel and H-11 Steel . . . . .	212
XLVII.	Liner-Bore Stresses and Interfaces for a 6-Inch-Bore Multiring Container With $K = 8.5$ , $N = 5$ , $k_1 = 2.0$ , $k_n = 1.44$ , $n \geq 2$ , $\alpha_r = 0.5$ , and $\alpha_m = -0.5^{(a)}$ . . . . .	213
XLVIII.	Liner-Bore Stresses and Interferences for a 6-Inch-Bore Multiring Container With $K = 8.5$ , $N = 5$ , $k_1 = 2.0$ , $k_n = 1.44$ , $n \geq 2$ , $\alpha_r = 0.5$ , and $\alpha_m = -0.3^{(a)}$ . . . . .	214
XLIX.	Prestresses Developed in the Container Assembly at 80 F and 500 F . . . . .	221
L.	Stresses Resulting Solely From an Internal Pressure of 250,000 Psi . . . . .	221

LIST OF TABLES  
(Continued)

<u>Table</u>		<u>Page</u>
LI.	Compositions, Heat Treatments, and Hardnesses of the Components Used for Container I . . . . .	226
LII.	Safety Factors Estimated for the Components of Container I for Various Operating Conditions . . . . .	227
LIII.	Safety Factors Estimated for Liner, Sleeve 1 and Sleeve 2 of Container II for Various Operating Conditions . . . . .	235
LIV.	Composition, Heat Treatment, and Hardnesses of the Components Used for the Four-Ring Assembly of Container III . . . . .	238
LV.	Stresses and Deflections in a Ring Segment, $k_2 = 2.0$ , $\alpha = 60^\circ$ , $\nu = 0.3$ . . . . .	242
LVI.	Deflections in Ring Segments, $\nu = 0.3$ . . . . .	243
LVII.	Stresses and Deflections in a Pin Segment, $k_2 = 4.0$ , $\alpha = 60^\circ$ , $\nu = 0.3$ . . . . .	249
LVIII.	Displacements and Maximum Hoop Stresses in Pin Segments, $\nu = 0.3$ . . . . .	251

### LIST OF SYMBOLS SECTION 3

$A_n, B_n$	= coefficients of materials in fatigue relations
$N$	= the total number of components in a container; $N$ also denotes the outermost component
$n$	= a specific component when numbered from inside out; i. e., $n = 1, 2, \dots, N$
$r_n$	= outside radius of component $n$ , inches
$r_{n-1}$	= inside radius of component $n$ , inches
$r_o$	= bore radius of container, inches (inside radius of liner)
$r_N$	= outer radius of container, inches
$k_n$	= wall ratio of component $n$ , $k_n = r_n/r_{n-1}$
$K$	= over-all wall ratio of container, $K = r_N/r_o = k_1 k_2 \dots k_N$
$K'$	= wall ratio of inner part of ring-fluid-segment container, $K' = r_3/r_o$
$E_n$	= modulus of elasticity of component $n$ , psi
$p_n$	= pressure acting on component $n$ at $r_n$ when $p \neq 0$ , psi
$p_{n-1}$	= pressure acting on component $n$ at $r_{n-1}$ when $p \neq 0$ , psi
$p$	= bore pressure, psi, $p_o = p$ (internal pressure acting on the liner)
$q_n$	= residual interface pressure acting on component $n$ at $r_n$ when $p = 0$ , psi
$q_r$	= residual interface pressure required at room temperature for a container designed for use at elevated temperature
$q_{n-1}$	= residual interface pressure acting on component $n$ at $r_{n-1}$ when $p = 0$ , psi
$S$	= shear stress, psi
$S_r$	= semirange in shear stress for a cycle of bore pressure, psi
$S_m$	= mean shear stress for a cycle of bore pressure, psi
$S_{min}$	= minimum shear stress during a cycle of bore pressure, psi
$S_{max}$	= maximum shear stress during a cycle of bore pressure, psi
$\sigma$	= design tensile stress of ductile steel, psi ( $\sigma \leq$ ultimate tensile strength)
$\sigma_1$	= design tensile stress of high-strength steel, psi ( $\sigma_1 \leq$ ultimate tensile strength)
$(\sigma)_r$	= semirange in tensile stress for a cycle of bore pressure, psi

**LIST OF SYMBOLS SECTION 3**  
(Continued)

- $(\sigma)_m$  = mean tensile stress for a cycle of bore pressure, psi
- $\sigma_y$  = yield tensile stress, psi
- $\sigma_u$  = ultimate tensile stress, psi
- $(\sigma)_{min}$  = minimum tensile stress during a cycle of bore pressure, psi
- $(\sigma)_{max}$  = maximum tensile stress during a cycle of bore pressure, psi
- $\sigma_r$  = radial stress, psi
- $\sigma_\theta$  = circumferential stress, psi
- $\sigma_z$  = axial (longitudinal) stress, psi
- $\alpha_r$  = semirange stress parameter for high-strength steel,  $\alpha_r = (\sigma)_r / \sigma_1$
- $\alpha_m$  = mean stress parameter for a high-strength steel,  $\alpha_m = (\sigma)_m / \sigma_1$
- $M_1$  = bending moment on ring segment
- $M_2$  = bending moment on pin segment
- $u$  = radial displacement, inches
- $v$  = circumferential displacement, inches
- $\nu$  = Poisson's ratio
- $r, \theta, z$  = cylindrical coordinates for radial, circumferential, and axial directions, respectively
- $\Delta_n$  = interference required (as manufactured) between cylinder,  $n$ , and cylinder,  $n + 1$ , inches
- $\Delta_{12}$  = interference required (as manufactured) between the liner, segments, and cylinder, 3, of the ring-segment and ring-fluid-segment containers, inches
- $\alpha_1, \alpha_2$  = coefficient of thermal expansion of material comprising rings 1 and 2

## INTRODUCTION

The purpose of this program was to develop the manufacturing capabilities of the hydrostatic-extrusion process. The program was divided into two phases with the following general objectives:

Phase I. Process-Development Studies

- Part 1. (a) To study the effect of critical process variables on pressure requirements and surface quality in hydrostatic extrusion of AISI 4340 steel, Ti-6Al-4V titanium alloy, and 7075 aluminum alloy.
- (b) To correlate all available hydrostatic-extrusion-pressure data with material properties wherever possible in order to assist direction of the experimental effort and maximize the information developed on the present program.
- Part 2. To explore the hydrostatic extrudability of TZM molybdenum alloy, beryllium, A286 iron-base superalloy, Alloy 718 nickel-base superalloy, powder compacts, and other selected materials.
- Part 3. To conduct a design study for high-temperature, high-pressure hydrostatic-extrusion tooling based on (1) estimated pressure requirements for high-ratio extrusion of materials of interest to the Air Force, (2) latest high-pressure-vessel technology, and (3) latest tooling materials available.
- Part 4. To conduct a process economic study on the construction, installation, and operation of equipment with the same operational and size requirements as the tooling developed in the previous program on Contract No. AF 33(600)-43328.

Phase II. Process-Application Studies

- Part 1. To evaluate the application of the hydrostatic-extrusion process for sizing and finishing conventionally hot-extruded (or rolled) structural shapes by various combinations of drawing and extruding. Primary emphasis was to be on AISI 4340 steel, although some effort was to be devoted to Ti-6Al-4V, 7075-0 aluminum, and selected refractory metals.
- Part 2. To determine the feasibility of producing wire and filaments from beryllium, TZM molybdenum alloy, and Ti-6Al-4V titanium alloy by combinations of hydrostatic extrusion and drawing.

Part 3. To develop tooling and define process parameters necessary for the reduction of tube blanks to finish tubing from AISI 4340 steel, 7075-0 aluminum, and Ti-6Al-4V titanium.

The results of the experimental and analytical work connected with Phases I and II were covered in Interim Engineering Progress Reports I through IX.

This, the Final Technical Report in two volumes, contains the results of the program in their entirety. Volume I contains Section 1, "A Study of the Critical Process Variables in the Hydrostatic Extrusion of Several Materials" and Section 2, "Production Aspects of Hydrostatic Extrusion". Volume II contains Section 3, "Analysis of Several High-Pressure Container-Design Concepts" and Section 4, "Hydrostatic-Extrusion Containers Designed and Constructed in the Program". The experimental program started December 1, 1964, and was completed on July 8, 1967.



## XXII

### SUMMARY OF VOLUME II

The experimental work conducted in this program has taken the technology of the hydrostatic-extrusion process from the experimental stage to the threshold of its application in a production operation. Commercial exploitation of the process is possible without any further major experimentation and it is believed that this report gives the guidelines that will enable these steps to be taken immediately. What remains now is the complete design of production hydrostatic-extrusion equipment that will be competitive with conventional-extrusion equipment. At the time of this writing, a program is underway at Battelle-Columbus Laboratories in which such equipment is being designed. The program, "Design Study of Production Press for Ultrahigh-pressure Hydrostatic-Extrusion Equipment", is sponsored by the Metallurgical Processing Branch, Manufacturing Technology Division at Wright-Patterson Air Force Base, Ohio, on Contract No. AF 33(615)-67-C-1434.

One of the most important aspects of the aforementioned design study is the design of the high-pressure container. Section 3 of this report contains a thorough analysis of several concepts of high-pressure containers. This analysis will be drawn on heavily in the design study. Section 4 describes the development of three containers designed and constructed in this program.

Both Sections 3 and 4 are complete in themselves and each contains its own summary.