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STRENGTH AND ECONOMIC COMPARISON OF AUTOFRETTAGED VERSUS JACKETED PRESSURE VESSEL CONSTRUCTION by T. E. Davidson and D. P. Kendall

Report WVT-RI-6002-I, October 1960, 28 pages, 5 figures, 1 table. Industrial Preparedness Measure 8031-4231-03-46100-01. Report Unclassified

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LIST OF SYMBOLS

σ	Stress in pounds per square inch
σ_y	Yield Stress in pounds per square inch
E	Modulus of Elasticity
W	Diameter ratio $(\frac{b}{a})$
P	Pressure in pounds per square inch
P_{if}	Interface Pressure in pounds per square inch
P_i	Internal Pressure in pounds per square inch
P_f	Firing or Operating Pressure in pounds per square inch
P.F.	Pressure Factor, $\frac{P}{\sigma_y}$
$(\ )_t$	Tangential
$(\ )_r$	Radial
$(\ )_z$	Longitudinal
$(\ )_j$	Jacket
$(\ )_l$	Liner
$(\ )_r$	Residual

STRENGTH AND ECONOMIC COMPARISON OF AUTOFRETTAGED VERSUS JACKETED PRESSURE VESSEL CONSTRUCTION

Abstract

The theoretical elastic strength of autofrettaged and jacketed thick-wall cylinders is presented in the form of equations and graphs. The mechanism by which both processes increase the elastic strength of a thick-wall cylinder is discussed and illustrated graphically. The advantages of a combination of jacketing and autofrettage for very thick-wall, pressure vessel applications are discussed and illustrated by a specific example. The economic advantages of autofrettage over jacketing are presented by a cost analysis of two specific examples, namely the 175mm Gun, T256 and the 155mm Howitzer T255.

Cross-Reference Data

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Stress analysis

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CONCLUSIONS

Autofrettage is more effective than jacketed construction as a means of increasing the elastic load carrying capacity of pressurized thick-wall cylinders. As a result of this greater effectiveness, pressure vessel design based on the use of autofrettage offers the following significant advantages over a jacketed configuration:

1. Decreased weight - For the same yield strength level and allowable elastic operating pressure, an autofrettaged pressure vessel will weigh substantially less.
2. Increased allowable pressures - For the same yield strength level and configuration, the elastic load carrying capacity is greater.
3. Decreased material strength requirements - For the same operating pressure and configuration, the basic yield strength requirements are reduced.

Autofrettage offers a significant economic advantage over jacketed construction by eliminating the additional machining and material required in a construction of two or more pieces. For example, unit savings approaching $2500. are possible in large caliber gun tubes.

A combination jacketed and autofrettaged configuration may be utilized to extend elastic breakdown pressures beyond available autofrettage pressure capacity.

RECOMMENDATIONS

To realize the strength and economic advantages of autofrettage over jacketed construction, it is recommended that:

1. Autofrettage be considered as a substitute for jacketing as the primary method of manufacture for intermediate diameter ratio, pressure vessel applications such as gun tubes, where the production quantities justify the additional tooling costs.

2. A combination of autofrettage and jacketing be considered for thick-wall pressure vessel applications where operating pressures exceed 160,000 pounds per square inch.

T. E. Davidson

T. E. DAVIDSON
Chief, Metal Working Section

D P Kendall

D. P. KENDALL

Approved:

P K Rummel

P. K. RUMMEL
Chief, Industrial Processes Branch

Harold V. Mackey

HAROLD V. MACKEY
Lt. Col., Ord. Corps
Chief, Research & Engineering Div.

INTRODUCTION

As a result of the severe weight limitations and extreme mobility requirements placed on cannon by current and proposed warfare concepts, it has become necessary to consider means for substantially increasing the elastic load carrying capacity of gun tubes. The obvious approach is that of increasing the strength of the materials used in tube construction. Current yield strength levels of 160,000 - 190,000 pounds per square inch, however, are already approaching the limit of materials available for configurations such as gun tubes. The alternative is the use of design concepts and processes capable of increasing the elastic load carrying capacity. Two such techniques are autofrettage and jacketing.

The desire to increase the load carrying capacity of pressure vessels is not new. In this connection, over the years, such techniques as bore quenching, wire wrapping, and the more common jacketing and autofrettage have been devised. All of these techniques are based on the use of induced residual stresses to counteract the firing or operating stresses.

Jacketing has been widely used in gun tubes, even at the current high strength level, where weight was of primary concern. Recent investigations and developments now make it possible to consider the application of the autofrettage principle to current high strength materials.

OBJECTIVE

It is the purpose of this study to evaluate the relative benefits of jacketed versus autofrettaged thick-wall cylinder construction, from the standpoints of theoretical elastic strengths and manufacturing costs.

DISCUSSION

Autofrettage and jacketing are both processes that increase the elastic load carrying capacity of thick-wall cylinders by means of induced residual stresses. The elastic strength increase is a result of the residual stresses being opposite to the operating stresses, so that they must first be overcome prior to the onset of yielding. This phenomenon can be readily realized in the following equation for yielding at the bore of a pressurized thick-wall cylinder, based on the Von Mises yield criterion, and assuming $\sigma_z = 0$

$$(\sigma_t + \sigma_{tr} - \sigma_r)^2 + \sigma_r^2 + (\sigma_t + \sigma_{tr})^2 = 2\sigma_y^2 \quad (1)$$

where σ_{tr} is the residual bore stress, induced either by autofrettage or jacketing, and is opposite in sign to σ_t, the tangential component of the operating stress.

Jacketing

The residual stresses are produced in a jacketed cylinder in the following manner: an inner and an outer tube, usually referred to as the liner and jacket respectively, are made so that the outside diameter of the liner is larger than the inside diameter of the jacket by a predetermined amount. The jacket is then expanded by heating so that it can be slipped over the liner. As the jacket cools it attempts to return to its original size. This action is opposed by the liner, resulting in an interface pressure between the two tubes and a compressive residual stress in the liner and a tensile residual stress in the jacket. An example of this stress distribution is shown in figure 1A.

To produce the optimum conditions in a jacketed tube the interface pressure must be such that yielding under internal pressure will occur simultaneously at the inner surface of the liner and jacket. If the interface pressure is greater than this critical value, yielding will occur at the bore of the jacket at an internal pressure less than the optimum. If it is less than this critical value, yielding will occur at the bore of the liner at a similar pressure.

The elastic solution for a jacketed thick-wall cylinder has been previously reported (1, et al.). However, for the purpose of comparing the elastic load carrying capacities of jacketing and autofrettage pressure vessel design, it may be helpful to cover the main points of this solution.

To develop the relationships expressing the elastic strength of jacketed cylinders certain assumptions must be made:

1. Since weight is of primary concern, and therefore the highest yield strength material available is utilized, it is assumed that the liner and jacket are of equal yield strength, i.e., $\sigma_{yl} = \sigma_{yj}$.
2. Considering the simplest and the most common case of a single jacket type construction, it is also assumed that the liner and jacket have equal diameter ratios since this will yield the highest elastic strength, i.e. $W_l = W_j$.

From the above assumptions using Lames' equations, the stresses at the inner surface of the jacket are:

$$\sigma_{tj} = P_{if} \frac{W_j^2 + 1}{W_j^2 - 1} + P_i \frac{W_j^2 + 1}{W^2 - 1} \qquad (2)$$

$$\sigma_{rj} = -P_{if} - P_i \frac{W_j^2 - 1}{W^2 - 1} \tag{3}$$

As a result of assuming equal liner and jacket diameter ratios, i.e., $W_l = \frac{c}{a} = W_j = \frac{b}{c}$, then $W_l W_j = W_l^2 = W_j^2 = \frac{b}{a} = W$ where W is the total diameter ratio of the cylinder. Substituting $W_l^2 = W_j^2 = W$ and σ_{tj} and σ_{rj} from equations 2 and 3 into the Von Mises yield equation (assuming $\sigma_z = 0$)

$$\sigma_t^2 + \sigma_r^2 - \sigma_t \sigma_r = \sigma_y^2 \tag{4}$$

yields, for the elastic breakdown condition,

$$P_i \frac{W - 1}{W^2 - 1} + P_{if} = \sigma_y \frac{W - 1}{\sqrt{1 + 3W^2}} \tag{5}$$

At the inside surface of the liner

$$\sigma_{tl} = P_i \frac{W^2 + 1}{W^2 - 1} - 2P_{if} \frac{W_l^2}{W_l^2 - 1} \tag{6}$$

$$\sigma_{rl} = -P_i \tag{7}$$

Substituting the value of P_{if} from equation 5 yields

$$\sigma_{tl} = P_i \left[\frac{W^2 + 1}{W^2 - 1} + \frac{2W}{W^2 - 1}\right] - 2\sigma_y \frac{W}{\sqrt{1 + 3W^2}} \tag{8}$$

The elastic breakdown condition at the bore from equations 7, 8, and 4 is:

$$P_i \left[\frac{1}{2} + \frac{1 + W}{1 - W}\right] - 2\sigma_y \frac{W}{\sqrt{1 + 3W^2}} = \frac{\sqrt{4\sigma_y^2 - 3P_i^2}}{2} \tag{9}$$

Letting $Q = \frac{1}{2} + \frac{1 + W}{1 - W}$

and $R = \frac{W}{\sqrt{1 + 3W^2}}$

and squaring equation 9 yields a quadratic equation in P_i. Solving this yields:

$$\frac{P_i}{\sigma_y} = \frac{2QR + \sqrt{Q^2 + \frac{3}{4} - 3R^2}}{Q^2 + \frac{3}{4}} \tag{10}$$

A plot of this equation is shown in figure 2.

Autofrettage

The autofrettage process consists of subjecting the cylinder to internal pressure (overstrain pressure) of a large enough magnitude to cause plastic deformation. The residual stresses resulting from this operation are due to the material near the bore being deformed to a greater extent than that near the outside diameter, i.e. a plastic deformation gradient. When the pressure is released the outside material is prevented from returning to its original position by the bore material, which results in the type of residual stress distribution schematically shown in figure 1A.

In diameter ratios below approximately 2.2 optimum autofrettage is obtained when the entire wall is plastically deformed, i.e., the 100% overstrain condition. In this case the maximum internal pressure that an autofrettaged cylinder can withstand without further plastic deformation is theoretically equal to the overstrain pressure. In diameter ratios above 2.2, however, the residual stresses resulting from the complete plastic condition are of such a magnitude that reverse yielding occurs. The maximum allowable, elastic pressure in an autofrettaged cylinder thus approaches a maximum. This relationship will be given later.

The magnitude of the pressure required to obtain 100% overstrain has been experimentally determined for steel with a 165,000 pound per square inch nominal yield strength (1) and is given by the following empirical relationship:

$$\frac{P}{\sigma_y} = 1.08 \log W \qquad (11)$$

This relationship, along with the following equation for elastic breakdown pressure in an unstressed monobloc cylinder based on the Von Mises yield criterion, is shown in figure 2.

$$\frac{P}{\sigma_y} = \frac{W^2 - 1}{\sqrt{1 + 3W^4}} \qquad (12)$$

Equation (12) has been experimentally substantiated by the authors.

Combination Autofrettage and Jacketing

Maximum autofrettage in diameter ratios greater than 2.2 is obtained when the induced residual stress at the bore equals the yield strength of the material. As previously discussed, in diameter ratios above 2.2 maximum autofrettage can be obtained at less than 100% overstrain. Therefore, as the diameter ratio increases, the interface between the plastic and elastic

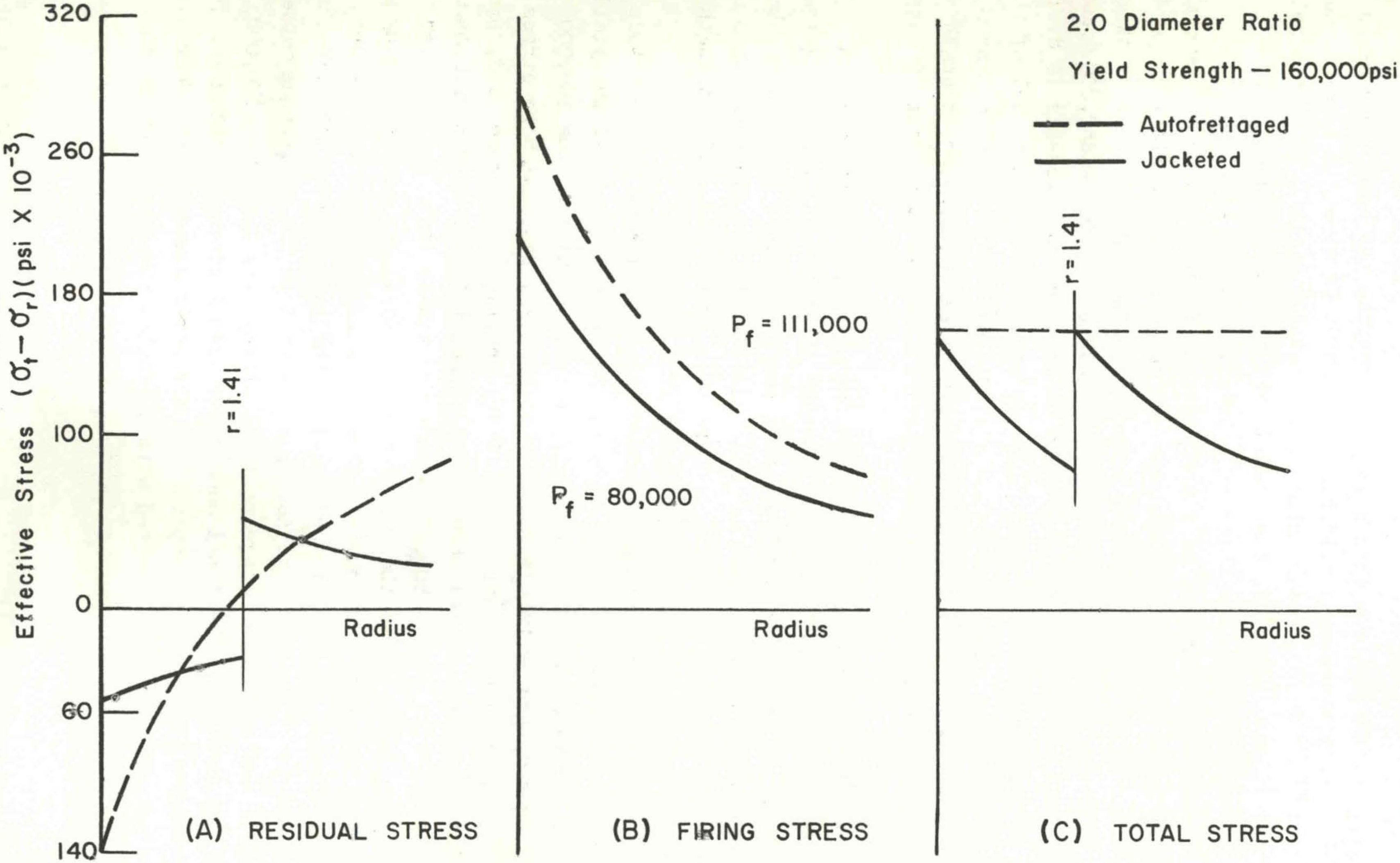

Figure 1. Summation of stresses in autofrettaged and jacketed cylinders

regions required for optimum autofrettage approaches the bore. This means then, that in very thick-wall cylinders, a high yield strength is required only near the bore with a lower value as the outside surface is approached. This phenomenon makes possible the consideration of a combination autofrettage-jacketing system for thick-wall pressure vessel applications.

To demonstrate the merits of a combination of autofrettage and jacketing, consider the hypothetical case of a pressure vessel, with an elastic operating pressure of 245,000 pounds per square inch and bore diameter of two inches. To obtain material with a yield strength of 245,000 - 250,000 pounds per square inch in a configuration common to most pressure vessels is difficult due to the hardenability limitations of steel. Even if material of this strength level were available to allow a single or even a two-piece construction, the inherent low ductility of materials at extremely high strength levels would represent a serious safety hazard from the standpoint of catastrophic failure.

Applying the phenomenon discussed in the prior paragraph, only the material near the bore needs to be of maximum strength thus permitting the use of a liner of 245,000 - 250,000 pounds per square inch yield strength with a lower strength jacket. In the case considered, the diameter ratio of the liner and jacket are 2.5 and 3.0 respectively with the yield strength of the jacket being 160,000 pounds per square inch.

Remembering that optimum autofrettage is obtained when the magnitude of the induced residual stress in the bore of the liner is equal to the yield strength of the material in compression, it is apparent that the 160,000 pound per square inch jacket is not able to induce a residual bore stress of 245,000 pounds per square inch. Also, if autofrettage alone were used, pressure of this magnitude is well beyond the capabilities of current autofrettage equipment which will attain 200,000 pounds per square inch. The required compressive residual stress then is produced by partially autofrettaging the liner to 190,000 pounds per square inch which will result in the residual stress distribution shown in figure 3A. Then the jacket is shrunk onto the liner with an interface pressure necessary to produce the difference between the required and the autofrettage residual stress i.e. 245,000 - 170,000 pounds per square inch. The final combined residual stress distribution is shown in figure 3B. Figure 3C depicts the algebraic summation of the residual and elastic stresses associated with a 245,000 pounds per square inch internal pressure.

In cylinders with a diameter ratio of greater than 2.2 where full autofrettage has been attained i.e., $\sigma_{tr} = \sigma_y$ the maximum elastic operating pressure is, from equation (1) assuming $\sigma_z = 0$

$$\frac{P}{\sigma_y} = \frac{3W^4 - 2W^2 - 1}{3W^4 + 1} \qquad (13)$$

The sample configuration considered then, will remain elastic up to a pressure of 245,000 pounds per square inch. If one slightly increases the overstrain pressure for the liner and/or the jacket interface pressure, the resulting residual stress at the bore will exceed the yield strength of the liner material and reverse yielding will occur. However, it is possible to operate such a vessel slightly above the optimum autofrettage pressures i.e., up to the new overstrain pressure, if a small amount of recoverable plastic deformation during operation is not harmful.

Strength Comparison

Figure 1 shows a comparison of the mechanism by which the residual stresses produced by jacketing and autofrettage increase the elastic strength. For simplicity it is based on the maximum shear stress (Tresca) theory of yielding which is slightly on the conservative side. The same analysis based on the Von Mises yield criterion would give similar results.

Figure 1A shows the residual stress distributions which would be produced in a cylinder with a total diameter ratio of 2.0 for both optimum autofrettaged and two-component jacketed construction. Figure 1B shows the elastic stress which would be produced by internal firing pressures of 80,000 and 111,000 pounds per square inch if the material was considered to remain elastic at these pressures. Actually, both of these pressures would produce plastic flow if the tube was of unstressed, monobloc construction.

By applying the principle of superposition and adding the residual and firing or operating stresses algebraically, figure 1C is obtained. From this it can be seen that the jacketed configuration cylinder will yield simultaneously at the bore of the jacket and the liner at a pressure of 80,000 pounds per square inch. In the autofrettaged cylinder, yielding will occur throughout the wall at a pressure of 111,000 pounds per square inch.

Figure 2 represents a plot of pressure factor (P.F.) versus diameter ratio for jacketed, autofrettaged and monobloc construction from equations (10), (11) and (12) respectively. As can be noted and as was shown in figure 1 for a specific diameter ratio, autofrettage offers a significant strength advantage over a two-component jacketed configuration. It should be noted

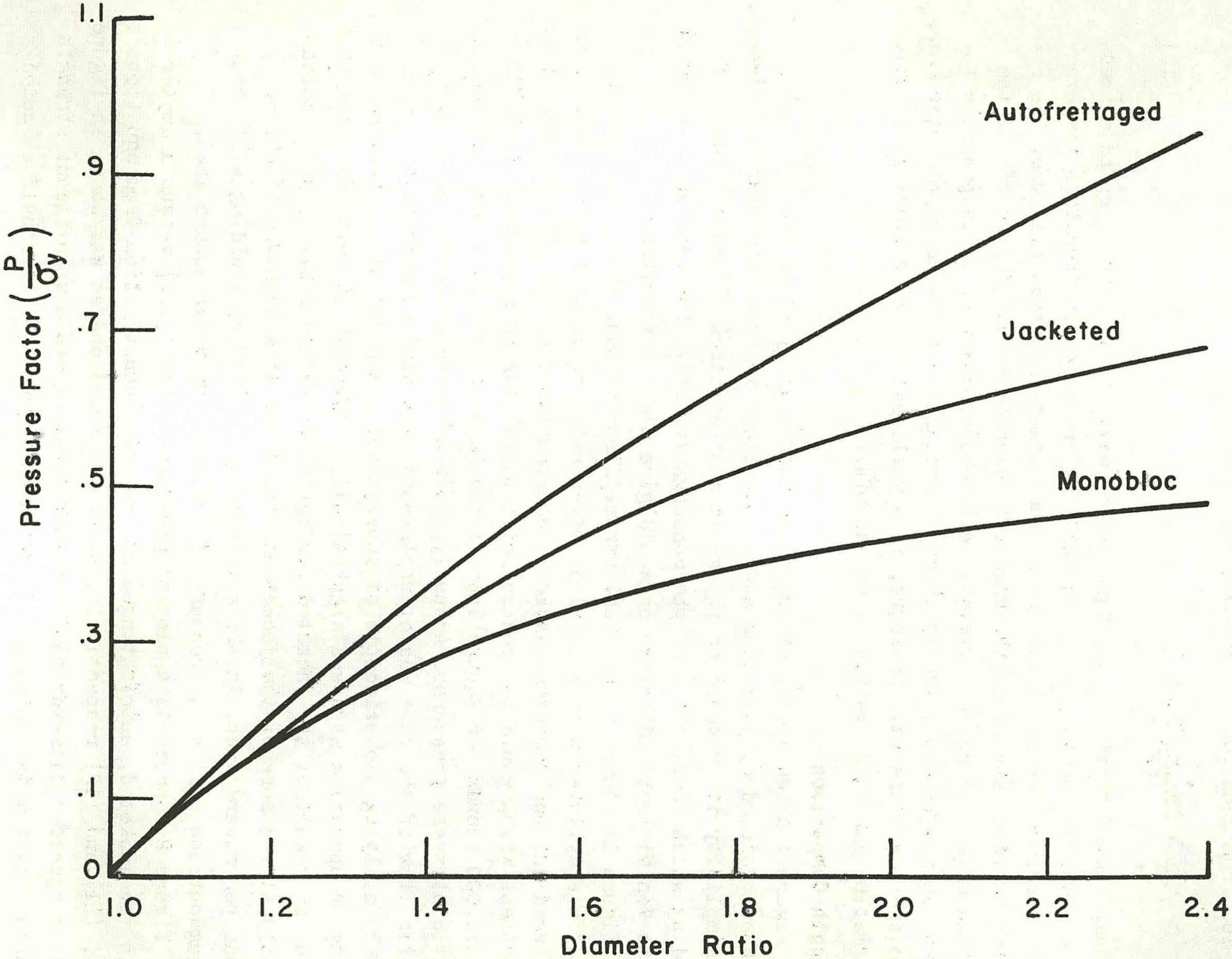

Figure 2. Pressure factor vs diameter ratio

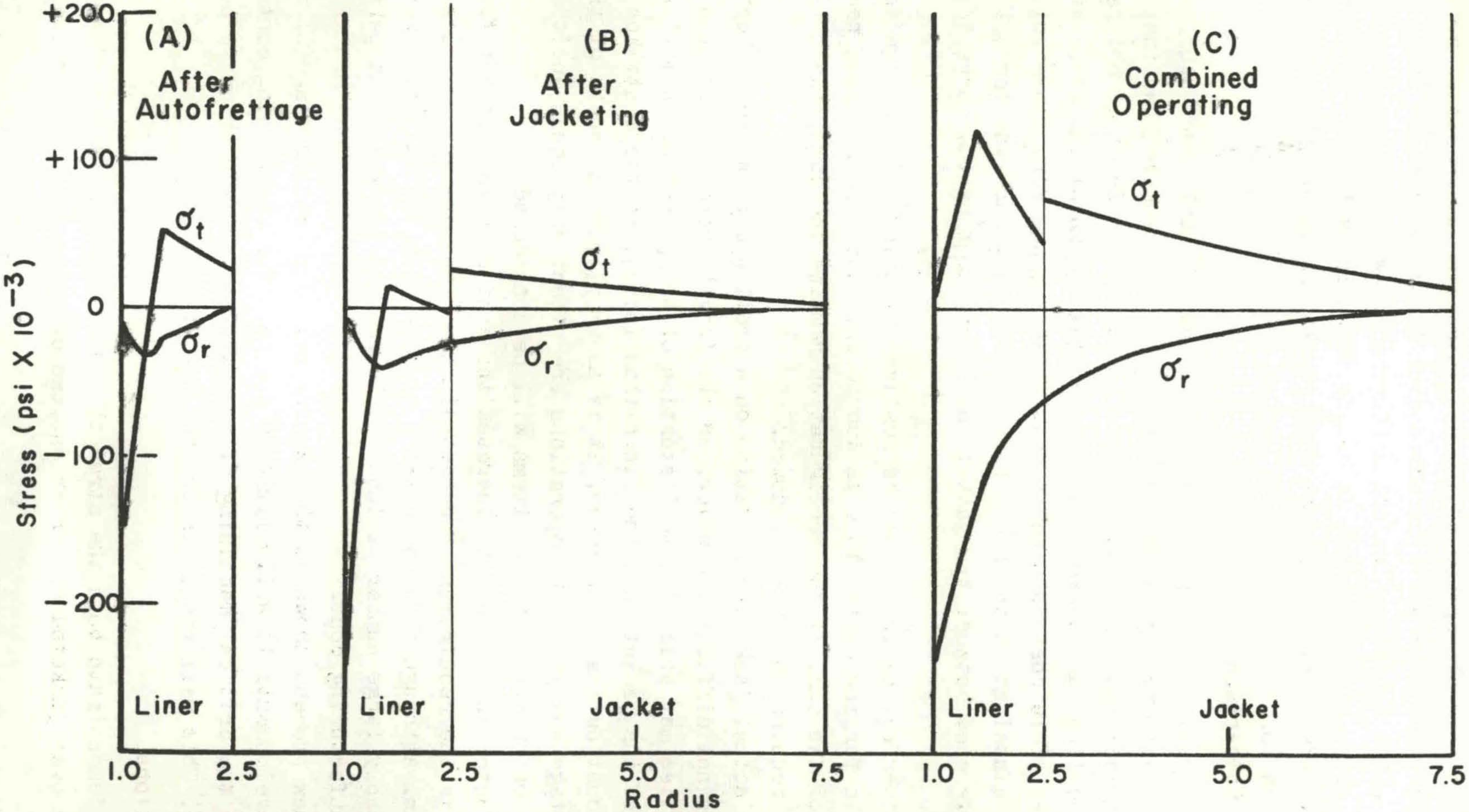

Figure 3. Summation of stresses in combination autofrettaged and jacketed cylinder

however, that as the number of jackets increases, the residual stress magnitude also increases and approaches that for autofrettage. Thus, for a multi-jacketed configuration the difference between the autofrettage and jacketed curve will decrease. It can be shown in fact, that an infinite number of jackets will yield the same results as autofrettage for any given diameter ratio.

Economic Comparison

The manufacture of pressure vessels, particularly gun tubes, based on the use of autofrettage is generally much less expensive than that associated with jacketed construction. This is due to autofrettage not requiring a separate liner and jacket thus eliminating the machining associated with the jacket. This cost is usually considerable since very close tolerances must be maintained in the bore of the jacket to insure the correct amount of interference between the jacket and liner and thus the correct interface pressure.

Another saving that could be realized by using autofrettage is a reduction in forging costs. This is due to only one forging being required instead of two and, if the configuration remains the same, the material strength requirements being reduced.

The actual jacketing operation on a small and relatively short pressure vessel is not difficult. However, as the length increases, as in a gun tube, difficulties may arise due to distortion of the jacket which may inhibit the placing of the jacket onto the liner thus increasing the cost. For the purpose of cost estimates, however, it is assumed that the costs of the actual autofrettage and jacketing operations are effectively equal and therefore only the major manufacturing items will be considered.

A factor which tends to increase the cost of using the autofrettage process is the requirement for restraining containers and pressure closures and seals. Although this comprises a considerable initial investment, over a reasonably large number of tubes it becomes an insignificant part of the unit manufacturing cost.

A new process known as the swaging method of autofrettage(2) is now under development. It will eliminate the need for restraining containers and also the critical machining of the exterior surface prior to autofrettage. This will result in further cost reductions.

Applications

To demonstrate both the strength and economic advantage of autofrettage over jacketed construction, two examples will be discussed. In both cases, the configuration will be fixed to that common to a jacketed construction.

175MM Gun T256

This gun tube, as schematically shown in figure 4, is designed as a two-piece construction with both jacket and liner having a yield strength of 160,000 - 190,000 pounds per square inch.

Table I depicts the relative costs of this tube for both the jacketed and autofrettaged configuration. As can be seen, the total savings per tube, due primarily to the elimination of the jacket, is $2454.00. Although not included, there may be further savings in basic material cost, as a result of having only a single forging instead of two.

As a result of having the configuration fixed, the autofrettaged tube may be fabricated of a lower strength material. Incorporating current autofrettage design factors, the material yield strength requirements may be reduced from 160,000 - 190,000 pounds per square inch to 120,000 pounds per square inch. This reduced material strength will not only enhance forging manufacture but may make possible substantial savings in machining costs as compared to that for higher strength materials.

155 MM Howitzer T255

This gun, as can be seen from figure 5, is substantially smaller than the prior example. In this case, also as shown in table I, savings of $542.00 per tube due to the elimination of the jacket are possible.

OPERATION	175MM T256	155MM T255
AUTOFRETTAGED		
Machining Tube Before Autofrettage	$3,784.00	$ 616.00
Machining Tube After Autofrettage	$6,732.00	$1,694.00
Autofrettage Tooling Cost (Unit cost based on 200 tubes)	$ 40.00	$ 50.00
	$10,556.00	$2,360.00
JACKETED		
Machining Liner Before Jacketing	$3,784.00	$ 616.00
Machining Jacket Before Jacketing	$2,494.00	$ 592.00
Machining Tube After Jacketing	$6,732.00	$1,694.00
	$13,010.00	$2,902.00
TOTAL SAVINGS	$2,454.00	$ 542.00

TABLE I. MACHINING COSTS - AUTOFRETTAGED AND JACKETED CONSTRUCTION

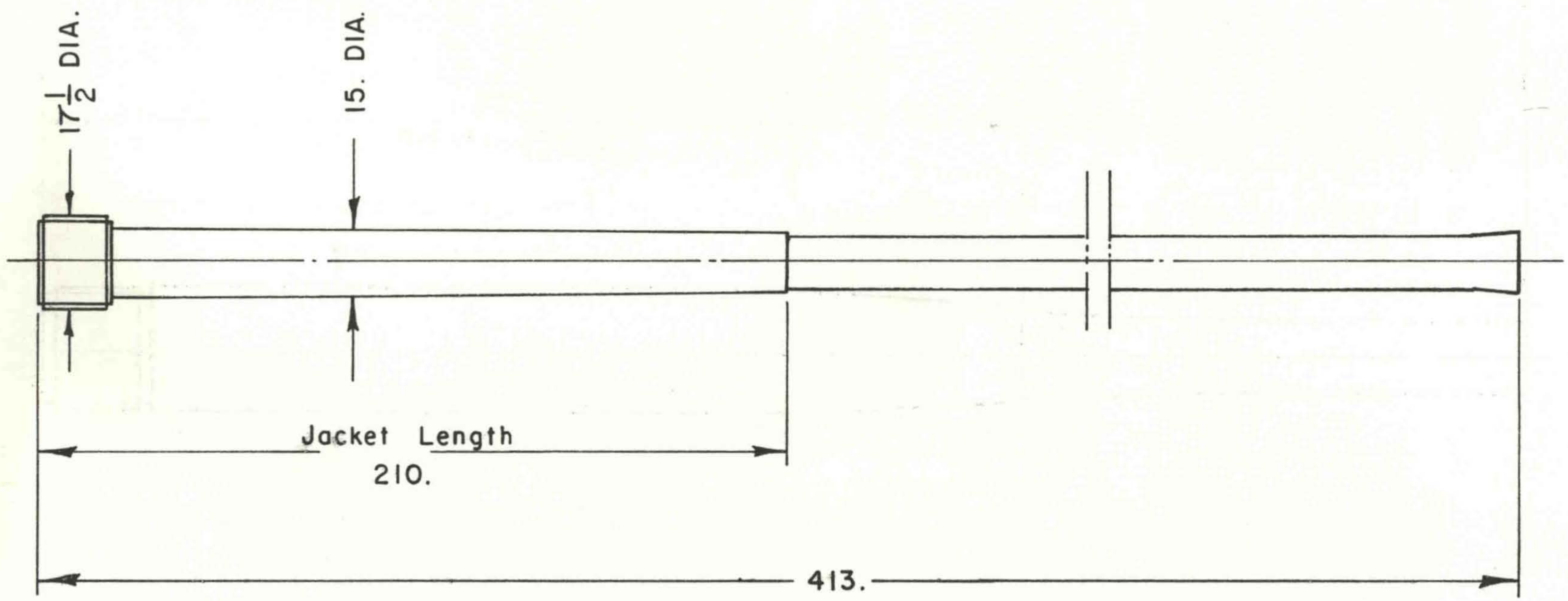

Figure 4. 175mm gun T256

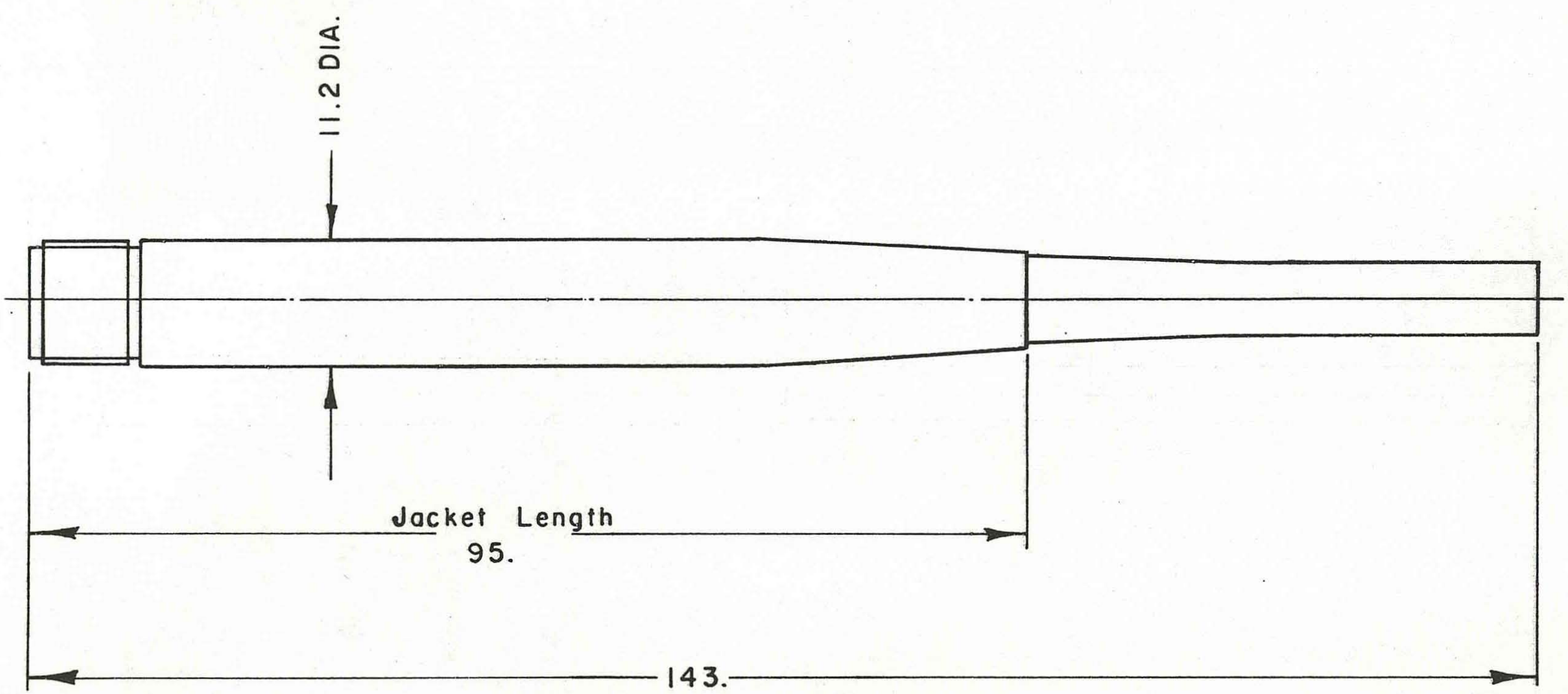

Figure 5. 155mm Howitzer T255

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