FINAL REPORT
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LOCKHEED MISSILES & SPACE COMPANY
HUNTSVILLE RESEARCH & ENGINEERING CENTER
HUNTSVILLE RESEARCH PARK
4800 BRADFORD DRIVE, HUNTSVILLE, ALABAMA

PAYLOAD SHROUDS STRUCTURAL OPTIMIZATION STUDY

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SUMMARY

Three computer programs were developed to serve as "Design Tools" for use in the preliminary design of Saturn Nose Fairings. The programs synthesize near-optimum structural arrangements for ring-stiffened, honeycomb sandwich, and ring-stringer-stiffened methods of construction. Separate manuals describe these programs, and furnish instructions for their use.

This report has as one of its objectives the presentation of certain optimization data derived by using the three programs. The data consist largely of graphs which show the dependence of shroud section weights upon major design variables. Brief discussions are presented where appropriate.

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INTRODUCTION

The study objective was to develop and use three computer programs for the preliminary design of Saturn Nose Fairings. Three types of shell construction were considered:

1. Ring-stiffened
2. Ring-stringer stiffened, and
3. Honeycomb sandwich.

The intended use of the programs is to serve as "Design Tools" with which reasonably accurate structural proportioning of nose shrouds can be rapidly accomplished. As such, these "Design Tools" will provide information on optimum designs that will require only refinement for hardware design.

Before the beginning of this contract, a substantial amount of work had already gone into the development and use of computer programs for the preliminary design of nose fairings. The initial work was done by Nevins and Helton (Reference 1), who developed programs for the optimization of ring-stiffened biconic fairings. This was followed by the work performed by Landis at Lockheed, also on ring-stiffened cone-plus-frustum configurations. The work of Landis was essentially an extension and refinement of the earlier work of Nevins and Helton, the primary purpose of which was to generate weight data needed for a nose shape optimization study in progress at Lockheed.

Accomplishments under the present contract include the following:

1. Permissible external geometries were extended to include configurations that include cylinders
2. Programs were developed which synthesize near-optimum designs using skin-ring-stringer and sandwich constructions
3. Improved analysis techniques and additional design options were added to the ring-plus-skin program.

TECHNICAL DISCUSSION

Two tasks were performed during the course of the study:

1. Three computer programs were developed
2. These programs were used to optimize a specified design.

Task (1) was by far the larger job, with task (2) being primarily a demonstration of the operability of the three programs. To enhance the usefulness of the programs, separate manuals (References 2, 3, and 4) were prepared for each program. These manuals contain the following material:

1. An overall description of the program
2. Operating instructions, including a sample problem
3. A discussion of the analyses used
4. A program listing, and
5. Definitions of major symbols used.

The manuals are generally similar to a previously published manual, Reference 5.

This report has as its primary objective the presentation of optimization data, as outlined in Reference 6. The external geometry used is illustrated by Figure 1. For this shape and the key assumptions shown in Table I, near-optimum weights were determined for the shroud cylindrical, frustum, and conical sections using each of the three methods of construction. Results are shown in Table II. Some "practical engineering judgement" was used in arriving at these results -- both in choosing practical program input constraints and in rejecting certain designs that had particularly undesirable features.

During the process of program development, a substantial number of individual design optimizations were made for each of the three methods of construction. From these optimizations several significant trends have been observed. Most of the trends were anticipated. In a few instances, the nature of the trend (or sometimes the lack of a well-defined trend) was suprising. Some of those findings which appear to be most interesting are presented graphically and discussed very briefly in the sections which follow.

Rings and Skin

Minimum practical conical section weight occurs with a large number of rings, as indicated by Figure 2. The same trend holds in the frustum section, as evidenced by Figure 3. Both of these curves present results using zee rings with B/t ratios of 15 and A/t ratios of 18 (see Figure 1A). While reasonable variations in B/t produce little change in weight, some improvement can be achieved by using larger values of A/t. Figure 4 shows how the sum of cone and frustum weights depends upon A/t.

Note from Figure 2 that imposition of a 600°F constraint does not introduce a weight penalty in the conical section, a fact contrary to initial expectations and findings. This was discovered by treating the total number of rings in each frustum of the cone as a design variable, irrespective of closest spacing.

Minimum weight is also achieved in the cylindrical section with close ring spacing. Two methods of general instability analysis were used for cylinders, Shanley's method and the method of Baruch and Singer. Results using both methods are presented in Figure 5, which shows cylindrical section weight as a function of the number of rings used. The analysis of Baruch and Singer is preferable, and is used in the final version of the program.

The numerical technique of solving the Baruch-Singer equations was developed by A. B. Burns of LMSC's Solid Mechanics Laboratory. Burn's solution of the Baruch-Singer equations permits inclusion of lateral pressure effects, either bursting or collapsing. This capability was used to assess the sensitivity of optimum structural weight to internal static pressure differential (from freestream) at the time of maximum external loads. Note from Figure 6 that the sensitivity is large for designs with widely spaced rings, less for designs with closely spaced rings.

Honeycomb Sandwich

If no intermediate rings are used, minimum conical and frustum section weight is achieved. A fairly substantial penalty is introduced by using additional rings, as is shown by Figures 7 and 8. Note that the same Figure illustrates graphically the effect of introducing various minimum face thickness constraints. Similar effects are found in the cylindrical section, as illustrated by Figure 9.

All of these results were achieved when the final version of the sandwich program was used, which embodies as a subroutine the buckling analysis program developed by B. O. Almroth. An earlier version of this program used a less desirable modified "equivalent EI" approach to panel design, with buckling analyses based on the same techniques used in skin-plus-rings design, and described in Reference 5. Results of this earlier approach were available for use in this report and are included here in Figures 10, 11, and 12. Note that results from the two approaches are generally similar. It is interesting to note from Figure 11 that a weight penalty of approximately 10% is introduced by using standard gauges.

The joint configuration used for weight calculations is shown in Figure 13. Panel edge members were conservatively ignored in determining the ring effective moment of inertia. No weight increases were added for longitudinal splices and aerodynamic heating effects were ignored in the sandwich studies.

Ring, Stringer, and Skin

In the cylindrical section, minimum practical weight occurs with about half as many rings as in a ring-skin structure. Typical results are shown in Figure 14. This particular graph is for a design using 144 zee section stringers in the first bay. In upper bays, the program halves the number of stringers if this leads to a more efficient design -- then halves the number again in the next bay if this is lighter, etc. In this particular instance, the minimum number of stringers was not allowed to become less than 18. For most of the designs represented on Figure 14, the number of stringers actually did decrease to 18, usually fairly quickly.

For certain applications, such a design may not be acceptable. Accordingly, a design study was made in which the previously described halving process was not allowed. The number of stringers was held at 144, and optimum weight determined as a function of the number of rings used. Results are shown by Figure 15.

Note that there is a relatively small penalty for not decreasing the number of stringers in the upper bays, and that the trends of weight versus number of rings are slightly different from the case where the number of stringers was decreased.

In deriving data for the studies described above, a beam column analysis was used for the stringers, and ring moment of inertia requirements were determined using Shanley's method. This approach makes it convenient for one to examine the effects of lateral pressure, either bursting or crushing.

Such an examination was made. At the time of maximum αq, internal pressures of

1. ambient
2. 0.5 psi below ambient
3. 1.0 psi below ambient, and
4. 0.5 psi above ambient

were assumed, and designs optimized for various numbers of rings for each of the four assumptions. Results from this examination are shown in Figure 16. This particular graph is for a design using 144 stringers in the first bay, with the number of stringers decreased by halving in an optimum manner as the design progressed upward. The minimum number of stringers allowed was 18.

A similar examination was made for designs with 144 stringers continued throughout the cylindrical section. Data from this examination is presented in Figure 17.

For both of these examinations, the results were as anticipated for cases where crushing pressure (internal pressure lower than ambient) was imposed -- i.e., the structures became significantly heavier with increasing crushing pressure. Weight versus spacing trends were essentially unchanged by increasing crushing pressure.

For cases with bursting pressure, the results were completely unexpected. Instead of pressure stabilization making the structures lighter in weight, a pronounced increase in weight occurred. This effect is shown by Figures 16 and 17. Apparently the reason for the weight increase is that when a stringer is being analyzed, the program first checks the sign of N_ϕ, the line load. When N_ϕ is compressive, the maximum compressive bending stress is determined by using a beam column analysis, and the results added to the direct compressive stress. Likewise, if N_ϕ is a tensile load, the maximum tension bending stress is determined and added to the direct tensile stress. When a significant bursting pressure is present, the tensile stresses can become governing, which leads to appreciable increases in weight.

It could be argued with some justification that the analysis techniques used in discovering this surprising trend ignore important factors.* This effect should be investigated further.

Attempts were made to determine trends of weight versus the number of stringers used. Although results were somewhat disappointing, the following facts became apparent from these attempts.

1. In the cylindrical section, ring and stringer spacing effects are quite interrelated, as shown by Figure 18. In retrospect, this kind of relationship is obviously to be expected.

2. In the cone and frustum sections, a similar ring-stringer relationship exists. However, the program's optimum stringer halving process in the upper bays -- along with practical stringer ℄ to ℄ distances apparently makes possible the synthesis of a wide range of designs having essentially identical weights. Figure 19 gives some typical results.

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* Perhaps the most important is the radial extensional restraint provided by hoop forces in the skin. It must be remembered, however, that the applied pressures are not circumferentially uniform at the Mach numbers and angles of attack of interest.

FUTURE WORK

As a consequence of the work performed by Lockheed under both this contract and with internal company funding, it is clear that additional work in several areas is needed. Some further work on analysis techniques is warranted, and additional design studies - particularly for skin-ring-stringer fairings - are also desirable. Though these two kinds of efforts are quite different in nature, both have as their ultimate objective achieving the maximum practical structural efficiency in large nose fairings.

Work on general instability under combined loads is the most desirable analysis techniques task. A limitation of the Baruch-Singer analysis used (and most, if not all, alternate methods) is the fact that it is not valid for configurations with some elements buckled. Of particular interest would be comparisons of designs having no elements buckled with designs allowing skin panels to buckle (as was done in this study). With this goal in mind, Lockheed is funding studies which have as their goal the development of a better general instability analysis technique for structures with elements buckled.

For the first steps in the direction of further design studies, existing analytical tools can be used. The ring, skin and stringer program developed during this study is suitable in its present form for making the first of these investigations. Also, a Baruch-Singer general instability analysis was prepared during this study, and was attached to a version of the ring-stringer design program for use in the cylindrical section. However, limitations of available time and manpower prevented its use in making extensive preliminary design studies.

If very large fairings are to be built for Saturn V (or other) hammerhead vehicles, it is perhaps worthwhile to make design studies that take into account economic effects of fabrication parameters as well as structural efficiency effects of these parameters. Much of the routine economic work could be automated along with the structural design work.

REFERENCES

1. Nevins, Clyde D., and Benny W. Helton, An Investigation of Various Parameters Affecting the Structural Weight of Rocket Vehicle Nose Cones, NASA Report MTP-P&VE-S-63-4, George C. Marshall Space Flight Center, Huntsville, Alabama, 17 October 1963.

2. Landis, Ivan M., Automated Nose Fairing Design-Ring and Skin Construction, LMSC/HREC Technical Report A712552, November 1965.

3. Adams, Zeb V., Automated Nose Fairing Design - Honeycomb Sandwich Construction, LMSC/HREC Technical Report A712573, November 1965.

4. Hendrix, E. S., Automated Nose Fairing Design-Ring, Skin and Stringer Construction, LMSC/HREC Technical Report A712572, November 1965.

5. Landis, Ivan M., A Computer Program to Determine the Minimum Weight Design for Ring-Stiffened Nose Fairings, LMSC/HREC Technical Report A711099, May 1965.

6. Letter dated November 12 from James B. Dalton II to E. S. Hendrix, R-P&VE-SAA-65-78.

7. Dean, William G., Thermodynamic Design Curves for Estimating Nose Fairing Skin Thicknesses for a Saturn Ascent Trojectory, LMSC/HREC Technical Memorandum AO36548, September 1964.

8. Hendrix, E. S., Optimum Nose Shape Study - Cone and Cone Plus Cylinder Configurations for Saturn V Vehicles, LMSC/HREC Technical Memorandum A710293, December 1964.

TABLE I

KEY ASSUMPTIONS MADE IN OPTIMIZATION STUDIES

Material	Characteristics of a high strength aluminum alloy were used. The elastic limit was taken as 40 ksi; elastic modulus used was 10.5 x 10^6 psi.
Loading Conditions	Critical combinations resulting from pressure, drag, and bending moment were calculated within the program. These external loads were determined at M = 1.5, α = 8.5°, and $\overline{q}$ = 765 PSF, which are representative design conditions for Saturn-type vehicles.
Venting	Component loads are a function of venting characteristics which set internal pressure time histories. For most of the studies, it was assumed that internal pressure and free-stream pressure are equal at αq max. (The significance of this assumption was examined in certain instances.)
Aerodynamic Heating	Studies were made both with and without considering aerodynamic heating effects. When heating effects were considered, the skin was treated as a heat sink, and limited in temperature to 600°F. (See References 7 and 8.)

TABLE II

NEAR-OPTIMUM WEIGHTS, USING DIFFERENT CONSTRUCTION METHODS

Section of Shroud	Ring-Skin Construction	Ring-Skin-Stringer Construction	Sandwich Construction
Cone	1,000	600*	375*
Frustum	2,100	1,000	600
Cylinder	5,200	2,300	2,000

*Without thermal protection - Imposition of a 600°F constraint will increase the ring-skin-stringer weight to something less than 1300 lb if no thermal protection is used. A heat sink design was not considered for sandwich.

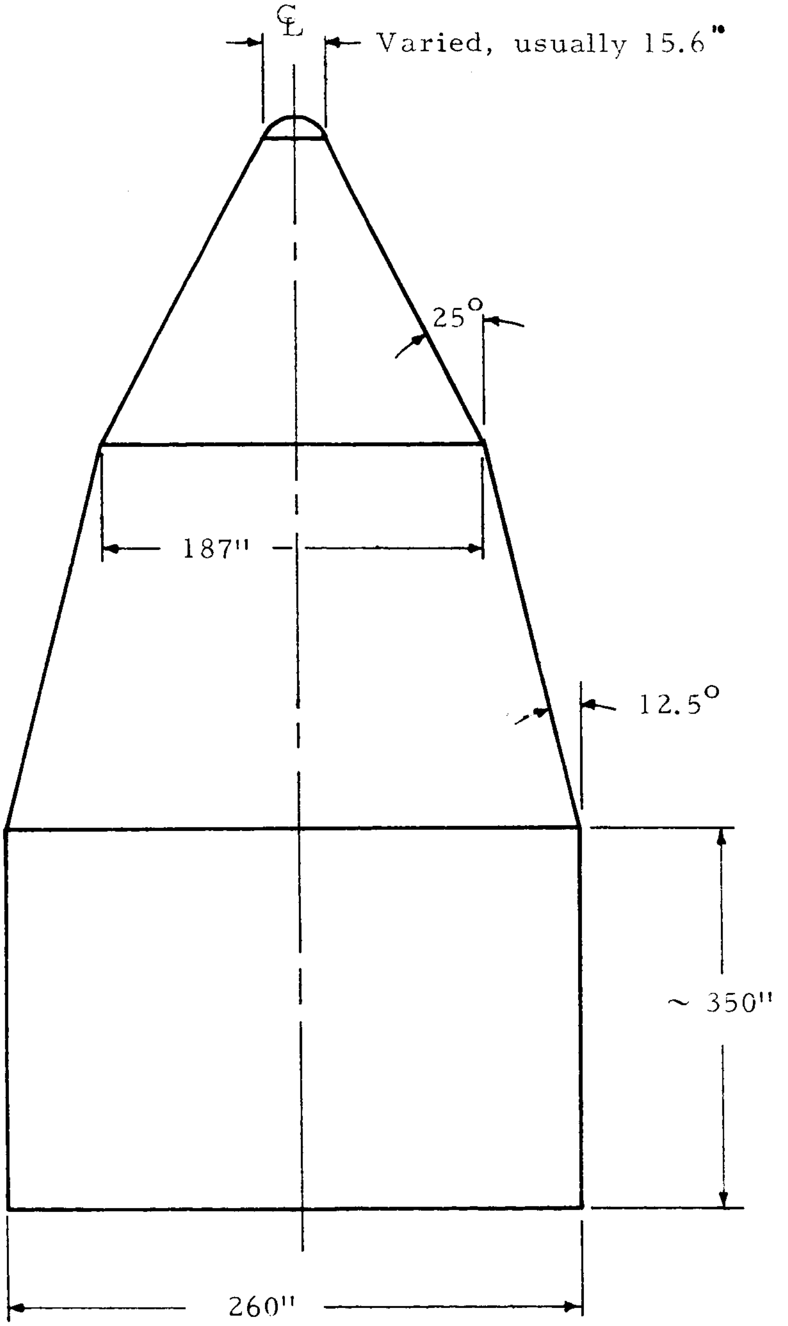

Figure 1 - External Geometry Used in Studies

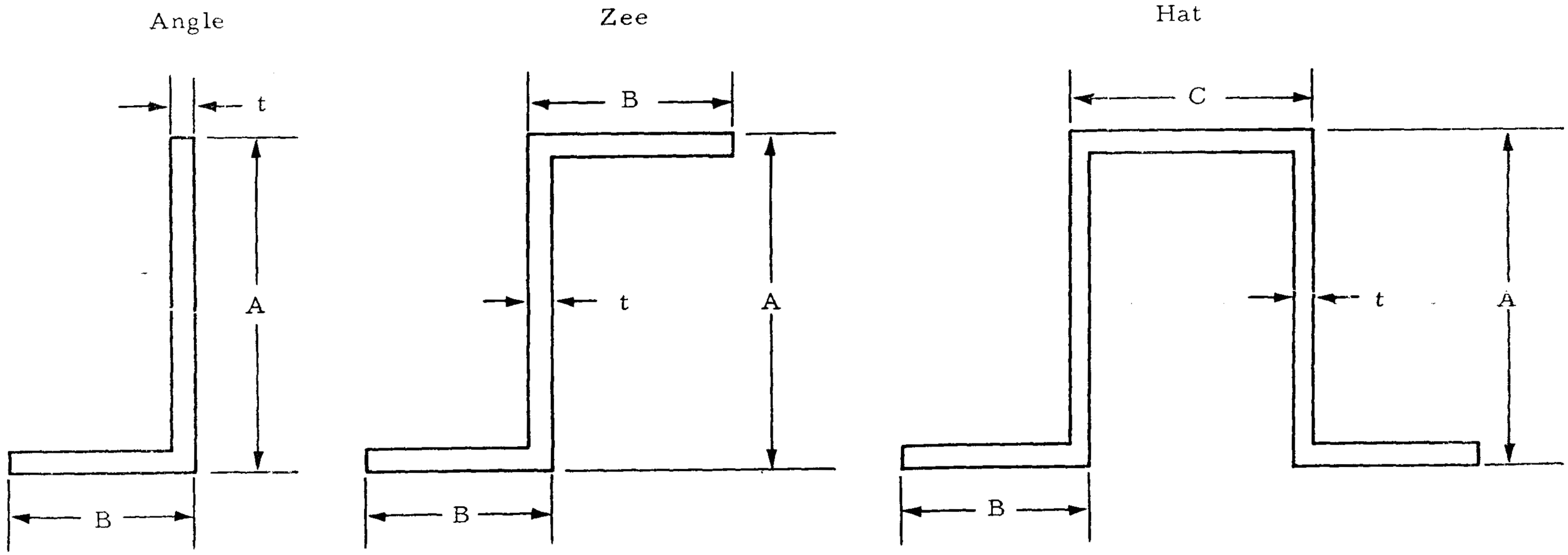

Figure 1a - Stiffener Cross-Section

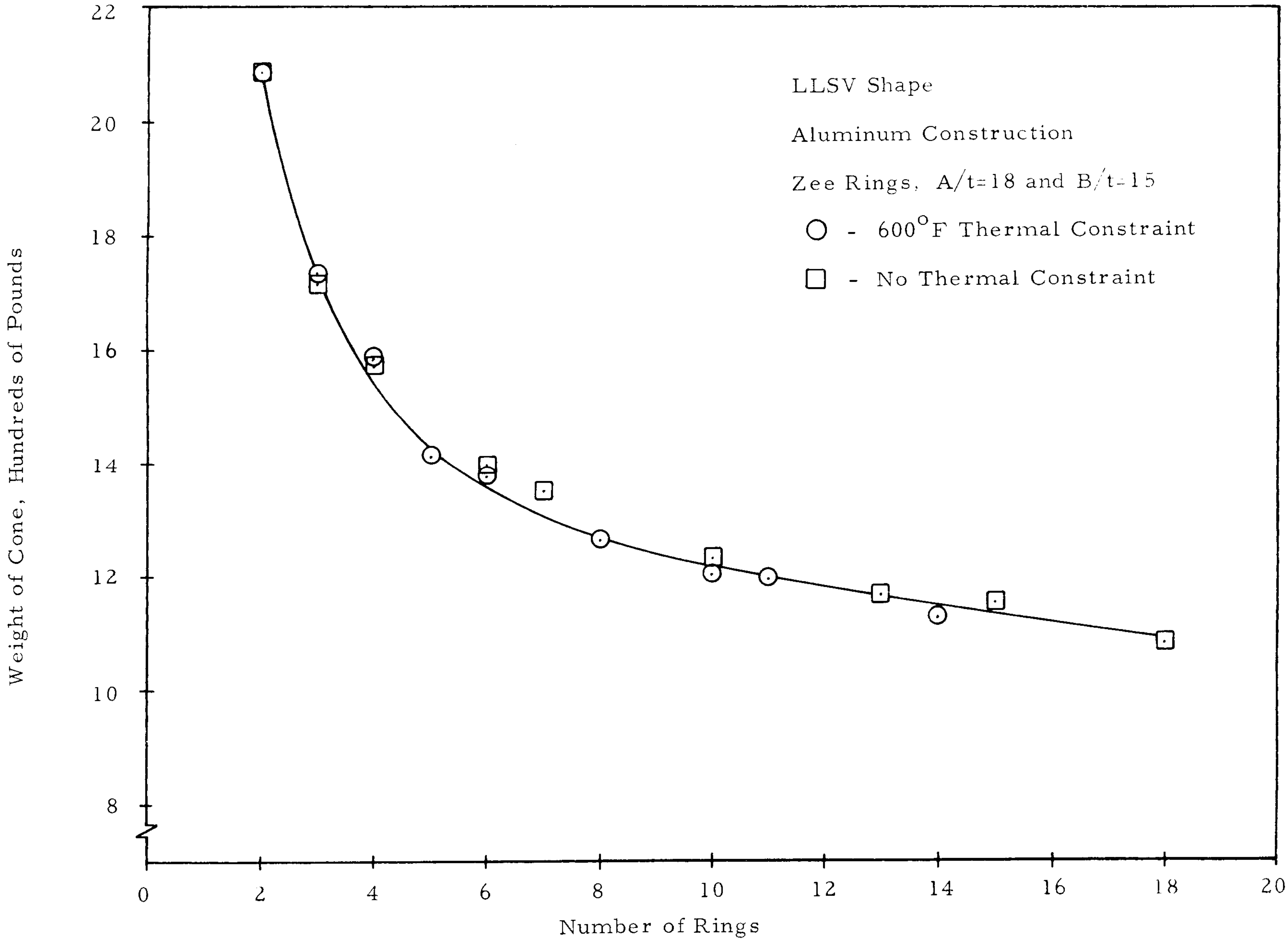

Figure 2 - Typical Effect of Number of Rings on Ring-Stiffened Conical Section Weight

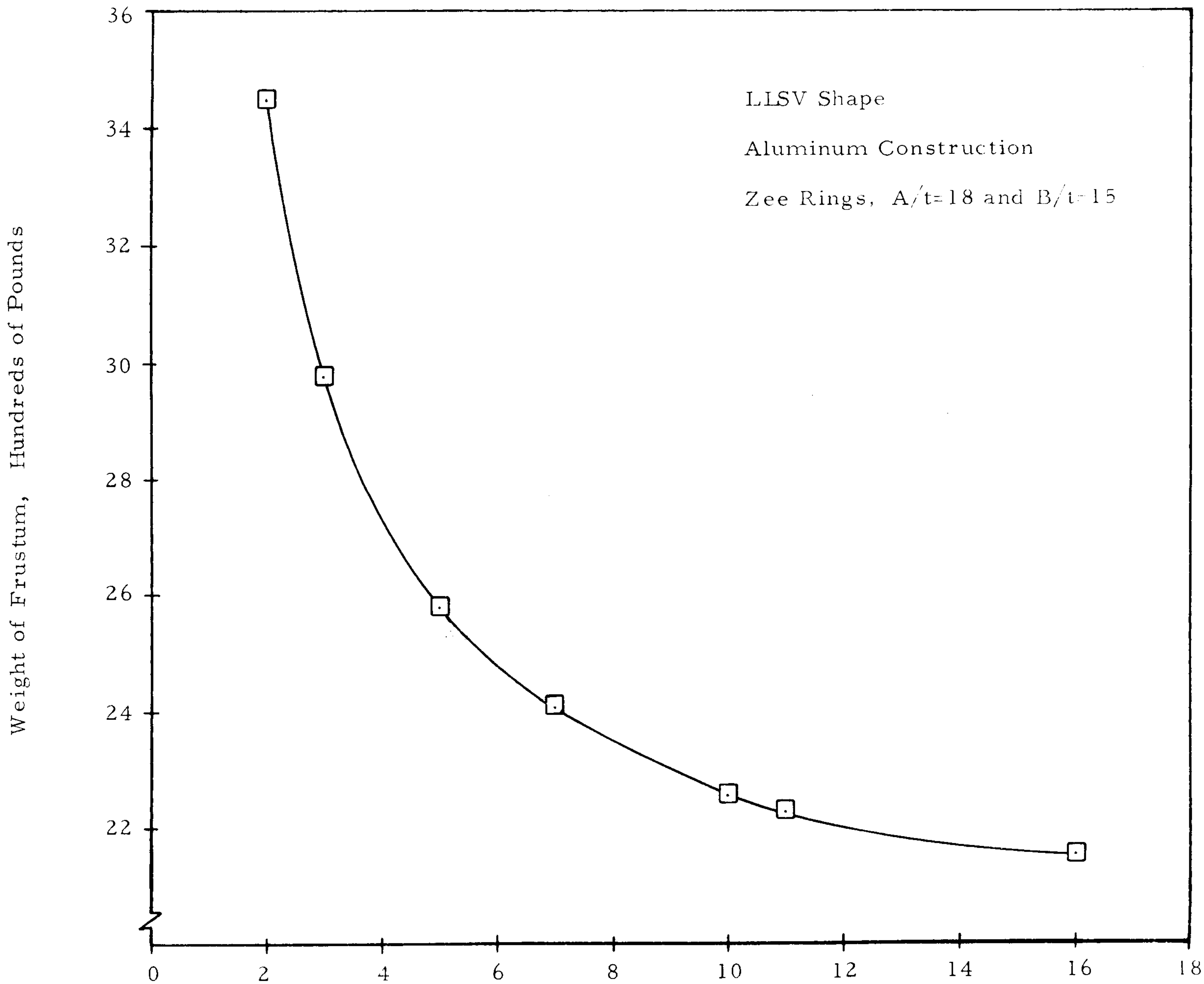

Figure 3 - Typical Effect of Number of Rings on Ring-Stiffened Frustum Section Weight

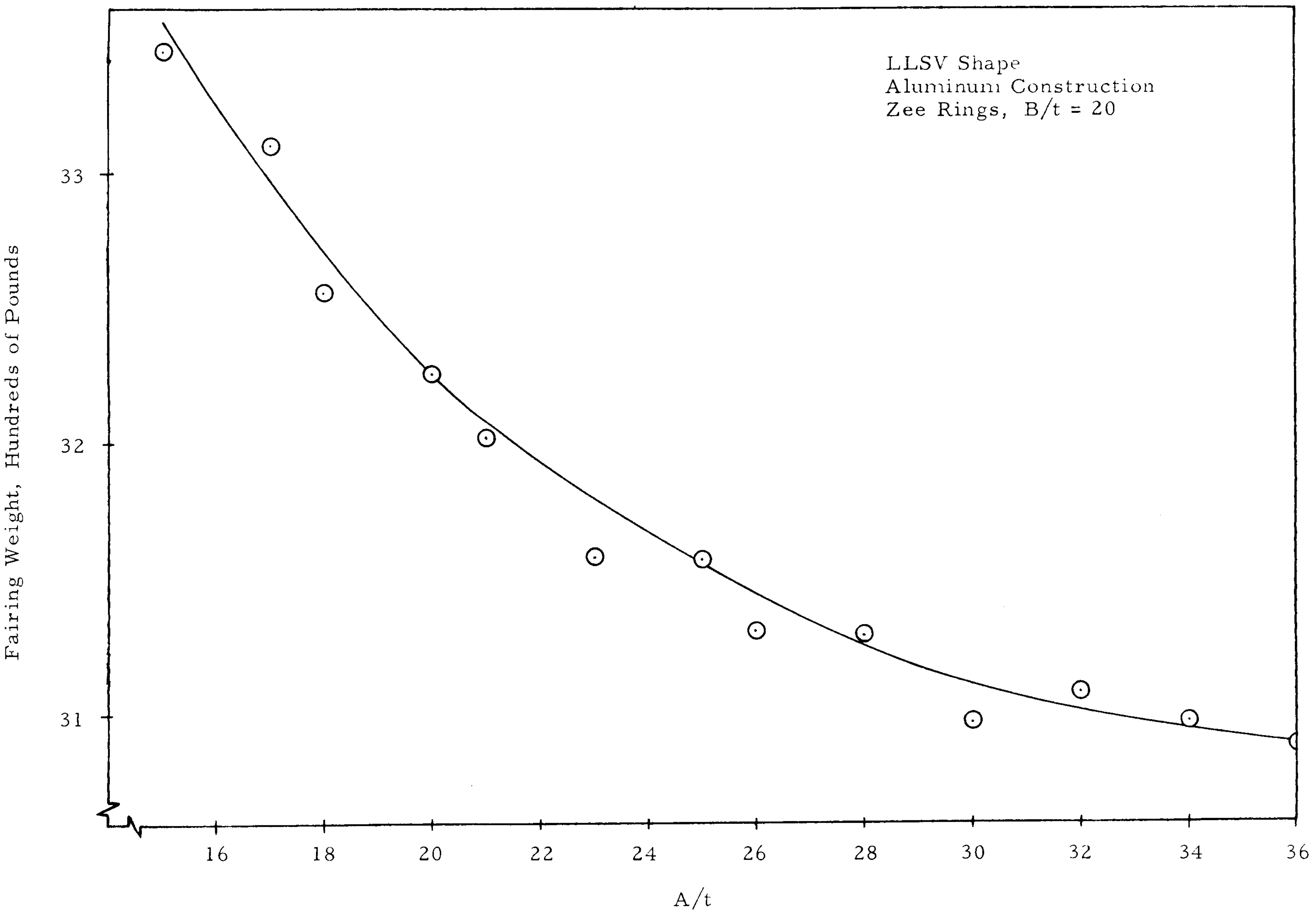

Figure 4 - Typical Influence of A/t on Fairing Weight

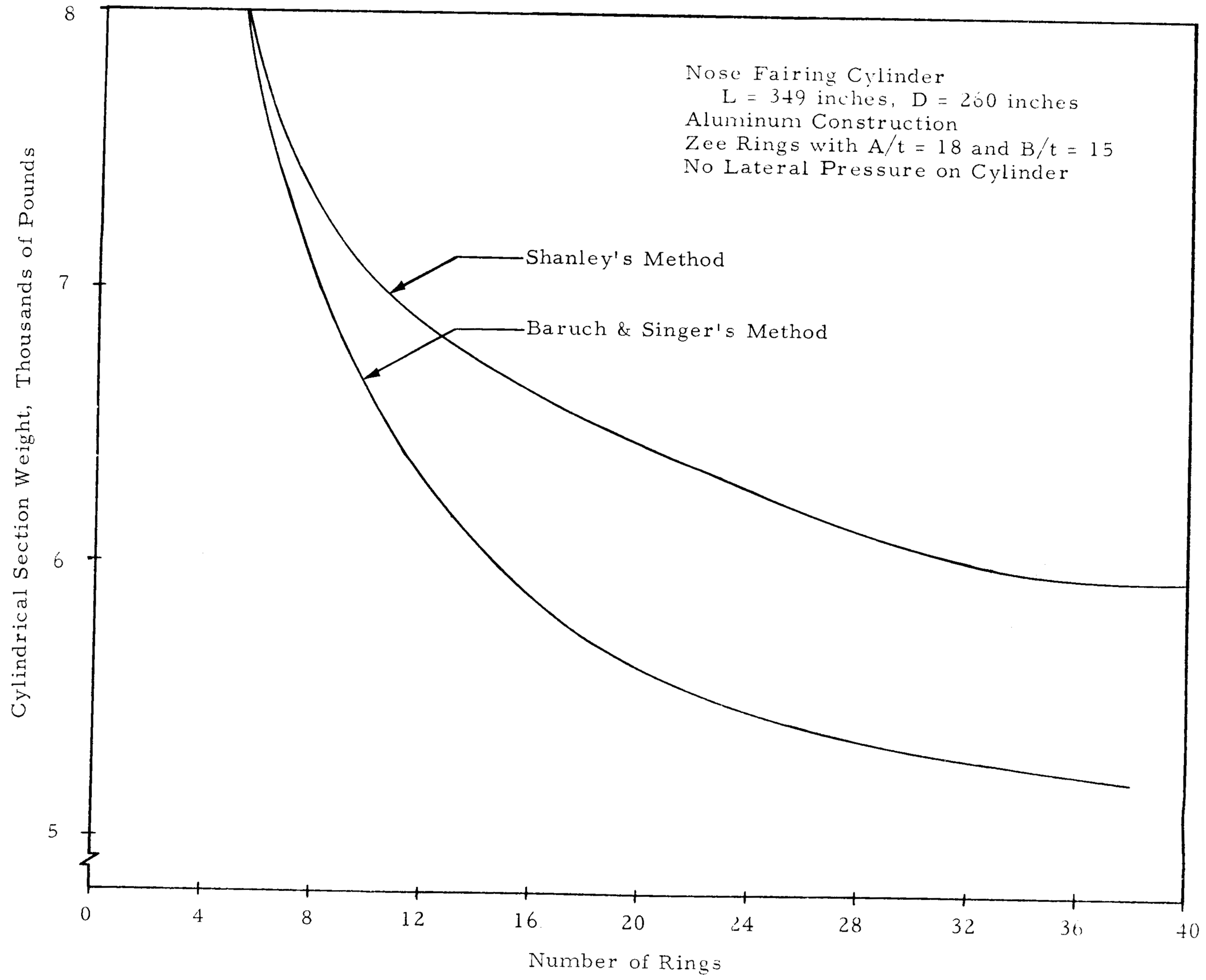

Figure 5 - Typical Effect of Number of Rings on Cylindrical Section Weight

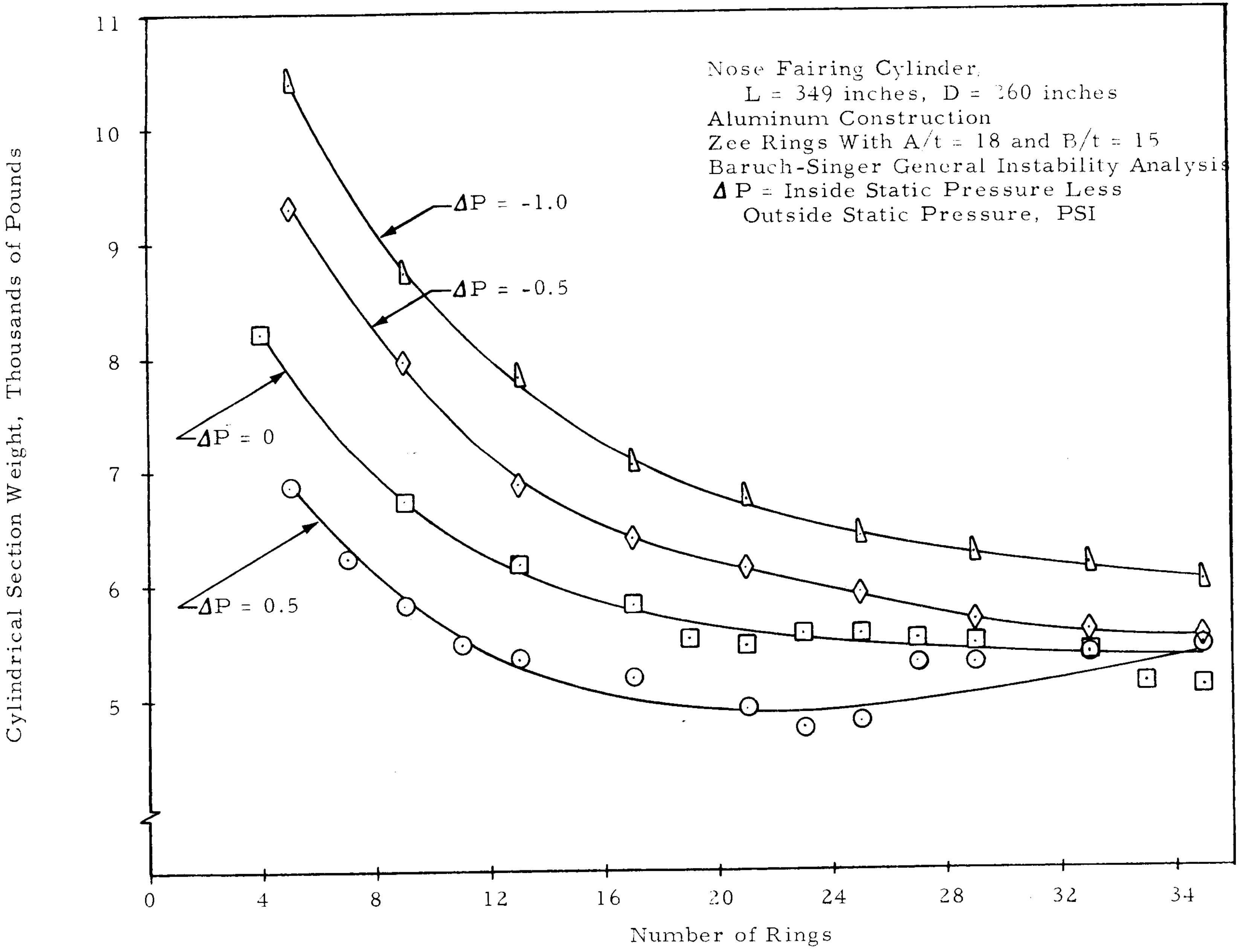

Figure 6 - Typical Effect of Number of Rings and Static Pressure Differential at Max αq on Cylindrical Section Weight

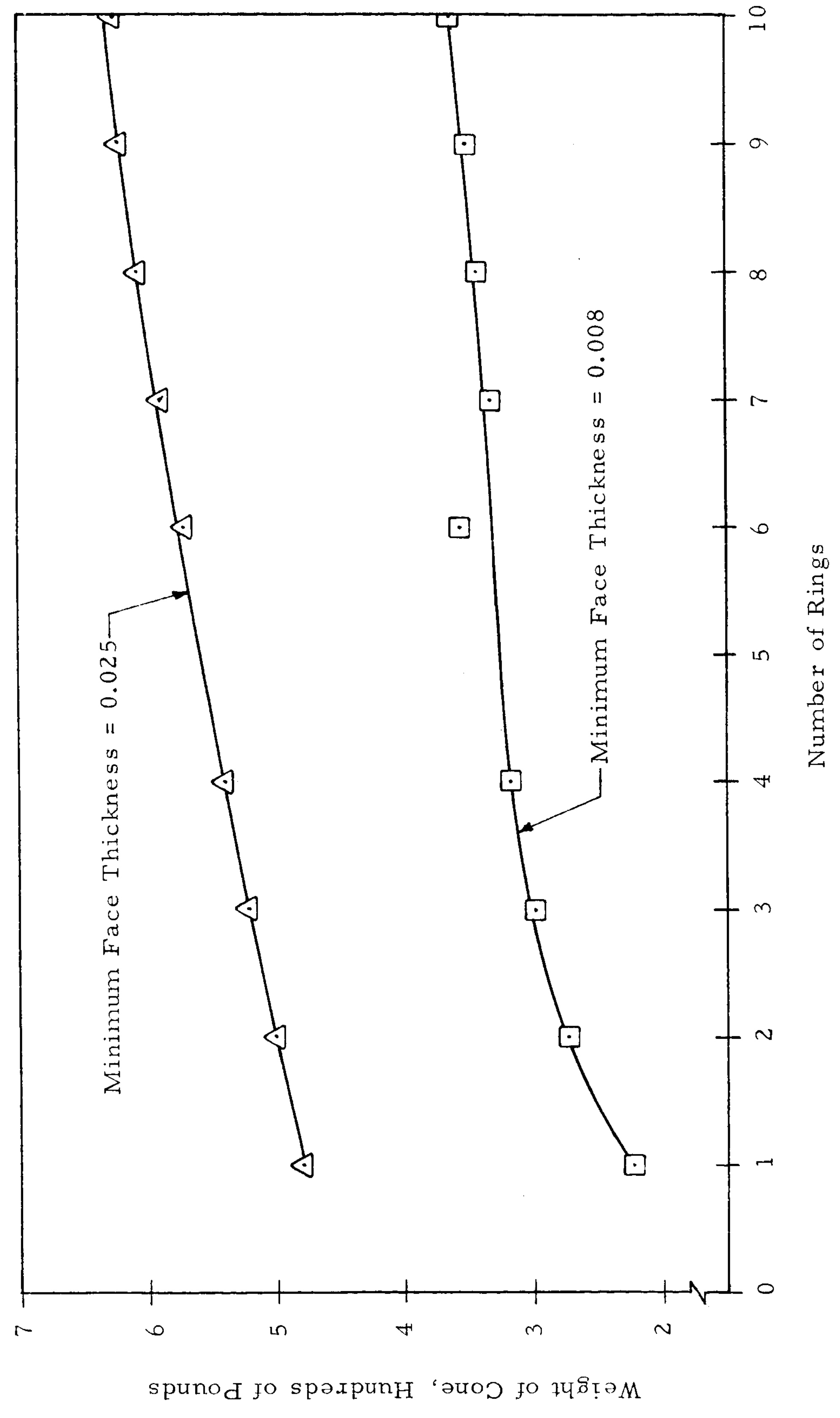

Figure 7 - Effect of Number of Rings on Weight of Sandwich Conical Section

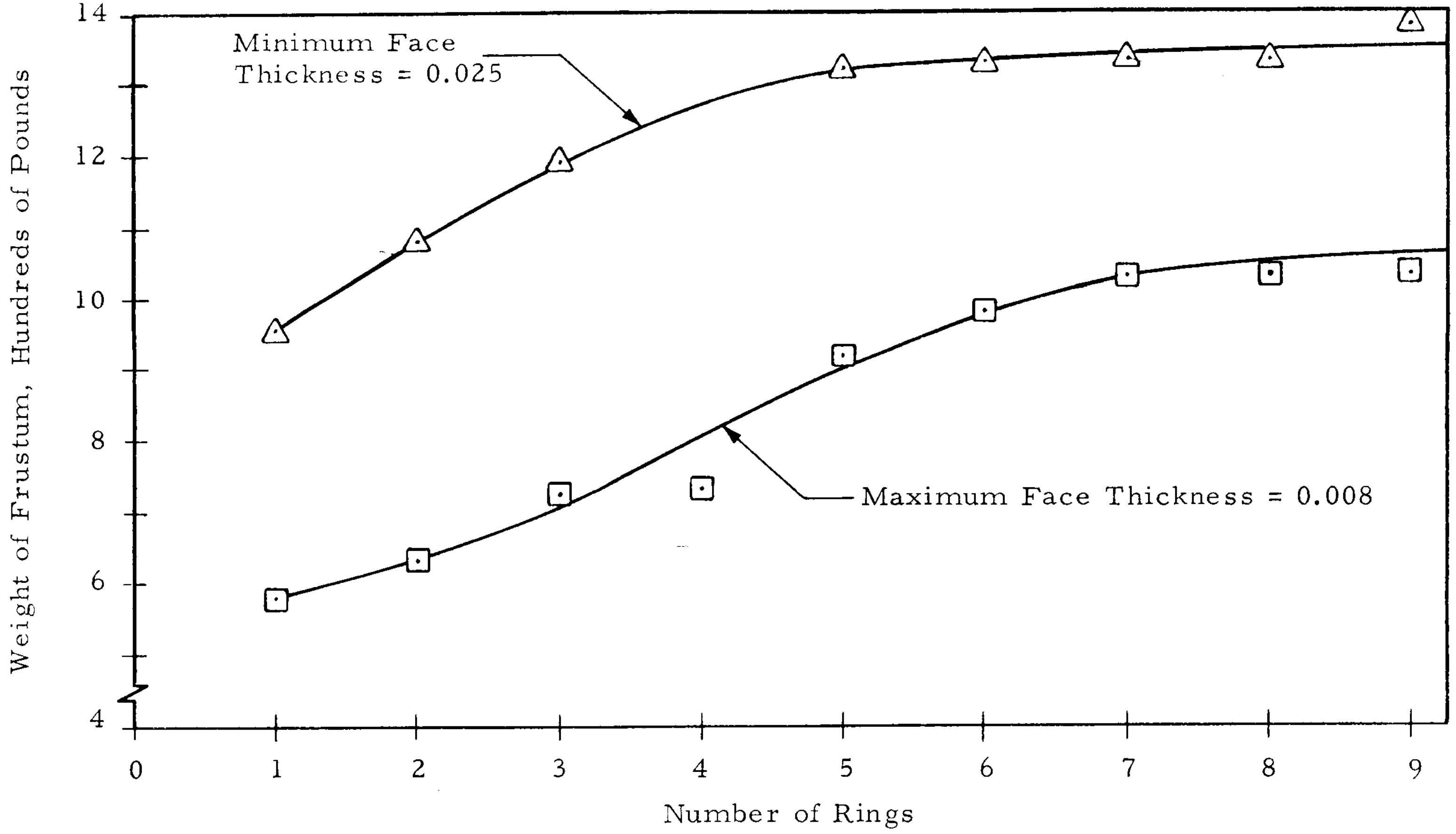

Figure 8 - Effect of Number of Rings on Weight of Sandwich Frustum Section

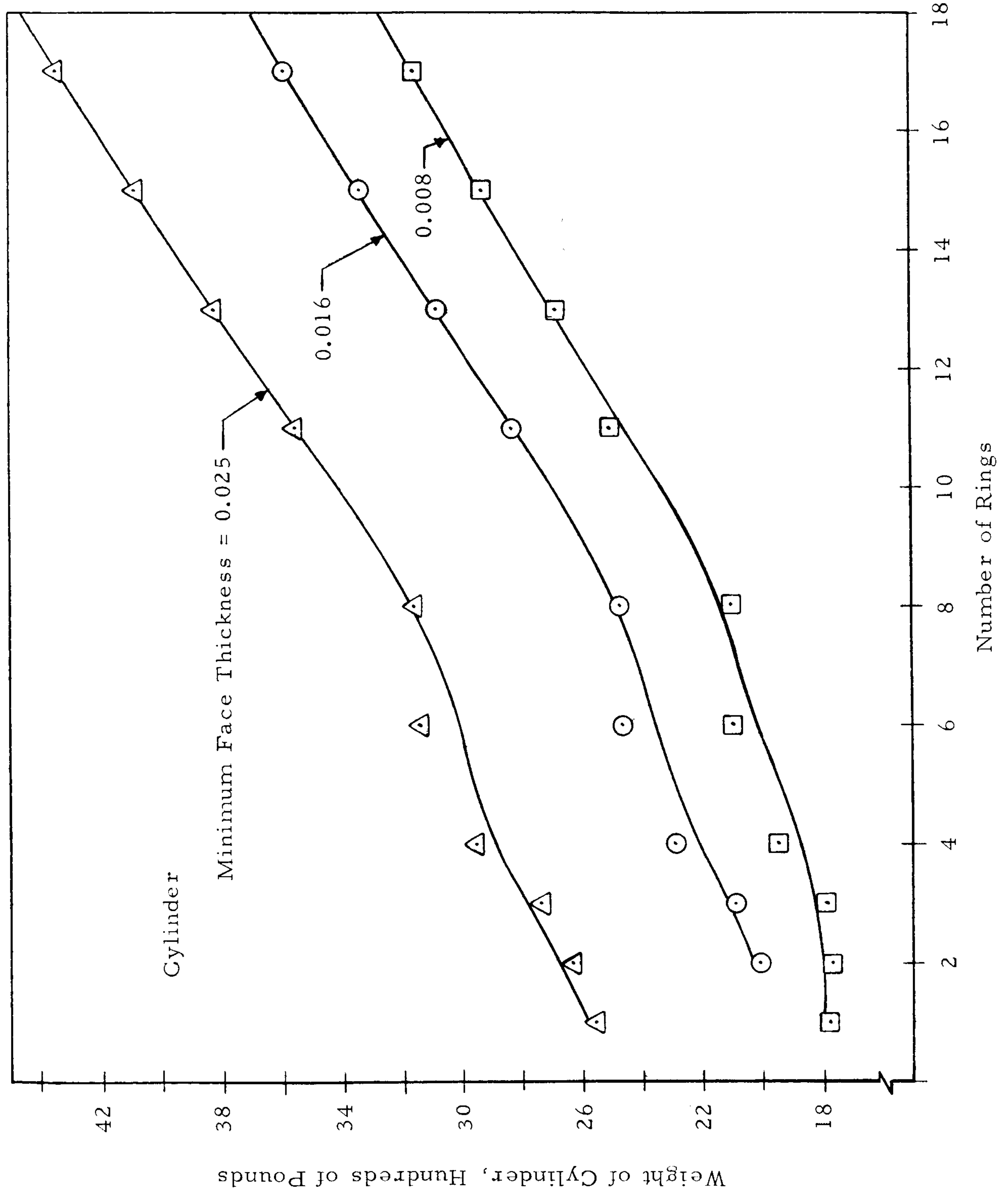

Figure 9 - Effect of Number of Rings on Weight of Sandwich Cylindrical Section

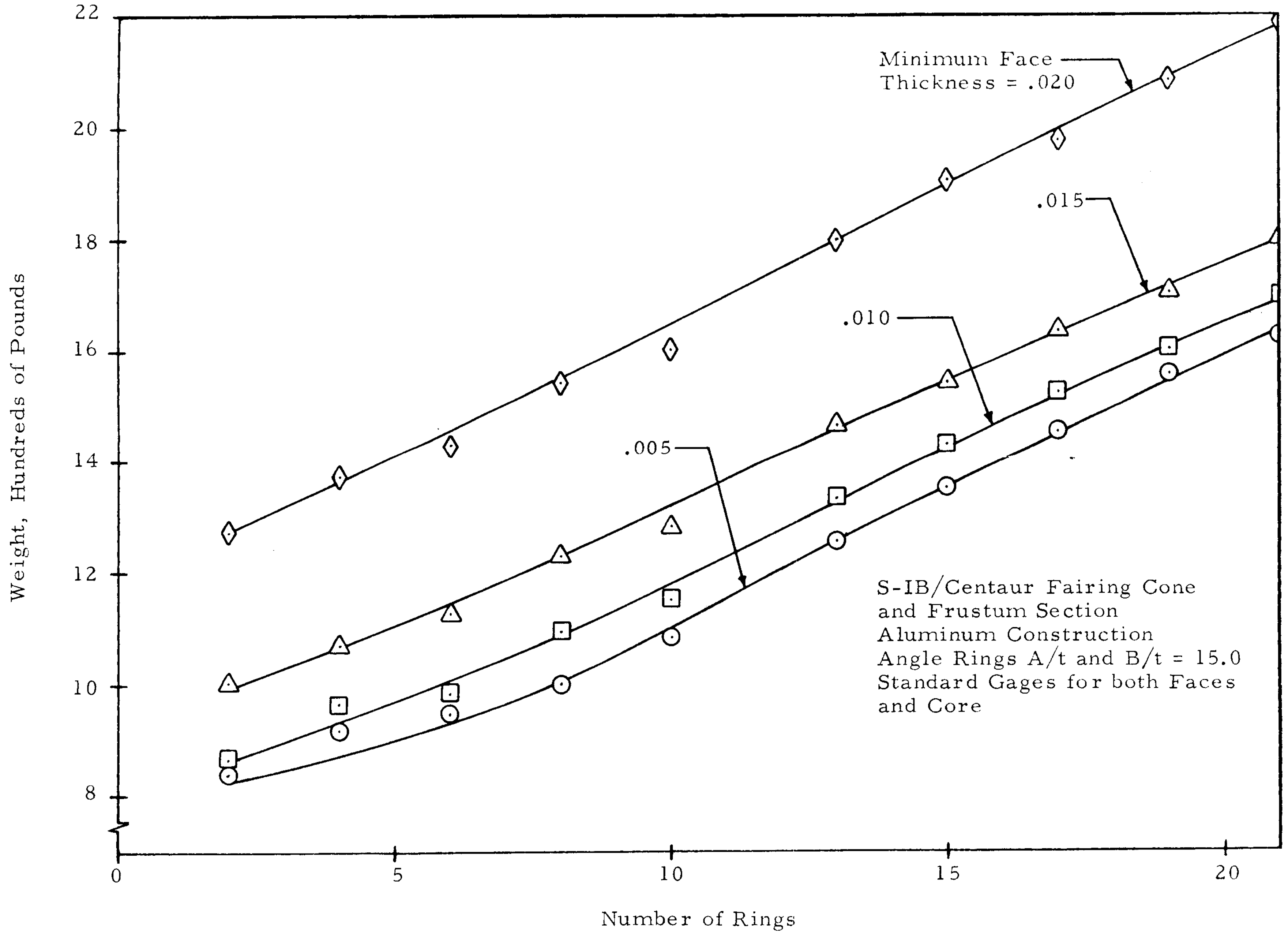

Figure 10 - Effect of Number of Rings on Weight of Sandwich Cone and Frustum Section

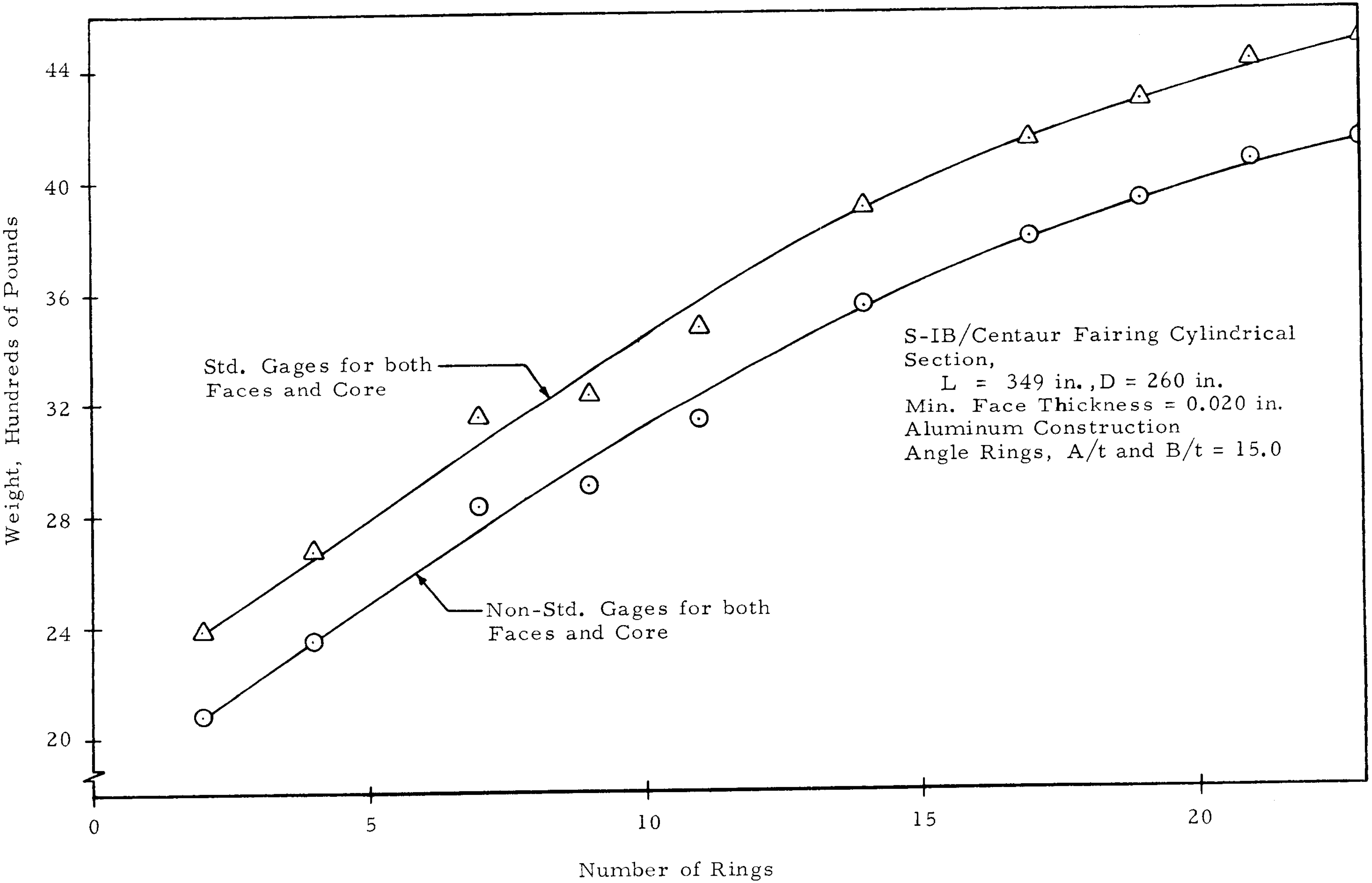

Figure 11 - Effect of Number of Rings on Weight of Sandwich Cylindrical Section

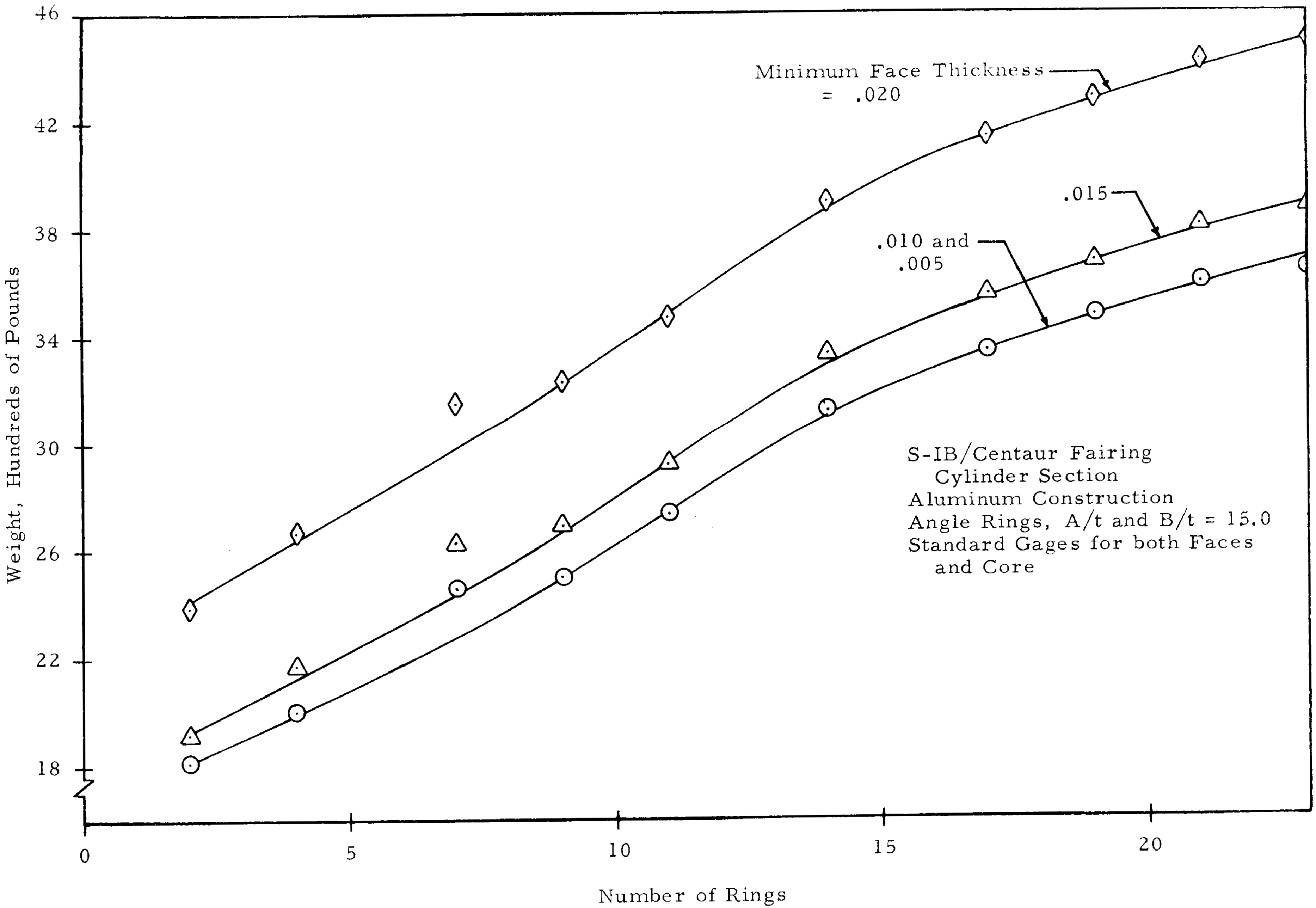

Figure 12 - Effect of Number of Rings on Sandwich Cylindrical Section Weight

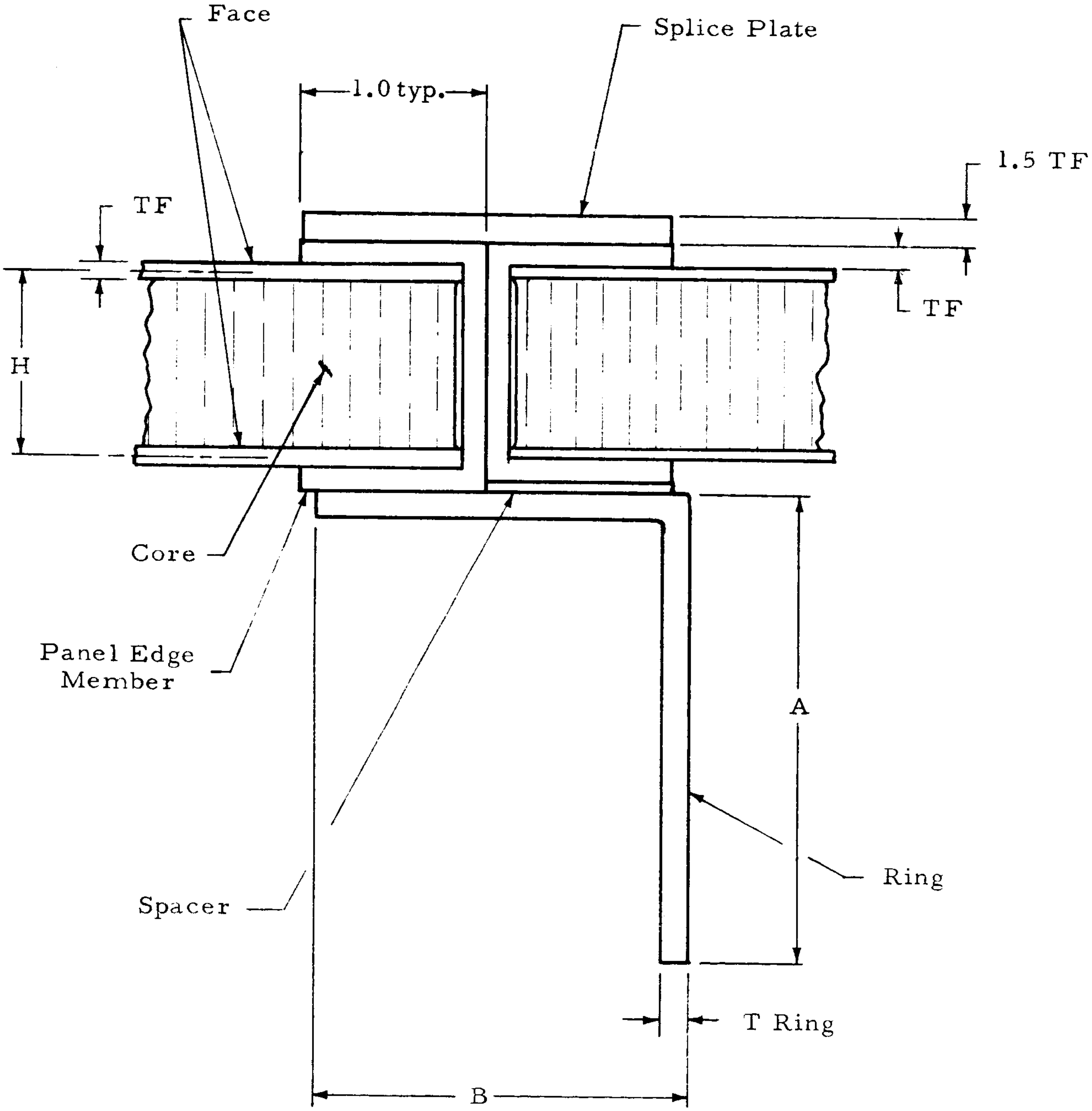

Figure 13 - Sandwich Joint Configuration used for Weight Calculations

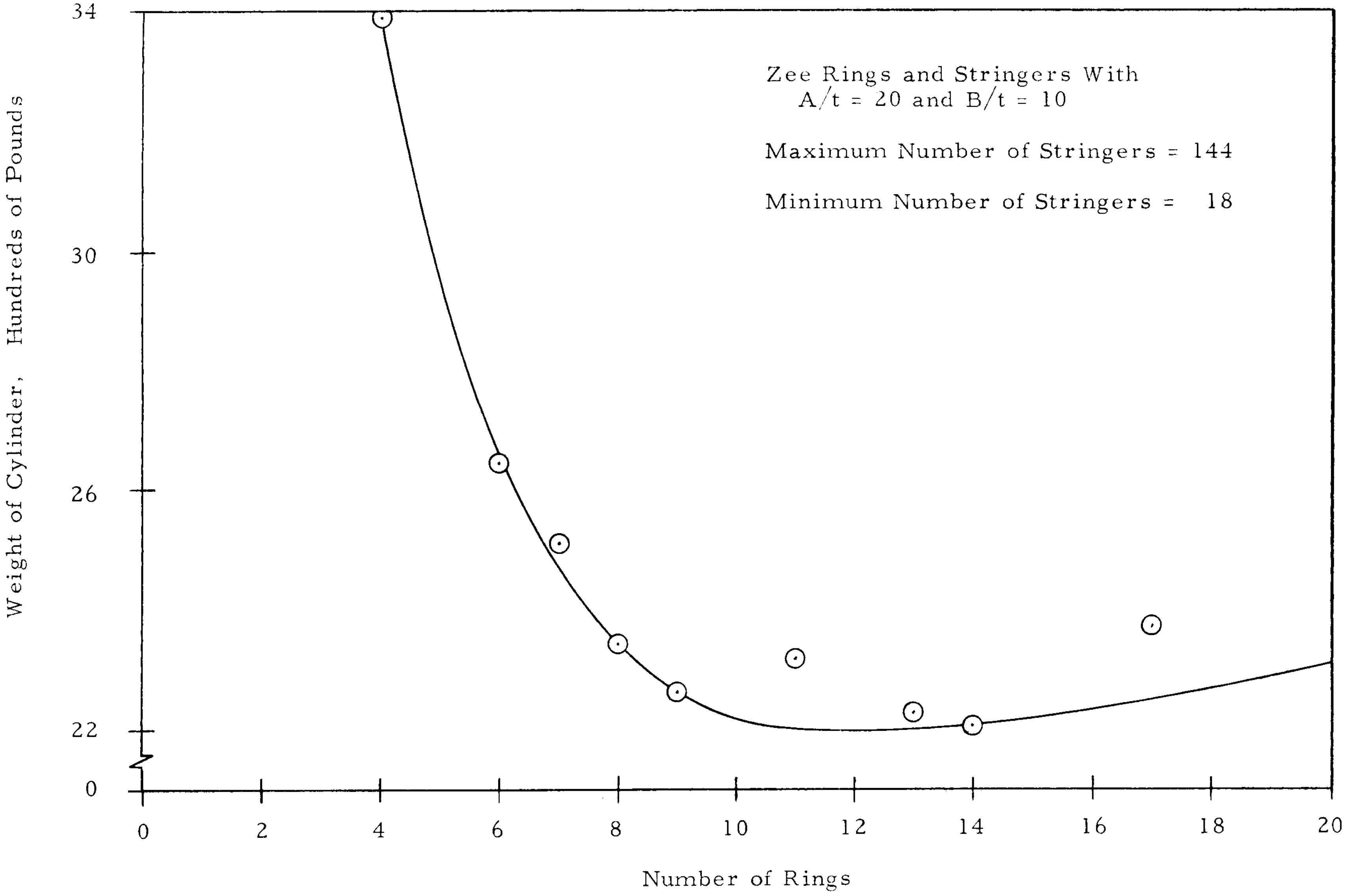

Figure 14 - Typical Effect of Number of Rings on Cylindrical Section Weight - Ring, Skin and Stringer Construction

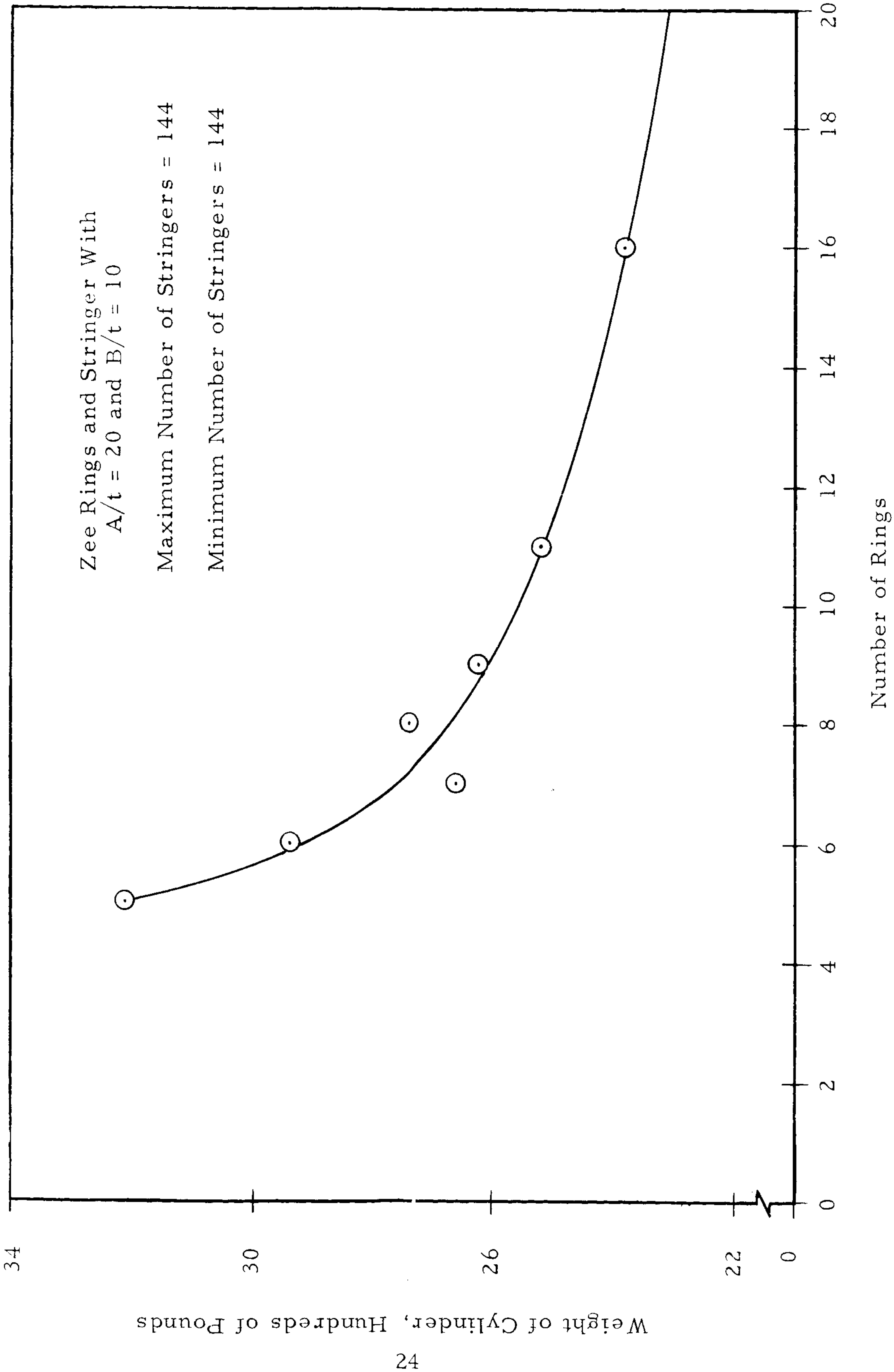

Figure 15 - Typical Effect of Number of Rings on Cylindrical Section Weight - Ring, Skin and Stringer Construction

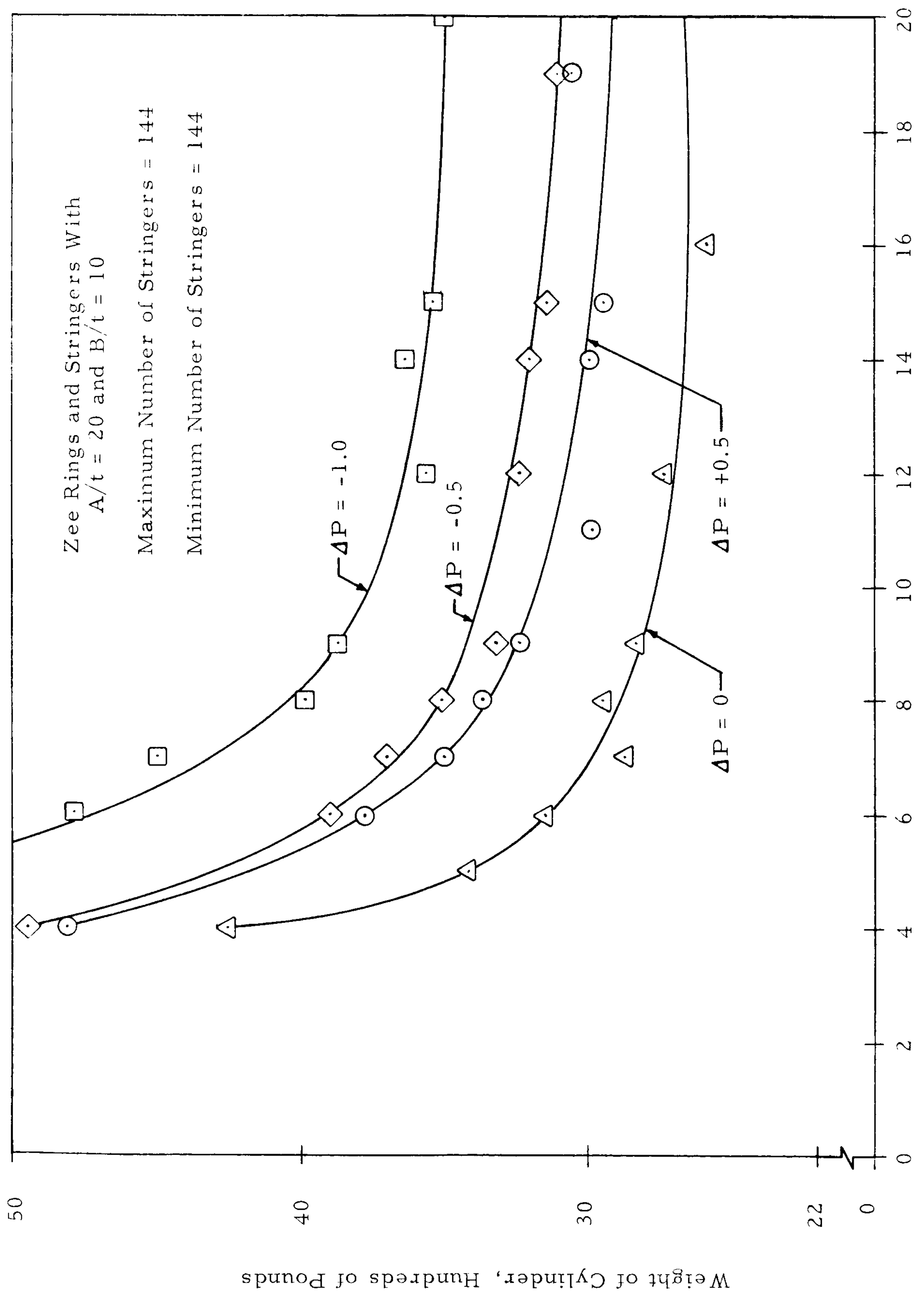

Figure 16 - Typical Effect of Number of Rings and Lateral Pressure on Cylindrical Section Weight - Ring, Skin, and Stringer Construction

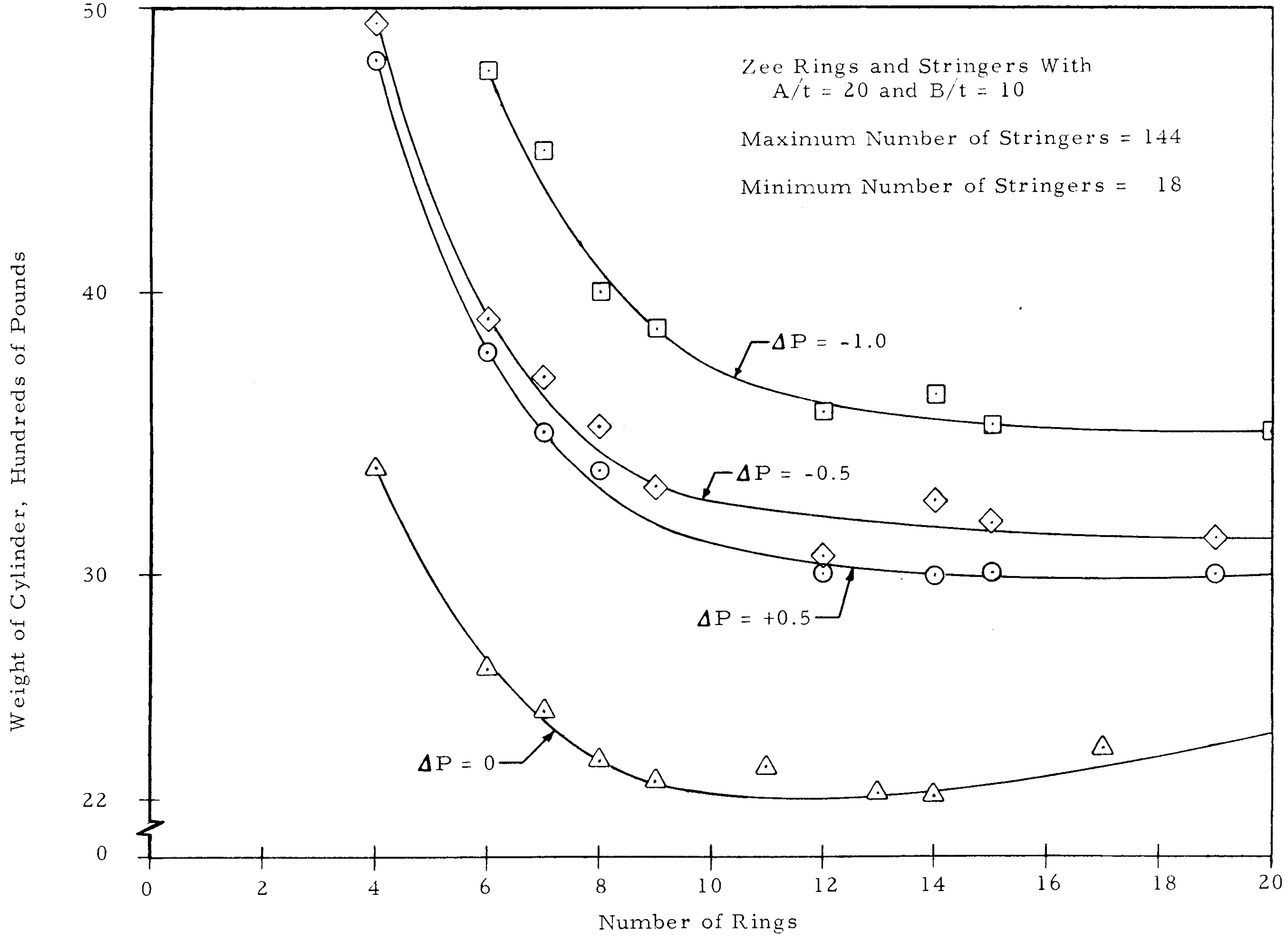

Figure 17 - Typical Effect of Number of Rings and Lateral Pressure on Cylindrical Section Weight - Ring, Skin, and Stringer Construction

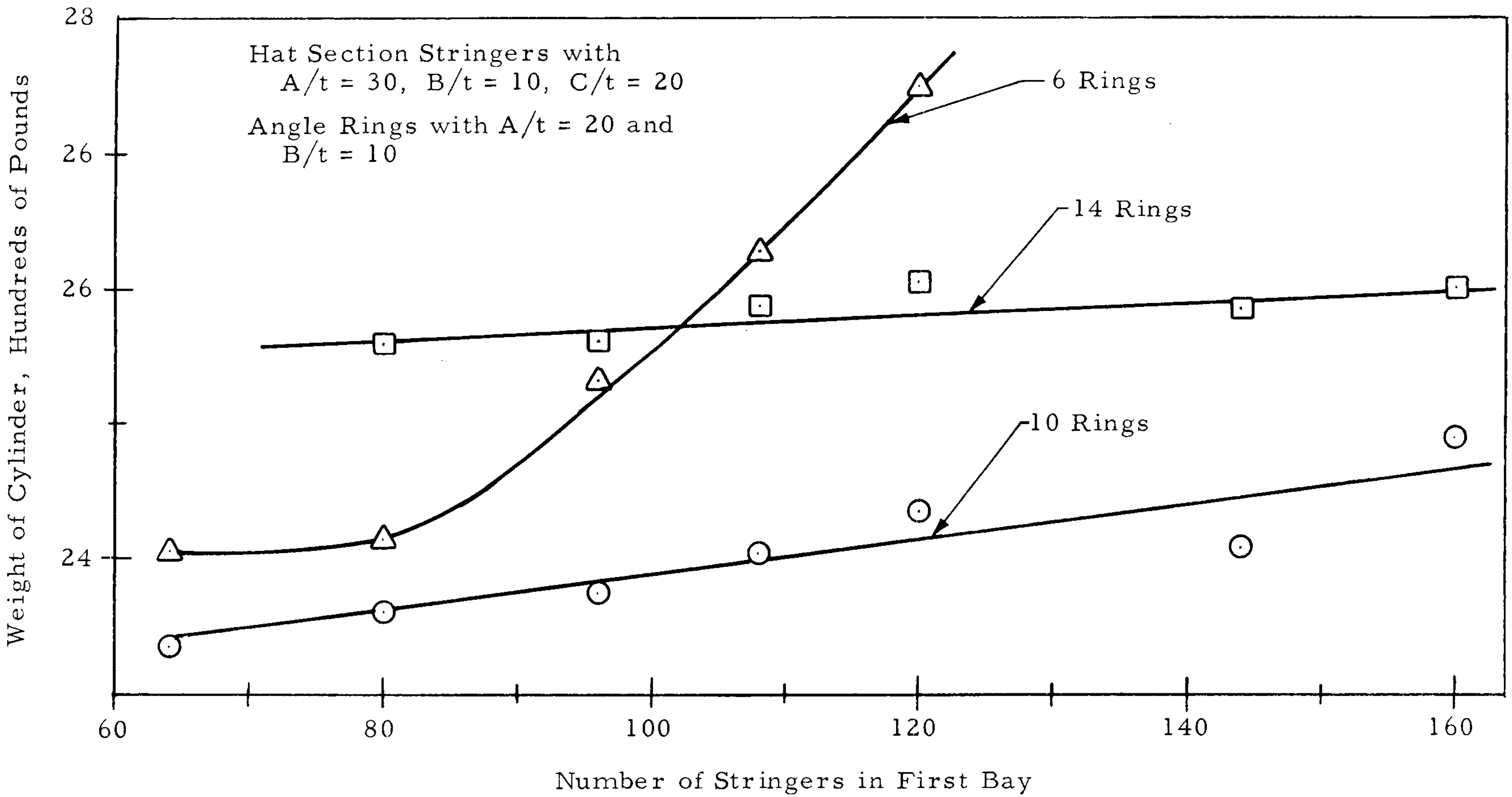

Figure 18 - Typical Effect of Number of Rings and Stringers on Cylindrical Section Weight

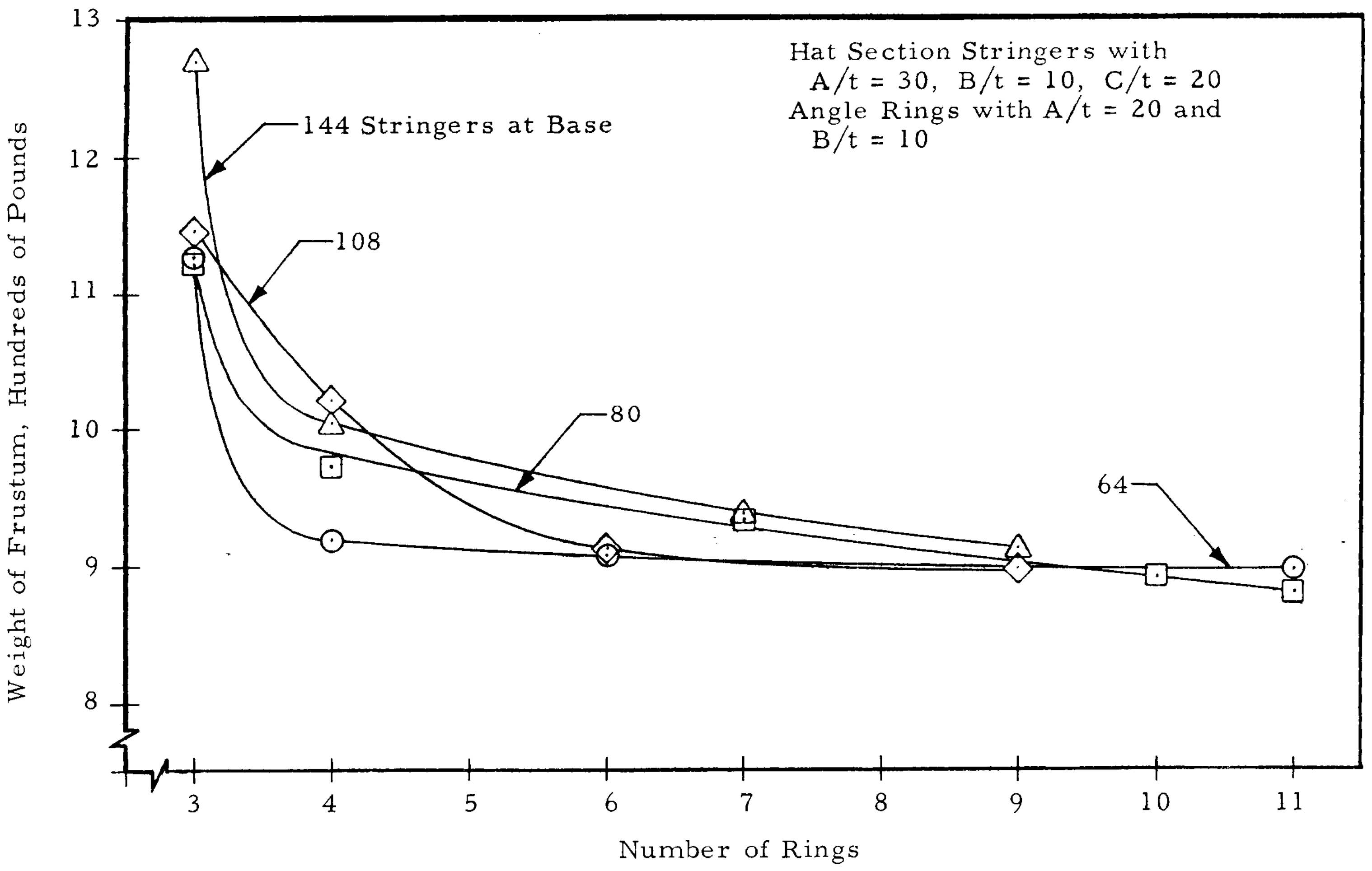

Figure 19 - Typical Effect of Number of Rings and Stringers on Frustum Section Weight