NASA TECHNICAL MEMORANDUM

(NASA-TM-82521) LIQUID HELIUM MANAGEMENT FOR GRAVITY PROBE-B (NASA) 36 p
HC A03/MF A01

N83-24830

Unclas
G3/35 03773

NASA TM- 82521

LIQUID HELIUM MANAGEMENT FOR GRAVITY PROBE-B

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December 1982

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM-82521	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Liquid Helium Management for Gravity Probe-B		5. REPORT DATE December 1982
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Charles Schafer		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration, Washington, D.C. 20546		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Atmospheric Science Division, Space Science Laboratory, Science and Engineering Directorate

16. ABSTRACT

The Gravity Probe-B (GP-B) experiment will be degraded if accelerations at a proof mass become larger than 10^{-10} g. This makes necessary the management of the configuration and dynamical behavior of the large amount of liquid helium present in the GP-B spacecraft dewar. Three approaches to the solution of this problem are discussed. It is concluded that the most promising technique involves the use of baffles into which the liquid helium can be forced during a relatively high spacecraft rotation period, and in which the liquid helium will be held by capillary forces during the operational period when the rotation rate is much lower. Some likely baffle configurations are suggested.

17. KEY WORDS Gravity Probe-B, low-gravity fluids, capillary forces, baffles, liquid helium	18. DISTRIBUTION STATEMENT Unclassified – Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	35	NTIS

MSFC - Form 3292 (May 1969)

For sale by National Technical Information Service, Springfield, Virginia 22151

ACKNOWLEDGMENTS

The author wishes to express his thanks to Drs. G. H. Fichtl and F. W. Leslie of the Atmospheric Science Division, Space Science Laboratory, for their helpful discussions concerning low-gravity fluid mechanics and rotational fluid mechanics. Thanks are also given to Mr. S. A. Lowry, Structures and Propulsion Laboratory, for discussions concerning the balance of capillary and centrifugal forces in the Gravity Probe-B spacecraft.

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INTRODUCTION

The Gravity Probe-B (GP-B) experiment will require use of a large amount (approximately 700 lb) o. liquid helium (LHe) for purposes of component cooling and operation of a propulsion system. This propulsion system will orient the spacecraft, spin it, and null the effects of spacecraft drag to less than 10^{-10} g. The LHe will be contained in a dewar which comprises the bulk of the GP-B spacecraft (Fig. 1). The dewar is shown schematically in Figure 2. It is essentially a cylindrical tank i. which a cylindrical package containing the gravitational experiment system is mounted coaxially. Ove. .he lifetime of the experiment (approximately 1 yr), the LHe will be depleted so that at any time the annular region between experiment and dewar wall will contain both liquid and gaseous helium. The mass distribution of the LHe can have deleterious effects on experiment performance and spacecraft dynamics, as was discussed in another report [1], if it is not both axially and longitudinally symmetric. It was shown in Reference 1 that the configuration of the LHe is primarily the result of the balance between centrifugal forces and surface tension for the boundary conditions imposed by the spacecraft dewar. It was also shown that for the operational rotation rate of the GP-B spacecraft about its longitudinal axis (approximately 0.01 rad/sec), surface tension and centrifugal effects are comparable. This leads to a situation in which the LHe configuration is not highly predictable, and is very likely to be unsymmetric.

A measure of the relative importance of centrifugal forces compared to surface tension is given by the rotational Bond number B_r, where:

$$B_r = \frac{\rho\, \omega^2 r^3}{2\sigma} \quad .$$

Here

ρ = liquid helium density

ω = rotation rate

r = cylindrical bubble radius

σ = surface tension.

Values of B_r are plotted in Figure 3 for various values of r over the range of rotation rates from 0 to 0.1 rad/sec for a surface tension of 0.35 dynes/cm [2]. For the higher rotation rates, centrifugal forces are clearly dominant. In Figure 4, the plots are expanded to show the region of lower Bond numbers and lower rotation rates in more detail. It can be seen that at the planned operational rotation rate for

GP-B, surface tension will be slightly dominant, particularly for the smaller radii of curvature (smaller ullage volume). Figures 5 and 6 show the same calculations, but assume that surface tension is 0.53 dynes/cm [3].

Since analyses indicate that an unsymmetric liquid helium distribution is expected, and since a symmetrical mass distribution is critical to the success of the GP-B experiment, some method must be devised to achieve symmetry. Approaches to the solution of this problem are discussed here.

LIQUID HELIUM MANAGEMENT METHODS

Since there are only two forces that significantly affect the LHe distribution in the GP-B dewar for a given fill factor, any scheme for controlling the distribution must make use of one or both of them. The possibilities are:

1) Use centrifugal forces to control the LHe configuration

2) Use surface tension to control the LHe configuration

3) Use centrifugal forces and surface tension simultaneously or in sequence to attain the required LHe distribution in the dewar.

As noted above, at the operational rotation rate of about 0.01 rad/sec, neither force is strongly dominant although surface tension will tend to be more important. For centrifugal forces to be clearly dominant, it would be necessary to increase the operational rotation rate by a factor of at least 5 (Figs. 3 and 5), and preferably by a factor of approximately 10 so that high dewar fill factors could be accommodated. The higher rotation rate approach to obtaining a symmetrical LHe configuration would work. There are several shortcomings to this approach, however. They are:

1) It would be very expensive in terms of propellant (helium) consumption to maintain the higher rotation rates. Any asymmetry resulting in nonzero products of inertia will tend to cause motion of the spacecraft to deviate from rotation about the longitudinal axis (which should be a principal axis). To compensate for this effect, a torque must be applied to the spacecraft which is proportional to the square of the rotation rate. This would have a significant effect in shortening the experiment lifetime due to the accelerated rate of liquid helium depletion.

2) When the centrifugal forces are much greater than surface tension effects, the LHe will assume a circular cylindrical configuration with the free surface coaxial with the experiment cylinder. That is, the LHe will fill the outer portion of the dewar symmetrically. This configuration has the potential for surface waves (sloshing modes) having wavelengths of the order of the dewar length. These could lead to disturbances in the mass distribution that would be disruptive to the experiment gyros. For large amplitude waves, the mass imbalances could be very large.

3) Another potential problem for this configuration is capillary instability. Long cylinders of gas on the rotational axis of a liquid in solid-body rotation have been observed to pinch off into separate bubbles when strongly perturbed [4]. If this occurred in the GP-B spacecraft, the result would be an unknown liquid-vapor configuration.

A second approach to solving the helium management problem has been suggested. This approach would use capillary forces by holding the LHe in a foamed material. Since the pressure drop across a fluid interface is given by $\Delta P = \sigma(1/R_1 + 1/R_2)$, where R_1 and R_2 are the principal radii of curvature of the interface, the pressure required to force a fluid out of (or into) a material having small pores can be very large. Foamed aluminum (which would be capable of withstanding the low temperatures and which would have relatively low density) can be obtained commercially with pore sizes of 0.25 in. (0.63 cm). For this pore size, and assuming a surface tension of 0.53 dynes/cm, characteristic pressures for forcing the LHe through the pores would be of the order of 0.84 dynes/cm. At a rotation rate of 0.1 rad/sec, centrifugal forces would dominate over much of the dewar (Fig. 7), but not over enough of the volume to reliably seat the LHe with the required symmetry. At the operational rotation rate, the capillary forces would dominate everywhere (Fig. 8) so that the location of regions of liquid relative to vapor regions would not be predictable.

This problem could be somewhat alleviated by going to larger pore sizes. Two problems with this approach still remain, however. First, it is probable that any foamed material would contain a dispersion in pore size around the target size. Regions where pore sizes were smaller would preferentially trap liquid, and regions of larger pore sizes would tend to preferentially contain vapor (depending on rotation rate and location in the dewar). This would tend to make mass distributions less predictable. Secondly, filling the dewar with foamed aluminum would significantly increase spacecraft mass. The foamed aluminum is reportedly available in density ratios (to solid Al) ranging from 0.02 to 0.05. Since the dewar volume is planned to be 2218 liters, this represents an additional mass of 120 kg for the 0.02 dense material, and 300 kg for the 0.05 dense aluminum.

A potential advantage of the foamed aluminum is that the liquid helium could be prevented from sloshing. This approach would probably require some active center-of-mass control system on the GP-B spacecraft due to the unpredictability of the liquid helium location.

Neither capillary forces nor centrifugal forces alone appear to offer a technically acceptable solution to the liquid helium management problem. A potential solution which makes use of both forces has been conceptually developed. The technique proposed involves use of the initially higher spin phase of the experiment in conjunction with a set of baffles or partitions to establish and maintain a symmetric liquid helium distribution.

After injection into orbit, the GP-B spacecraft will be subjected to a period of relatively high spin (as much as 0.1 rad/sec) for purposes of instrument calibration. During this high-spin period, angular momentum gets convected into the liquid helium in a manner discussed in another report [1]. If baffles are used, the characteristic time for the liquid helium to achieve solid-body rotation with the spacecraft is less than a day (several hours). When solid-body rotation is achieved, the pressure field due to centrifugal forces can be computed throughout the liquid helium. If the rotation rate is high enough during this initial phase, the centrifugal forces will dominate over surface tension. In the limit that surface tension can be neglected, configurations of the liquid helium in the dewar can be very simply predicted. The liquid helium will just fill the dewar axisymmetrically from the outer wall radially inward. When the rotation rate is reduced to the operational levels, and the liquid helium has de-spun (achieved solid-body rotation at the lower spin rate), the surface tension will again be dominant. For the case of a dewar consisting of an annular region between two cylinders, the liquid helium would rearrange itself in a rather unpredictable way and come to equilibrium in an unsymmetric configuration.

If the region between the experiment cylinder and dewar wall is filled with a set of partitions (baffles), the result of despin after achieving axisymmetry in a high-spin mode is very different. The surface of the liquid helium would be broken up into smaller areas bounded longitudinally by two baffles. The reduced rotation rate would change the shape of the meniscus between each set of baffles, but should not upset the overall symmetry of the system. Figure 9 shows schematically a section of the

GP-B dewar with baffles installed. The radius of the hole at the center of each baffle is labelled r_2. The gap between the baffle inner edge and the experiment cylinder is $a = r_2 - r_1$, where r_1 is the experiment cylinder radius. The size of the gap is a critical parameter in the problem, since it is directly related to the liquid helium initial fill factor and the value of the high initial spin rate (discussed later). The baffle spacing, b, is another important parameter; its specification is also discussed later. Figure 10 shows a baffle in plan view. Gaps are left around the other baffle perimeter at intervals to permit free passage of liquid helium. This is designed to enable all baffles to be in hydrostatic equilibrium with each other.

The sequence of events leading from an initial arbitrary, but probably unsymmetric, liquid helium configuration to a final symmetric configuration is illustrated in Figures 11 through 14. In Figure 11, the helium configuration is similar to that which would be expected after the GP-B spacecraft has been injected into orbit, but before the initial high rotation period has begun. There is a bubble of helium gas at one end of the dewar. This configuration is the result of the thrust which lifted the spacecraft into orbit. The amount of gaseous helium present at this time is of critical importance to the outcome of the helium management scheme and is a function of rotation rate and baffle configuration (gap size). Figure 12 shows the effect of rotating the dewar. Centrifugal forces begin to become dominant and the gaseous helium is driven by buoyancy toward the rotation axis. If the gaps between the inner edges of the baffles and the experiment cylinder are sized properly for the rotation rates available, surface tension can be overcome and the bubble of helium gas can be made symmetric. Figure 13 depicts the situation in which the liquid helium has spun up to the high initial rotation rate. The helium configuration has achieved the desired symmetry. The shape of the meniscus between any two adjacent baffles is determined by the zero degree contact angle (perfect wetting) of the liquid helium on the baffle and by the balance between surface tension and centrifugal forces. For the high rotation rate, menisci should be flattened as shown in Figure 13. Figure 14 shows the result of reducing the rotation rate to the operational level where surface tension is slightly dominant. The meniscus between adjacent baffles becomes more rounded (the radius of curvature increases). In the limit that centrifugal forces become unimportant (rotation rate $\omega \to 0$, or surface tension $\sigma \to \infty$), the menisci become semi-circles for the two-dimensional approximation where the survature in the θ-direction is neglected. The required symmetry for the helium is thus retained for the operational rotation rate.

When the individual cells formed by the baffles are nearly full, the shape of the meniscus will be affected by the configuration of the edge of the baffles. Three different baffle inner edge configurations are considered here. For baffles with straight edges, the menisci should have a cross-sectional shape like that shown in Figure 15 (details of meniscus curvature will be governed by a balance between surface tension and centrifugal forces for the boundary conditions that apply). To conserve weight in the spacecraft, it is expected that the baffles will be made very thin. In order to add stiffness to these thin plates, a ring could be attached to the edge of the baffle. This ring would be a short cylinder made from the same material as the baffles. One way to attach the stiffening rings would result in the configuration depicted in Figure 16. This is denoted the "L-end" configuration for its appearance in the cross-sectional view. The meniscus formed in a nearly full cell between two L-end baffles is also shown in Figure 16. This meniscus has a more complex and unsymmetric shape. A third way to attach the stiffening ring is in a "T-end" configuration shown in Figure 17. This configuration could support a flat meniscus for completely filled cells between the baffles. As the helium level drops during operation of the experiment, the shape of meniscus will undergo a change due to transition from attachment to the stiffening ring to attachment to the baffle. This sequence of events is illustrated in Figures 18 through 20.

The T-end baffles will permit maximum filling of the dewar, since the equilibrium liquid-vapor interface for that configuration will be a circular cylinder when the cells defined by the baffles are full. The gap which can be tolerated between the inner baffle edge and the inner cylinder is determined by the size of the vapor bubble which can be driven through the gap during the initial period of relatively high rotation rate. The rotational Bond numbers based on an average bubble radius of curvature which is one-half the gap size have been calculated as a function of rotation rate (i.e., initial higher rotation rate). For Bond numbers greater than one, centrifugal forces become dominant and the liquid helium can be successfully seated in the baffles in a symmetric configuration. Results of these computations are shown in Figures 21 and 22. Figure 21 shows the rotational Bond number as a function of high initial rotation rate assuming a surface tension value of 0.35 cynes/cm. Figure 22 gives the results assuming surface tension is 0.53 dynes/cm. In those figures, r represents half the gap width.

The volume of liquid helium present in the dewar at the beginning of the experimental period will be a determining factor for experiment lifetime. Some vapor space (ullage volume) is required to establish the initial symmetric liquid helium configuration. Assuming that the baffle region is filled completely with liquid helium, the minimum ullage fraction (vapor volume/total dewar volume) required for achieving the necessary LHe symmetry (for a surface tension value of 0.35 dynes/cm) is shown in Figure 23 as a function of the high rotation rate.

In order to drive the liquid helium into the baffles, capillary forces must be overcome by centrifugal forces. The forces required should be less than those needed to assure that the liquid-vapor interface can be driven through the gap between the baffle inner edges and the inner cylinder. This sets a minimum distance for the longitudinal separation between successive baffles (labelled b in Fig. 9); that is, b should be larger than the gap width (labelled a in Fig. 9). Further, if the T-end baffles design is used, the opening between edges of successive baffle stiffening rings should be greater than the gap size (a).

The maximum separation of the baffles will be limited by considerations of liquid helium sloshing and of interface stability. The wavelength of sloshing modes will be a function of the baffle separation distance (b). Placing the baffles close together will reduce sloshing effects by setting an upper bound on allowed sloshing wavelengths. The issue of stability of the liquid-vapor interface for this configuration has not been fully resolved. When the required symmetric liquid helium distribution has been established, each cell formed by successive baffles bounds a liquid-vapor interface which will be symmetric with the GP-B rotation axis. If the baffles are widely spaced, the interface might become unstable in much the same way a liquid cylinder becomes unstable and breaks up into drops (liquid cylinders of length less than their circumference are stable). Studies of interface stability may set an upper bound on baffle separation.

SUMMARY AND CONCLUSIONS

Experiment requirements for low acceleration levels at the gyro locations dictate that the liquid helium configuration in the GP-B dewar be axially and longitudinally symmetric and that sloshing of the liquid helium be minimized. Three approaches to liquid helium management were considered. The use of high rotation rates alone would shorten experiment lifetime due to increased rate of liquid helium consumption. Also, in this mode, the liquid-vapor interface may be subject to instabilities which could cause the helium distribution to become unsymmetric. A second approach to liquid helium management involves use of a foamed material (aluminum) to immobilize the liquid helium through capillary forces. This would prevent sloshing, but the distribution of liquid helium in the foam would not be amenable to prediction. For this technique to be used, an active balancing system would probably be required on the spacecraft.

The most promising helium management approach involves the use of partitions or baffles. These would be configured such that the liquid helium could be distributed symmetrically during the initial high-spin phase of the experiment period. The new boundary conditions imposed by the contact between the liquid-vapor interface and the baffles should result in a helium configuration which changes only slightly when the rotation rate of the spacecraft is reduced to the lower operational level. The baffles should also reduce sloshing by setting an upper bound on the wavelengths of allowed sloshing modes. Another benefit of the baffles is that they significantly decrease the amount of time required for the liquid helium to come into rotational equilibrium with the spacecraft when the rotation rate is changed. An initial liquid helium fill factor of about 90 percent appears possible through the use of baffles.

The proposed liquid helium management technique using baffles is expected to undergo experimental verification with low-gravity tests on model systems. These studies should also yield information on optimum baffle configuration and spacing. The stability of the liquid-vapor interfaces can be addressed theoretically and can be observed in the low-gravity experiments.

GRAVITY PROBE B

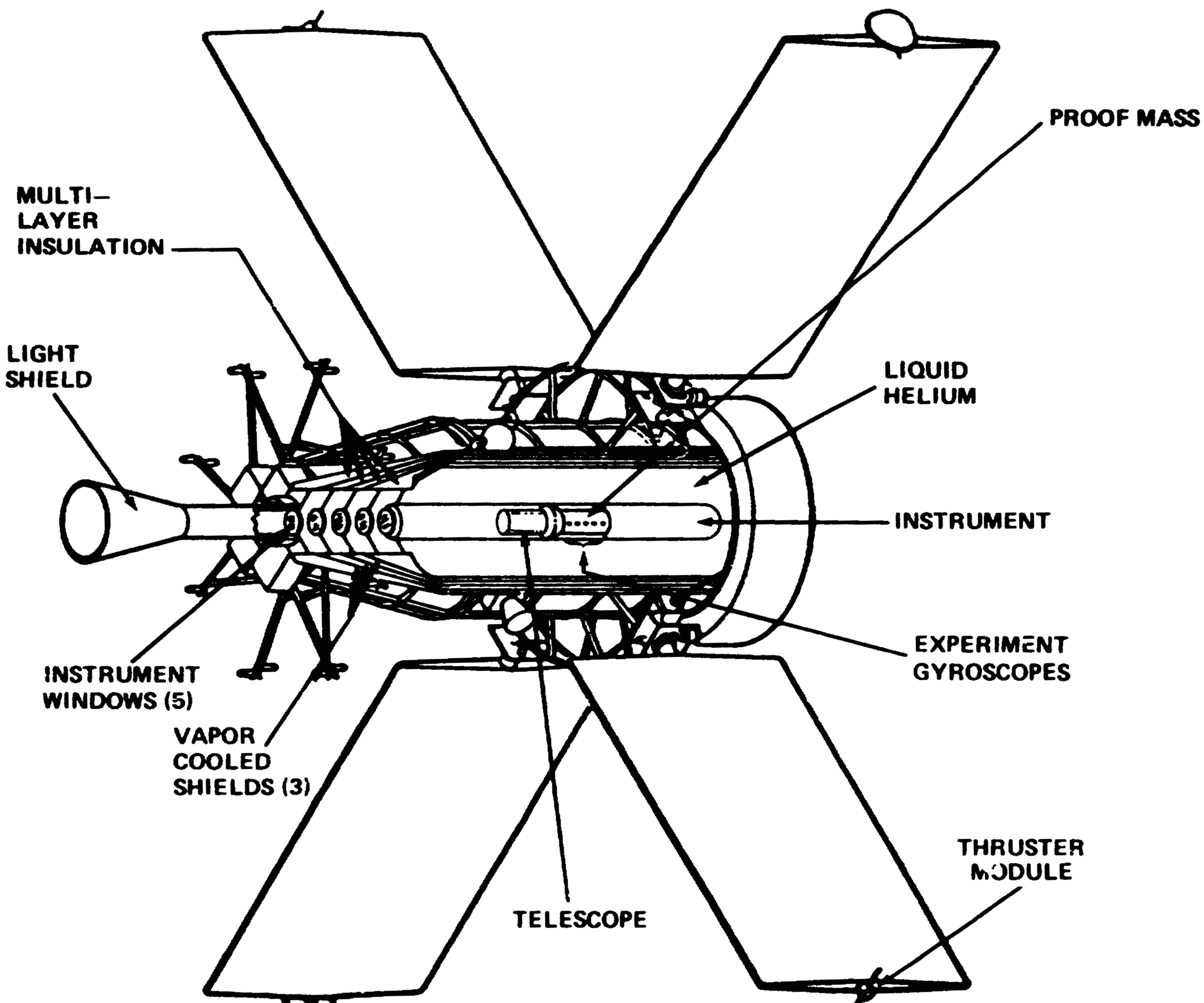

Figure vity Probe-B.

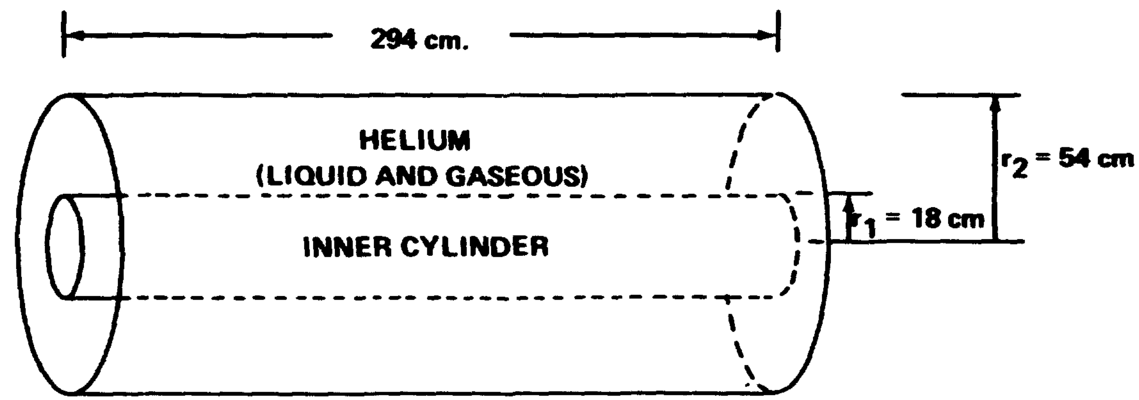

Figure 2. GP-B model system.

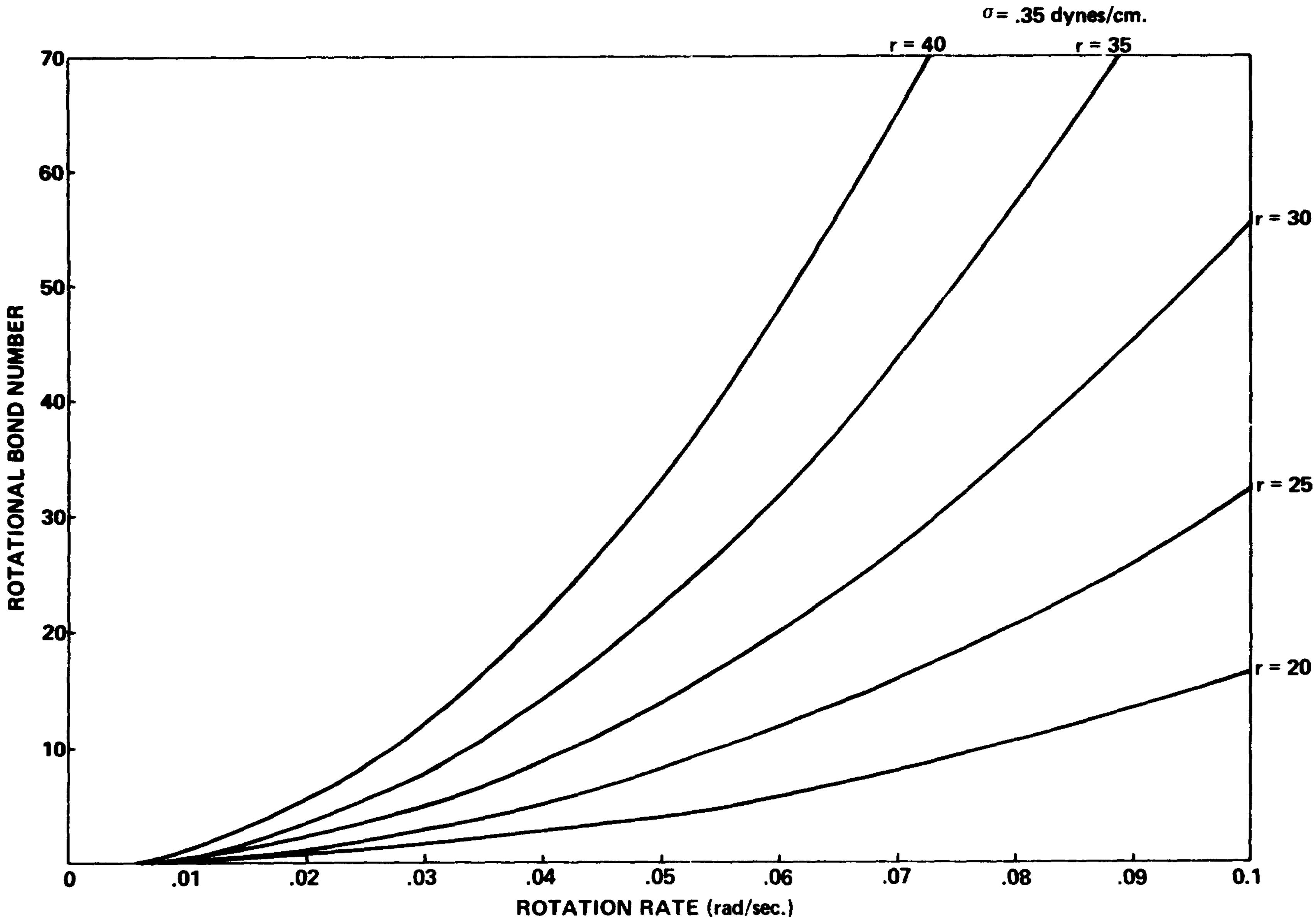

Figure 3. B_r versus ω.

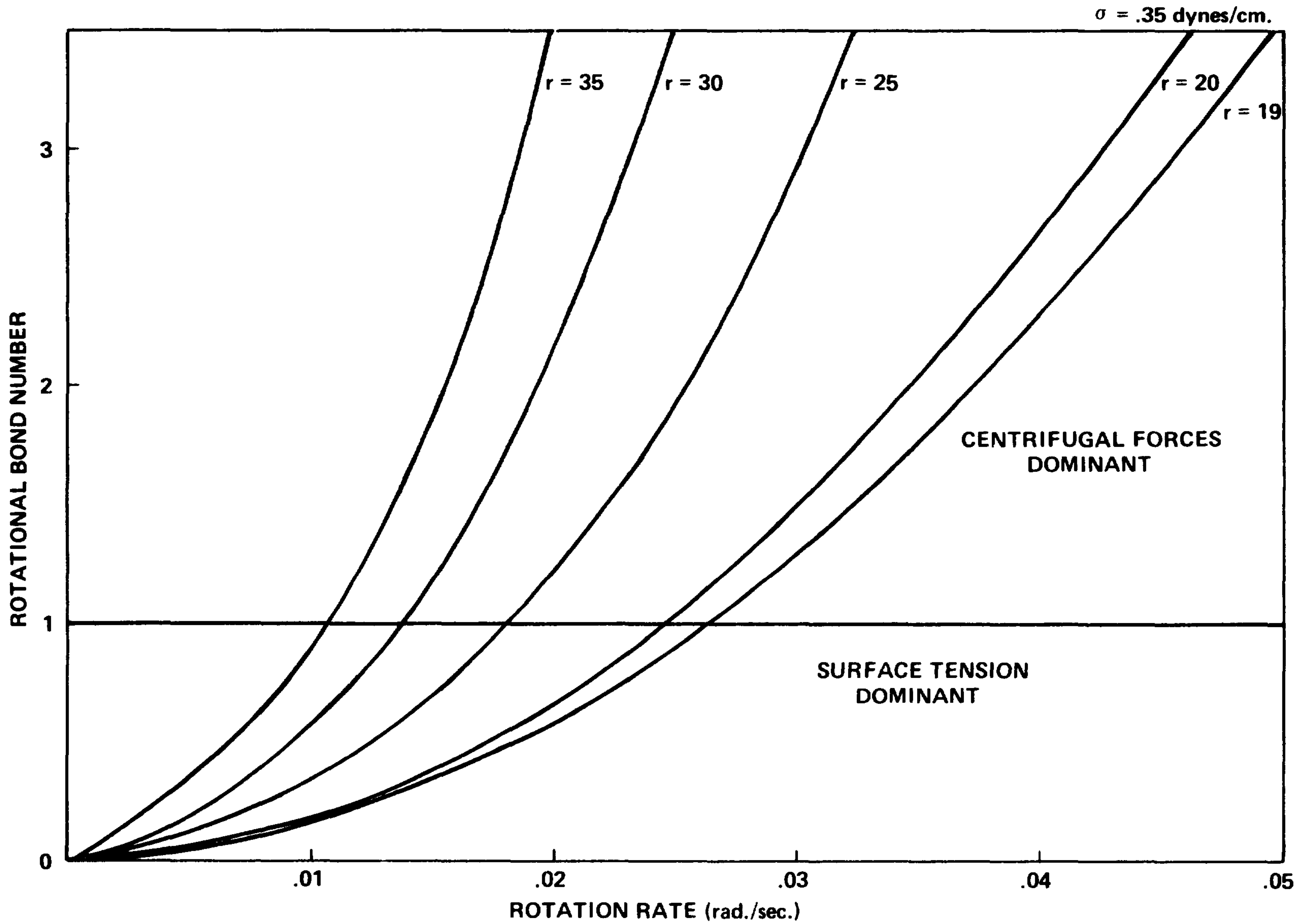

Figure 4. B_r versus ω.

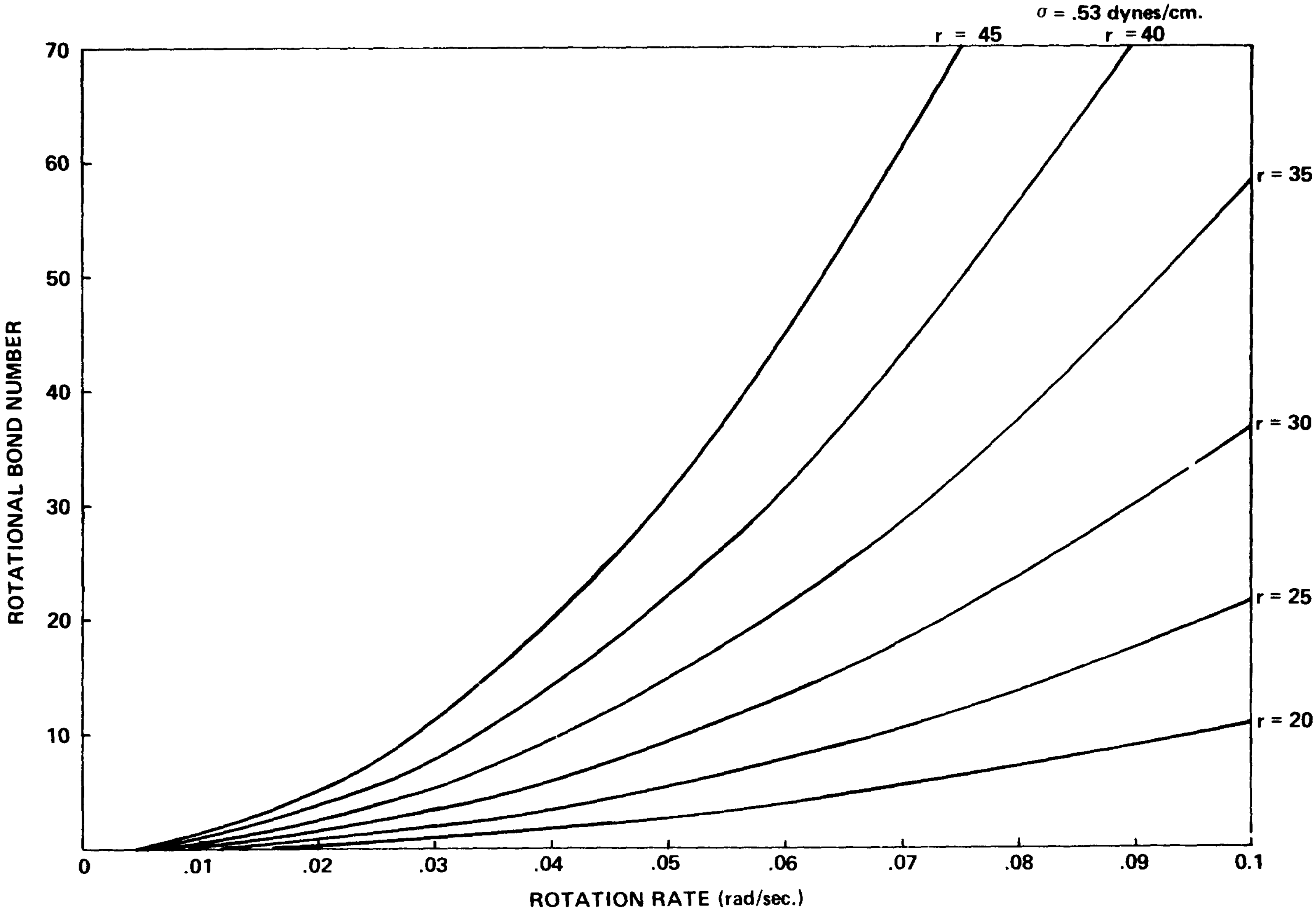

Figure 5. B_r versus ω.

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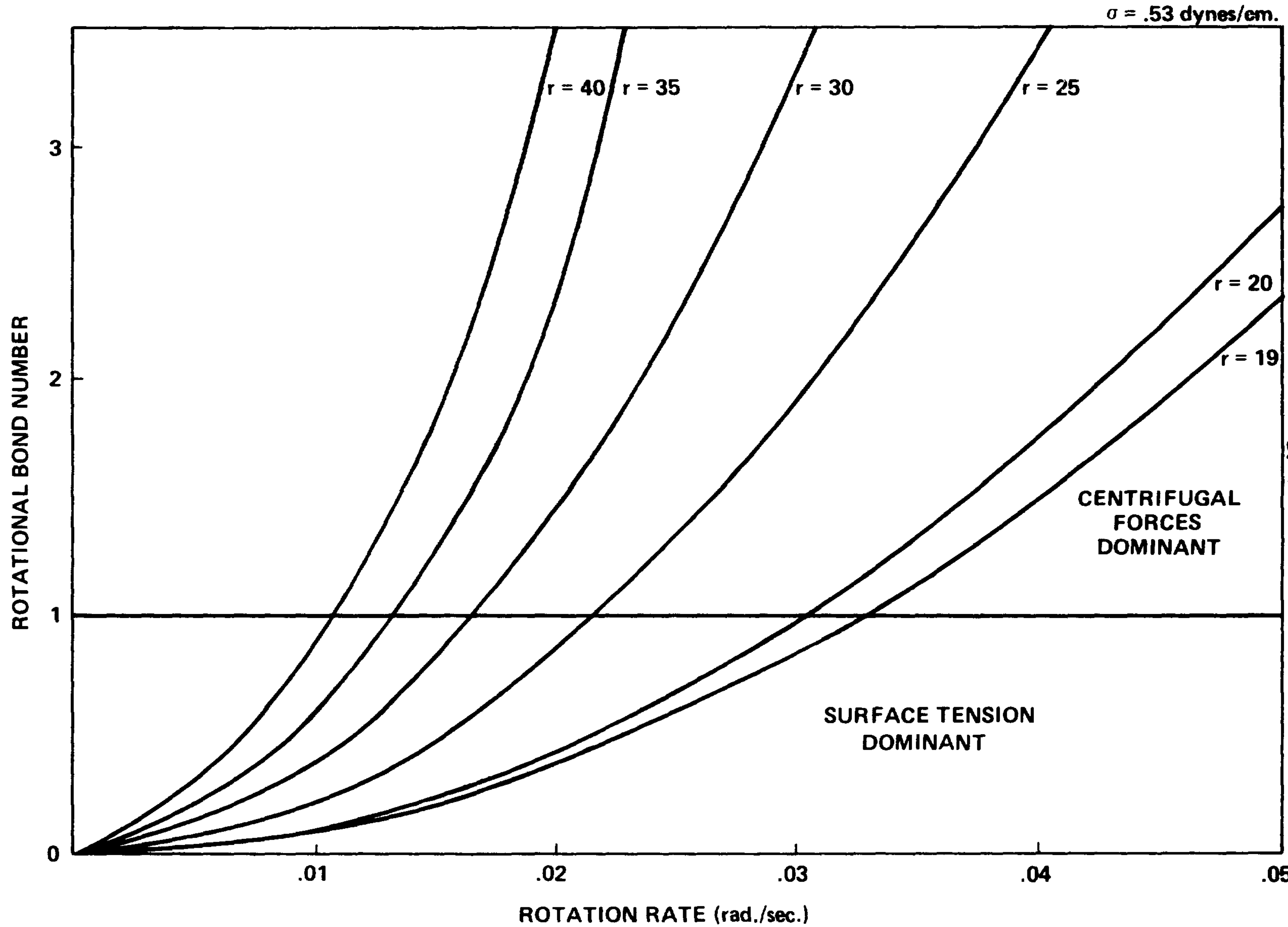

Figure 6. B_r versus ω.

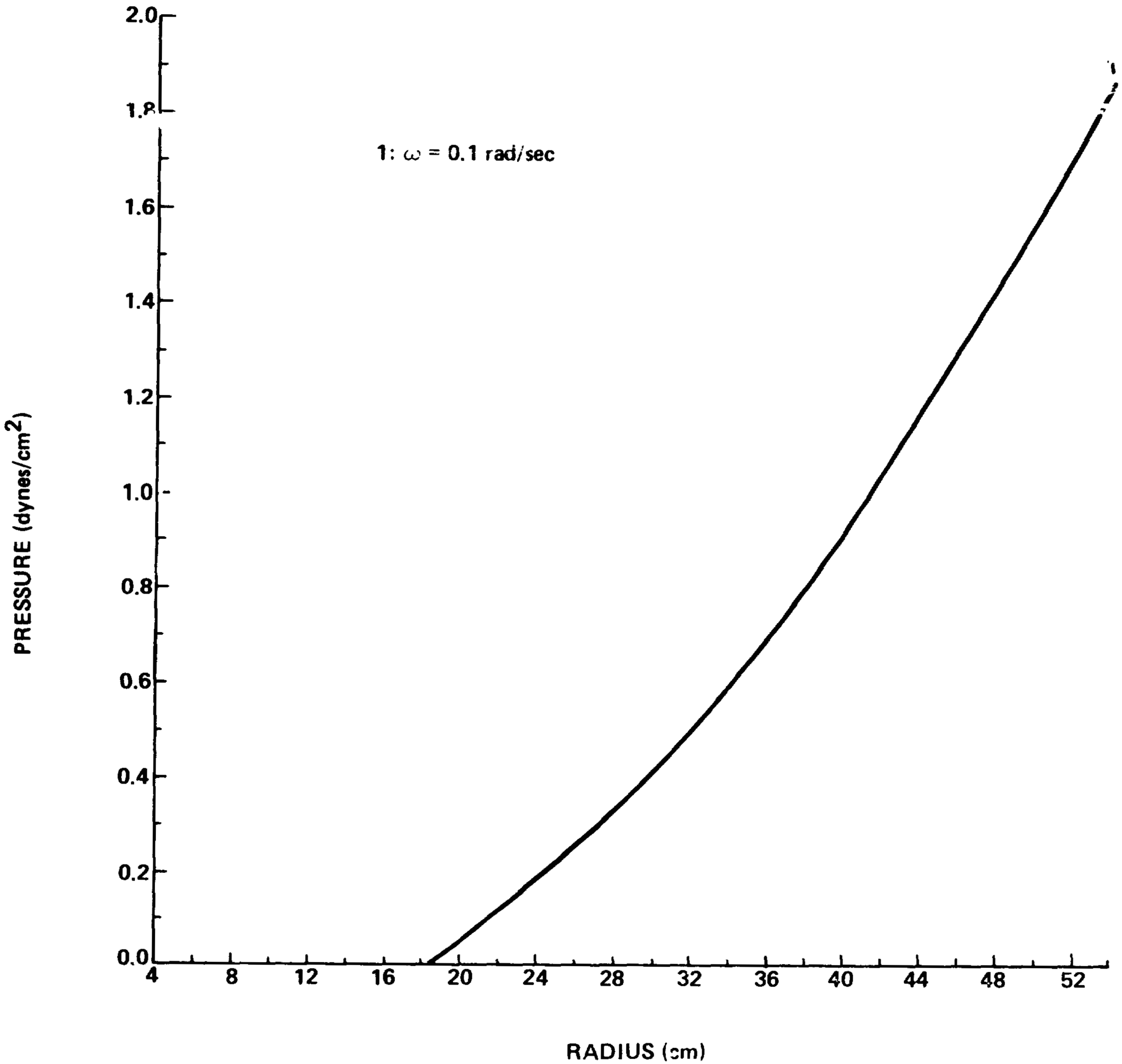

Figure 7. Pressure in LHe due to dewar rotation.

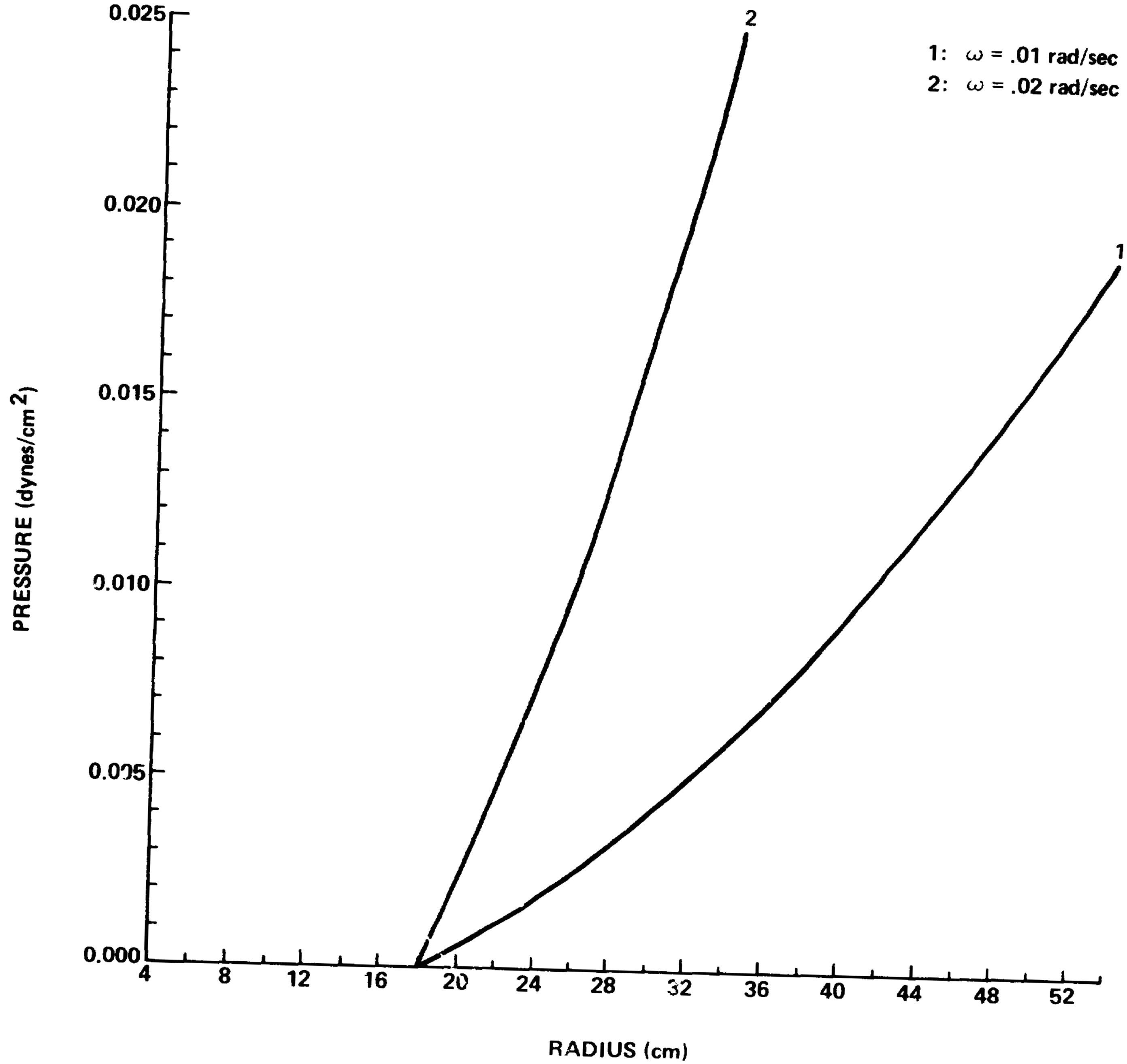

Figure 8. Pressure in LHe due to dewar rotation.

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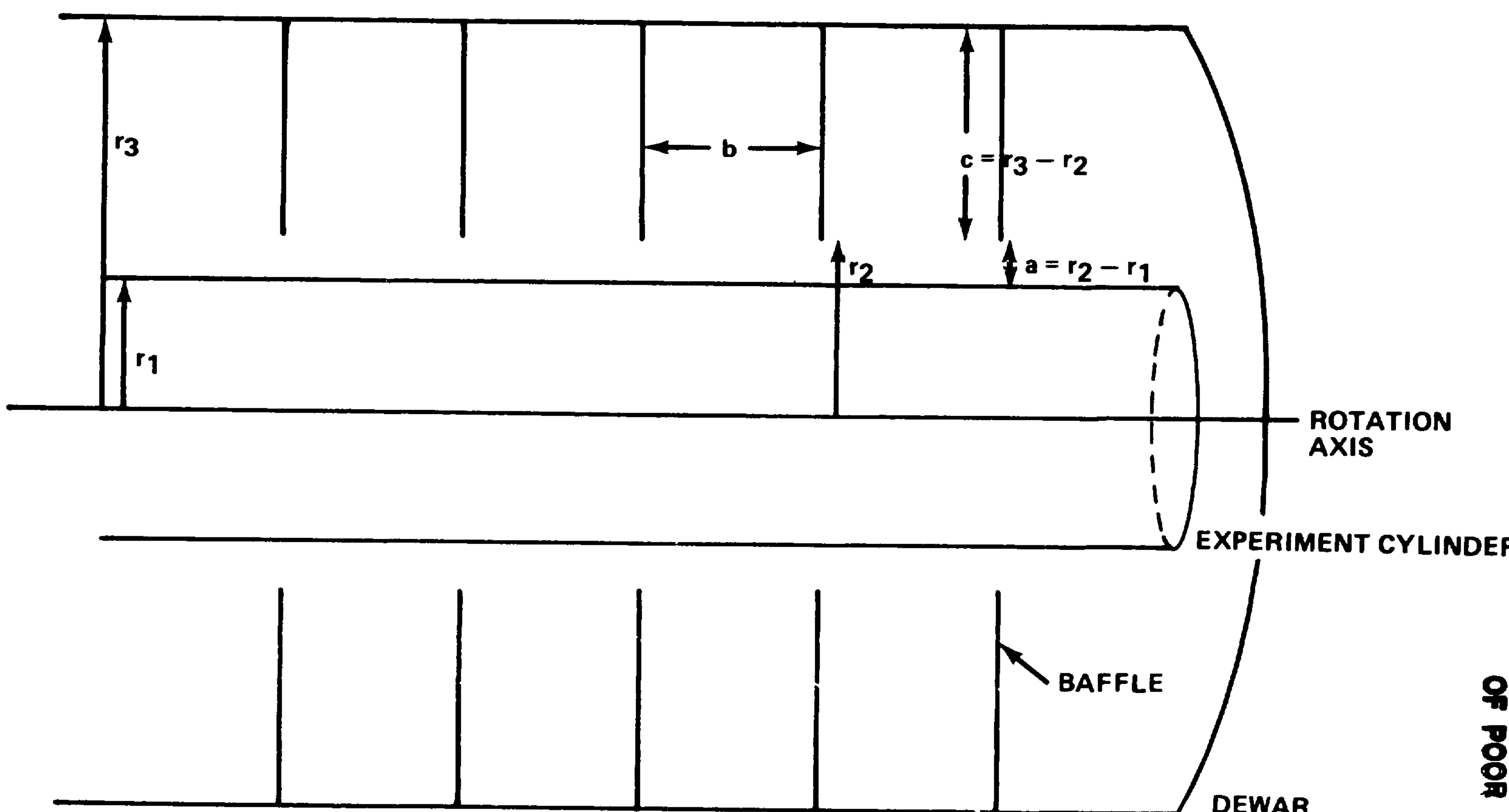

Figure 9. Dewar with baffles.

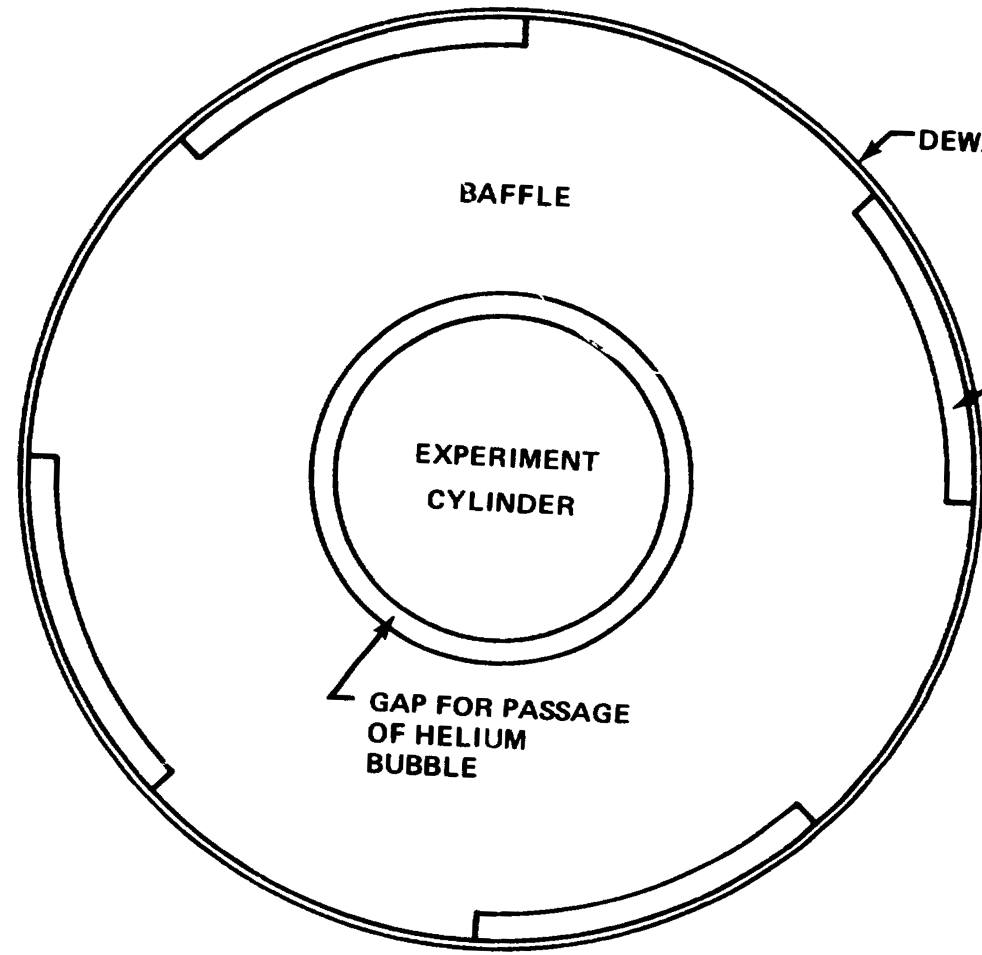

Figure 10. Baffle, view along rotation axis.

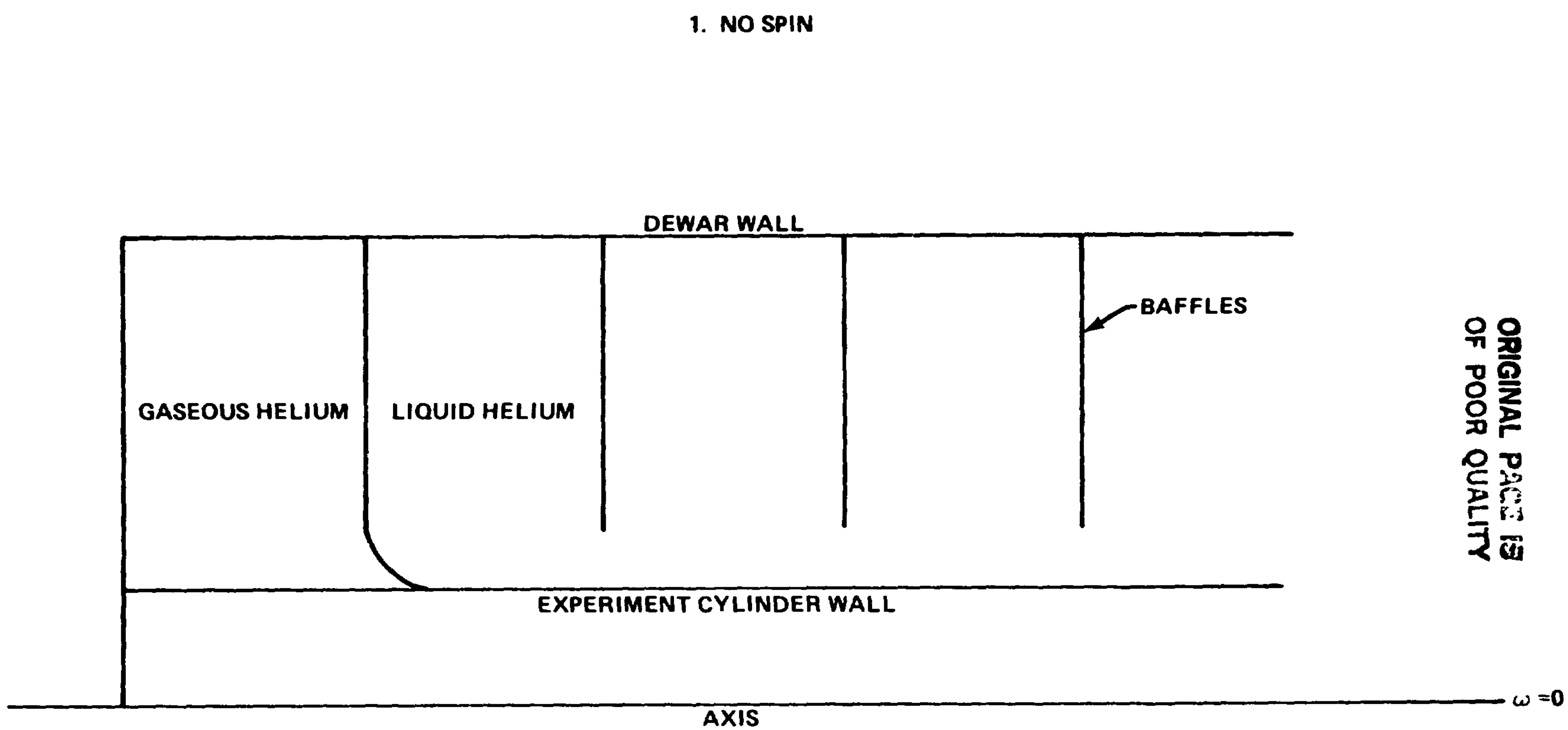

Figure 11. Helium configuration before spin-up.

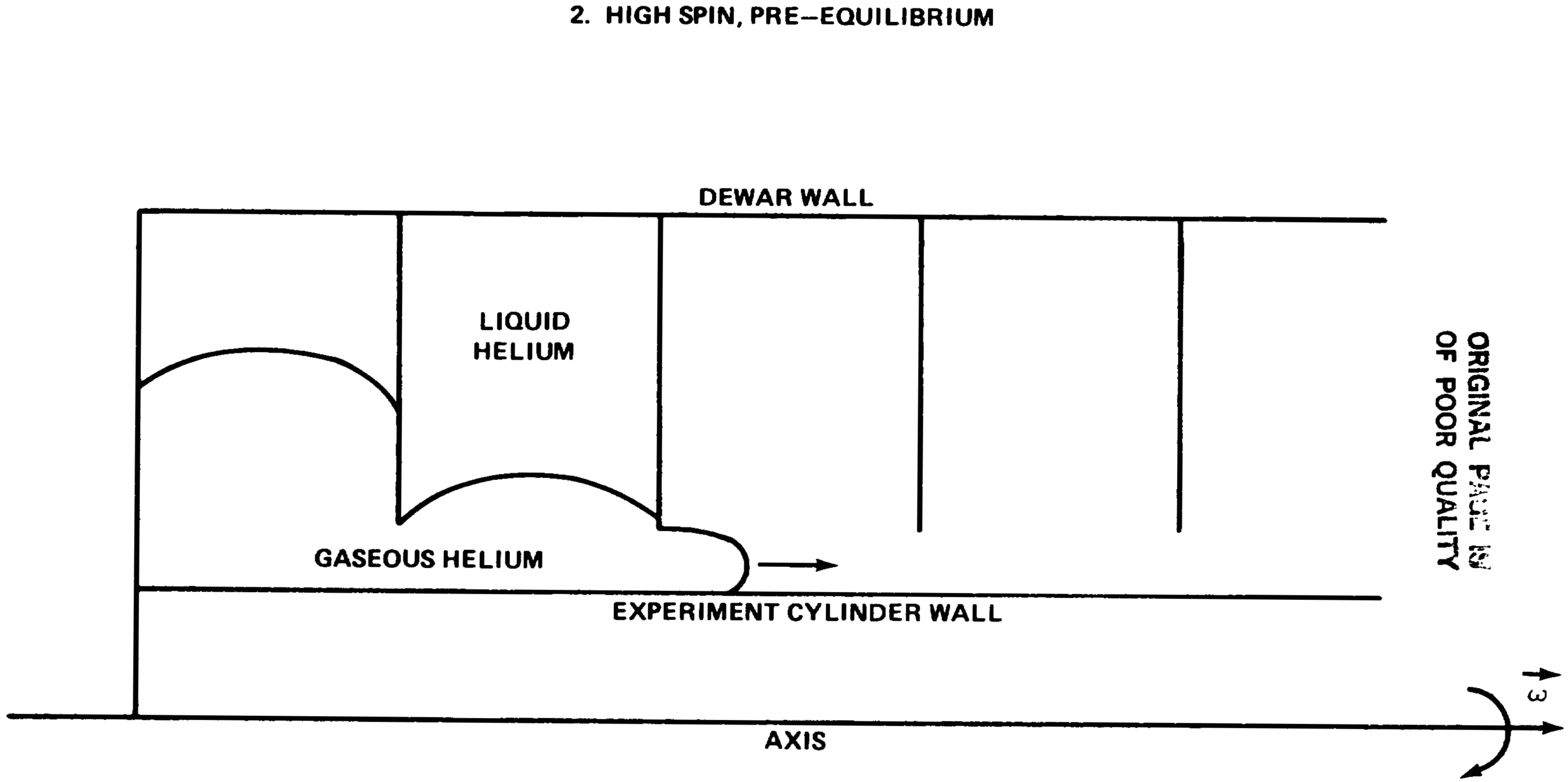

Figure 12. Helium configuration during spin-up phase (nonequilibrium).

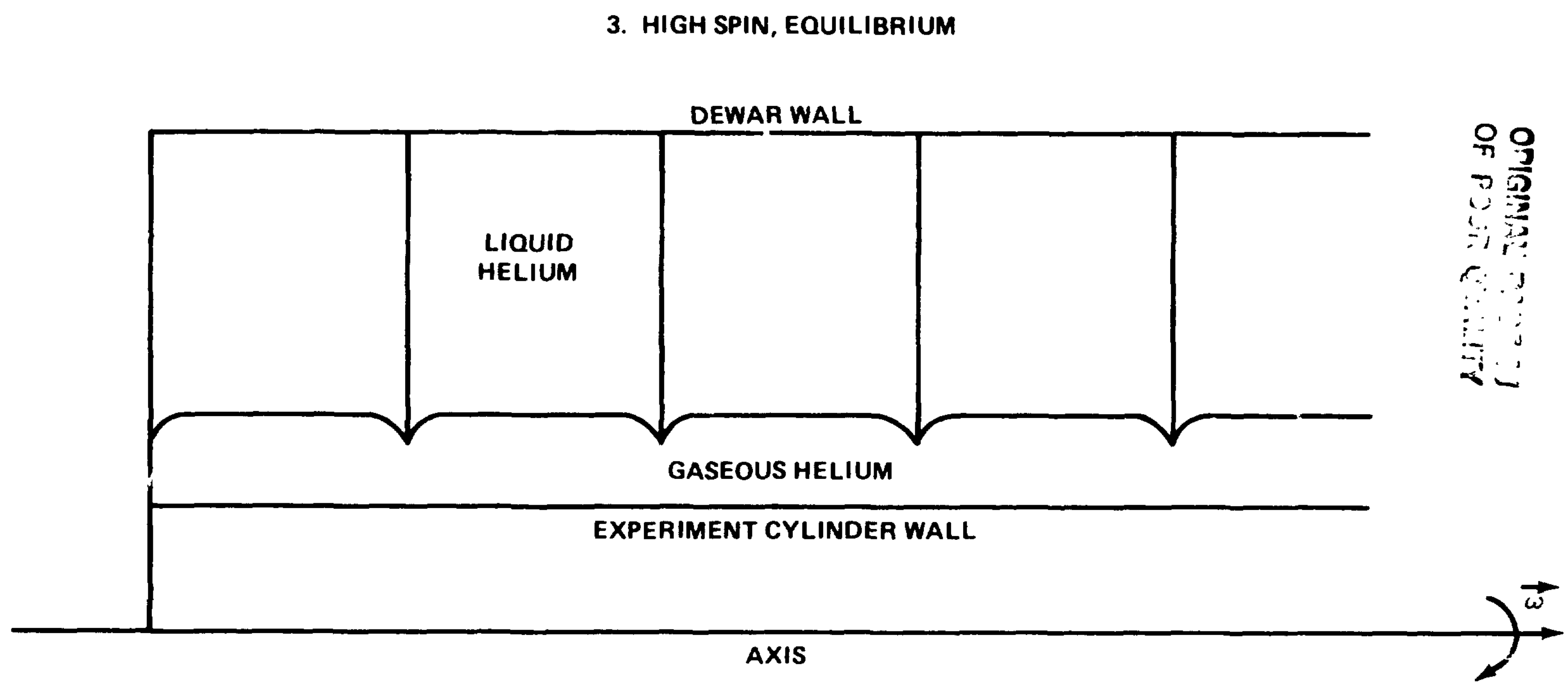

Figure 13. Helium configuration in static equilibrium at high spin rate.

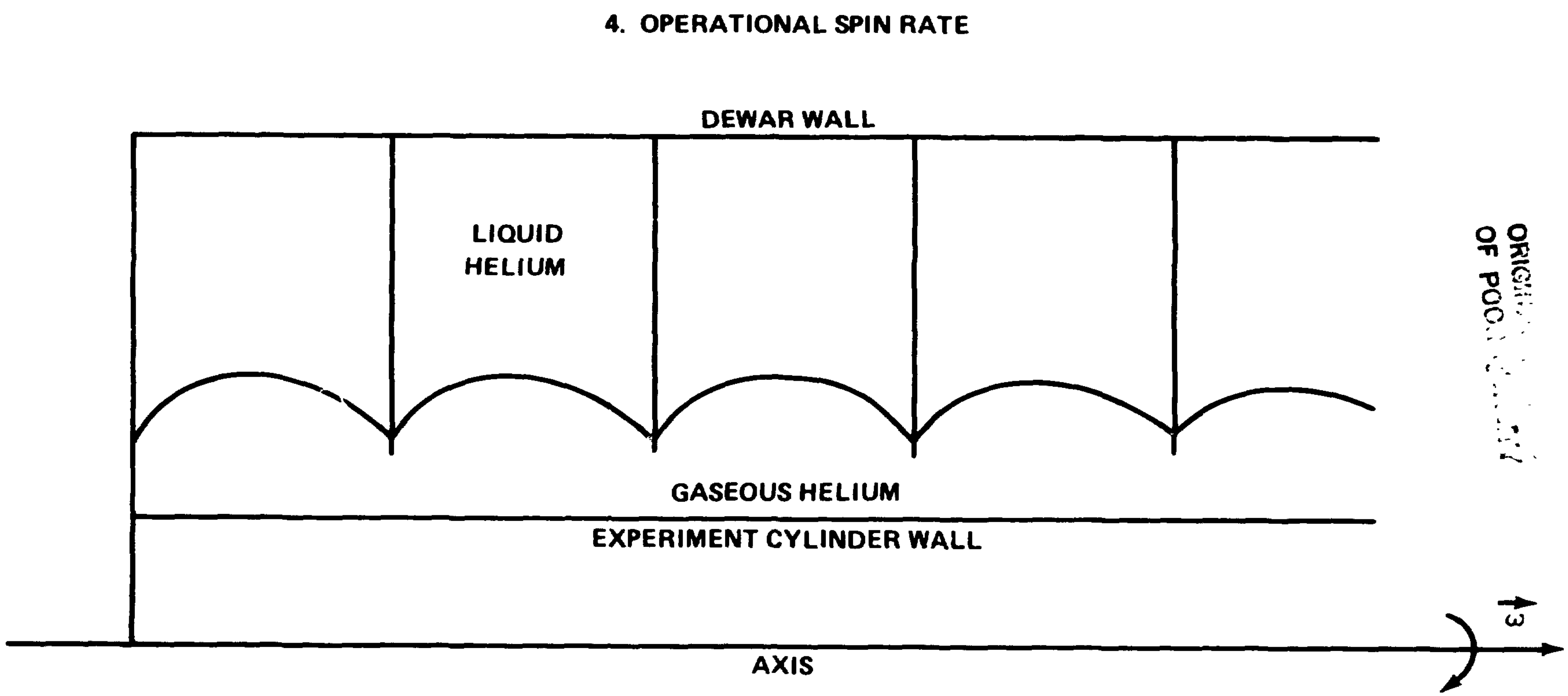

Figure 14. Helium configuration in equilibrium at operational spin rate.

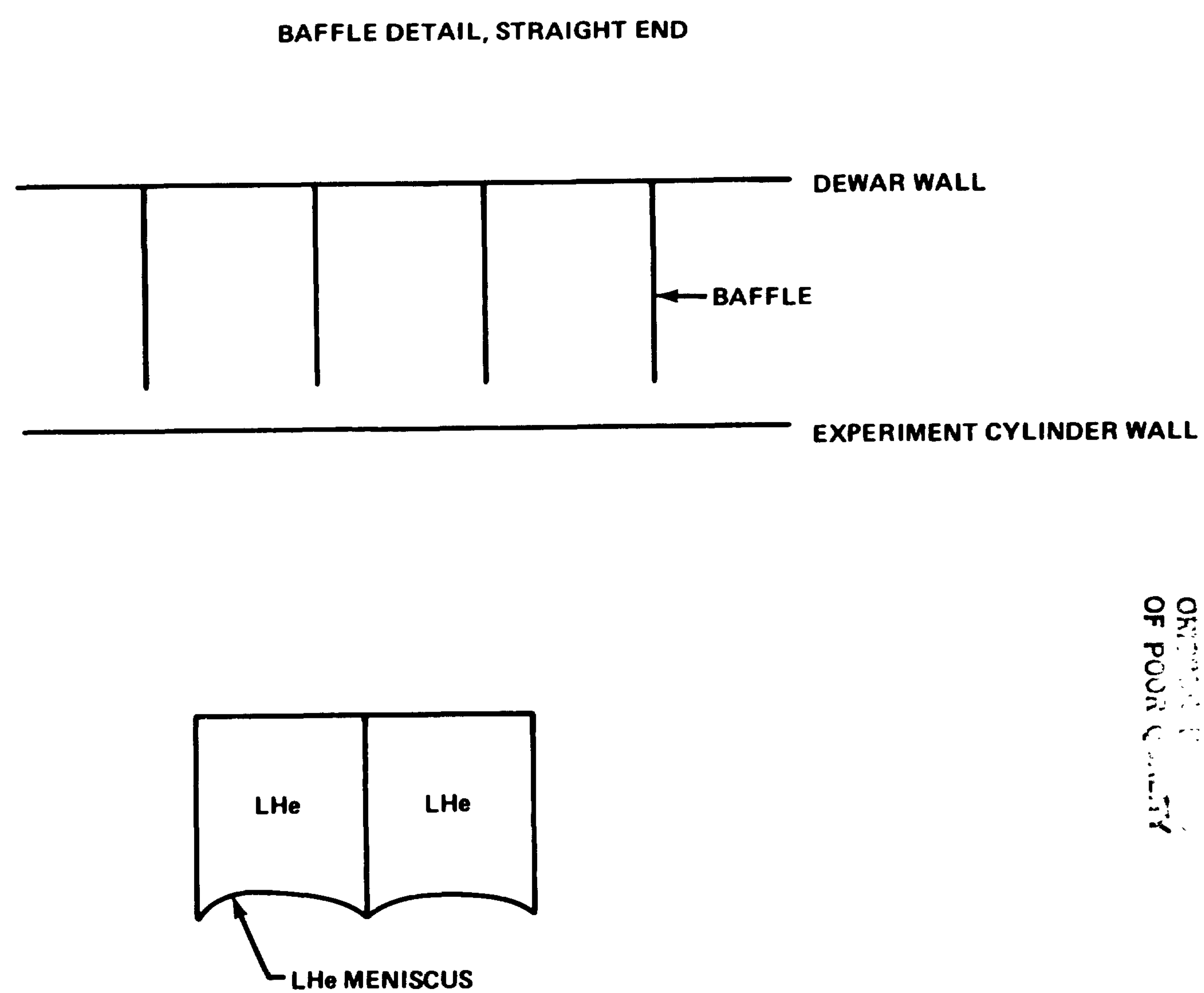

Figure 15. Baffle detail, straight end.

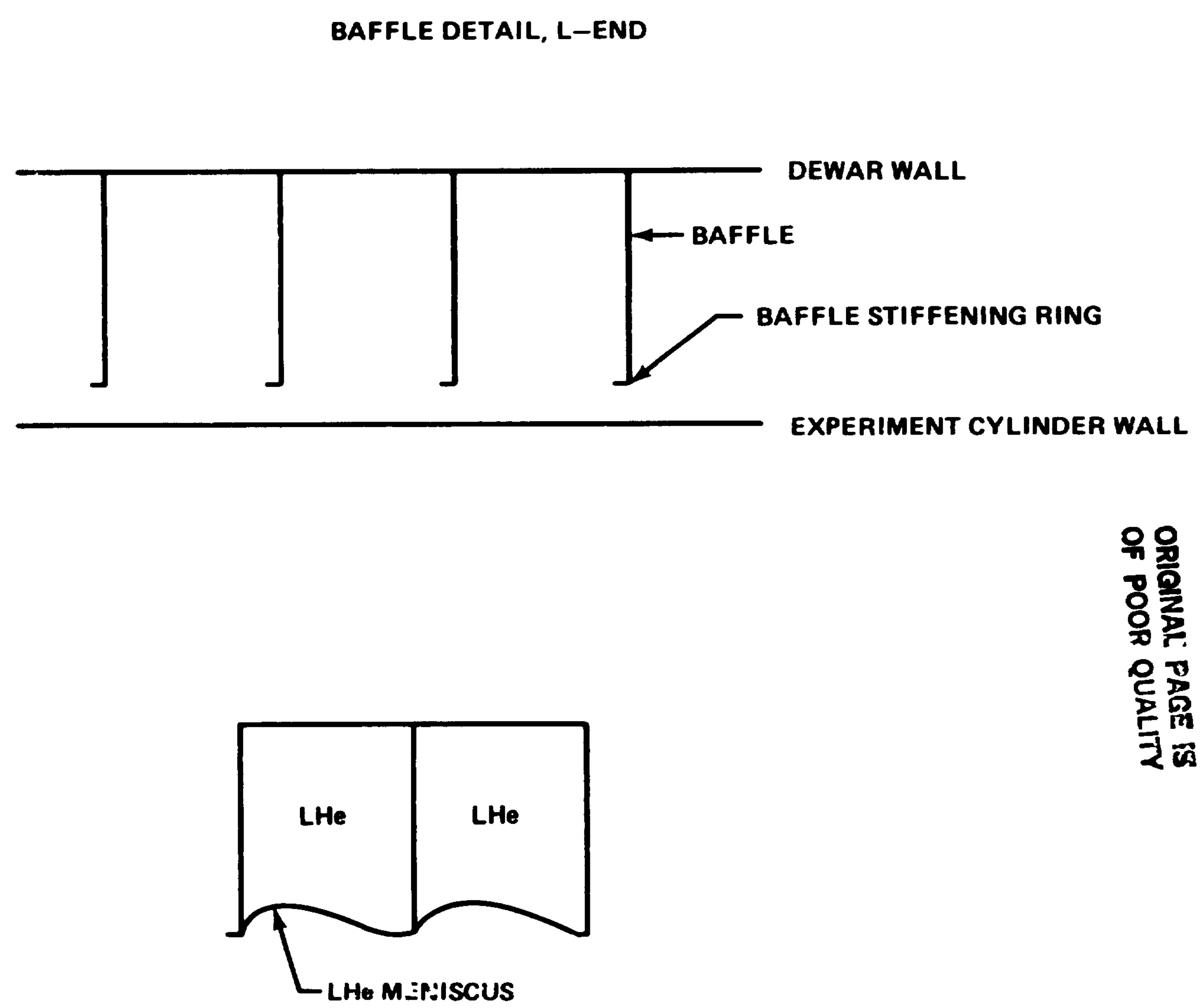

Figure 16. Baffle detail, L-end.

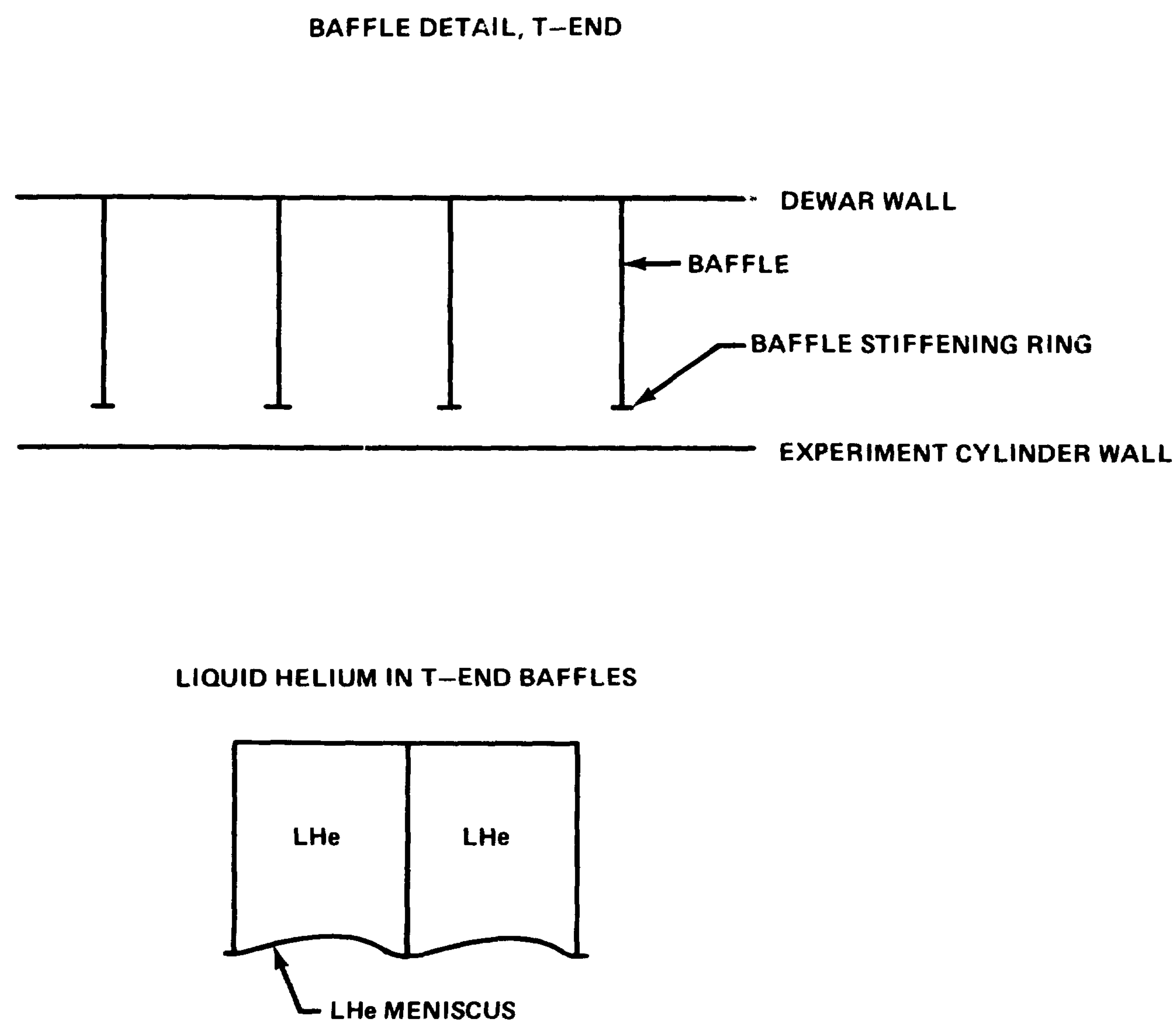

Figure 17. Baffle detail, T-end.

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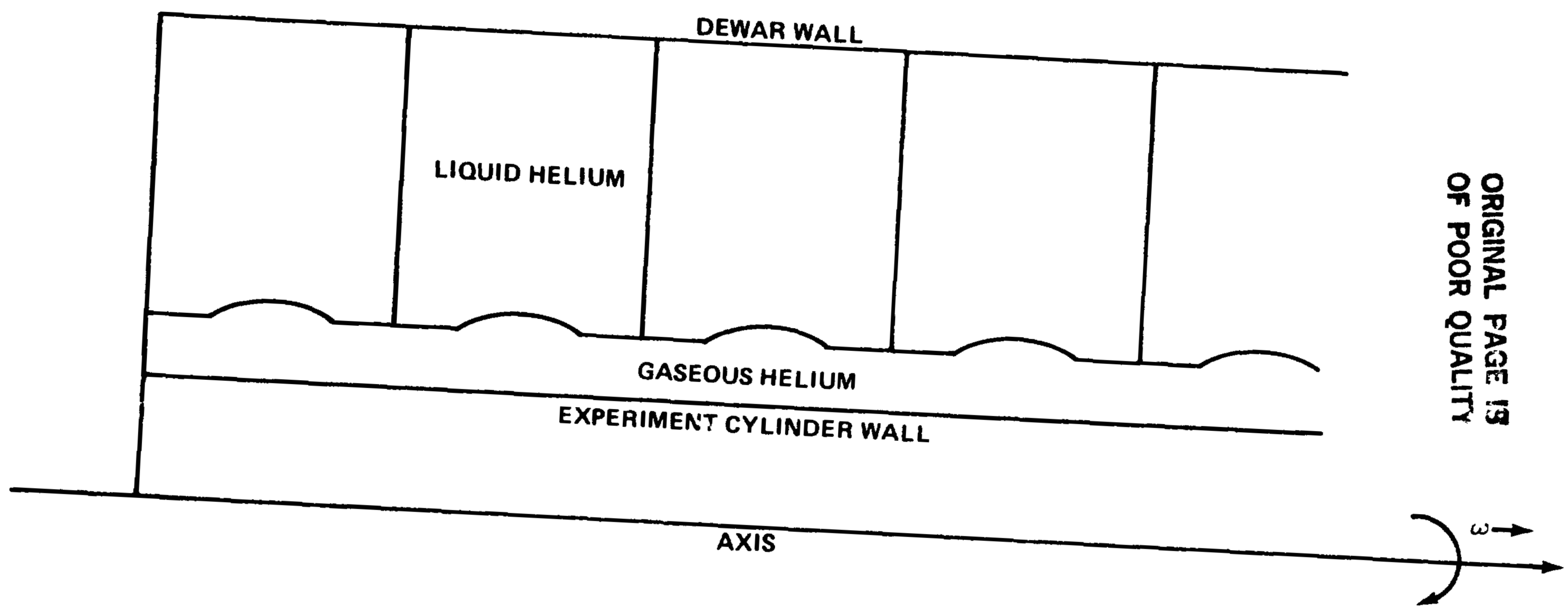

Figure 18. T-end baffles, meniscus attached to stiffening ring.

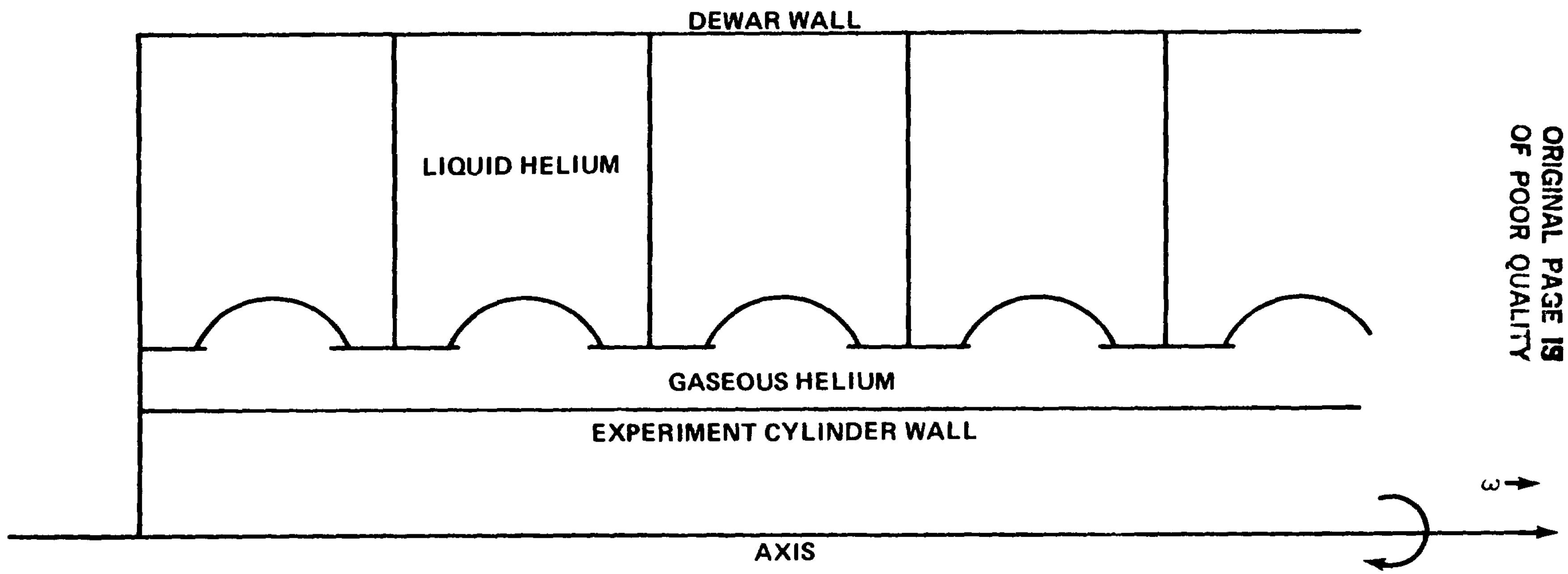

Figure 19. T-end baffles, intermediate configuration.

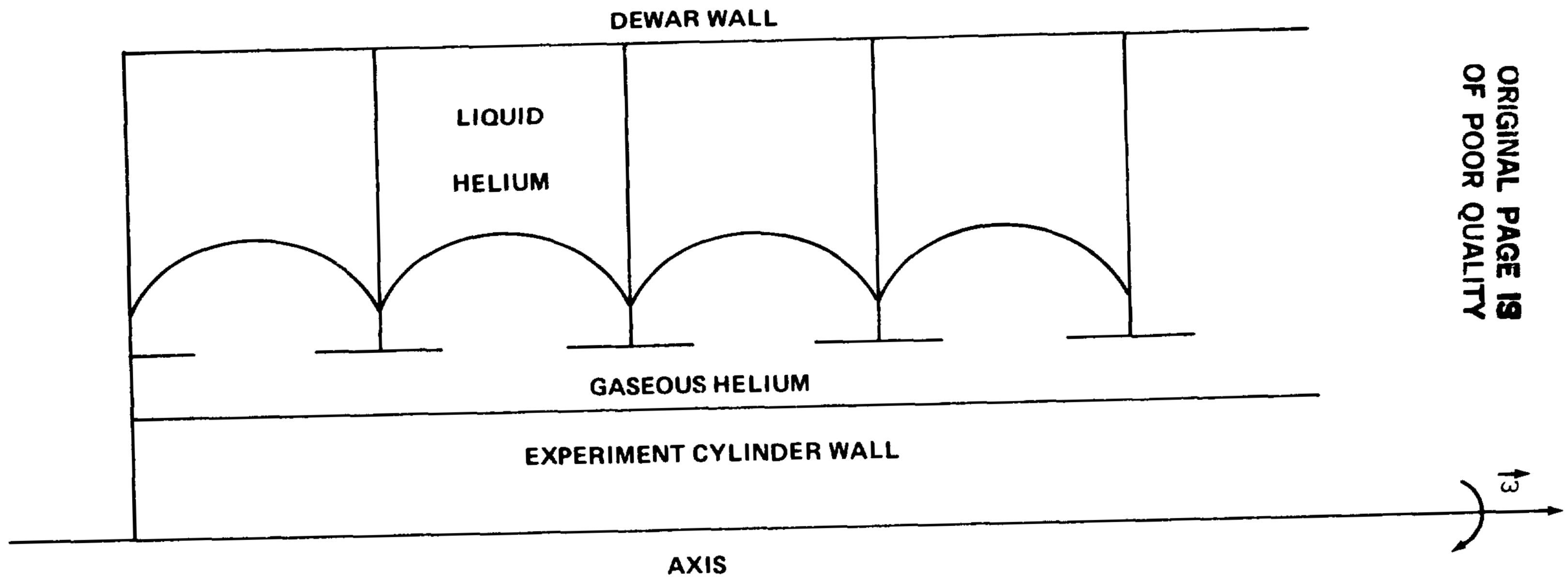

Figure 20. T-end baffles, meniscus attached to baffles.

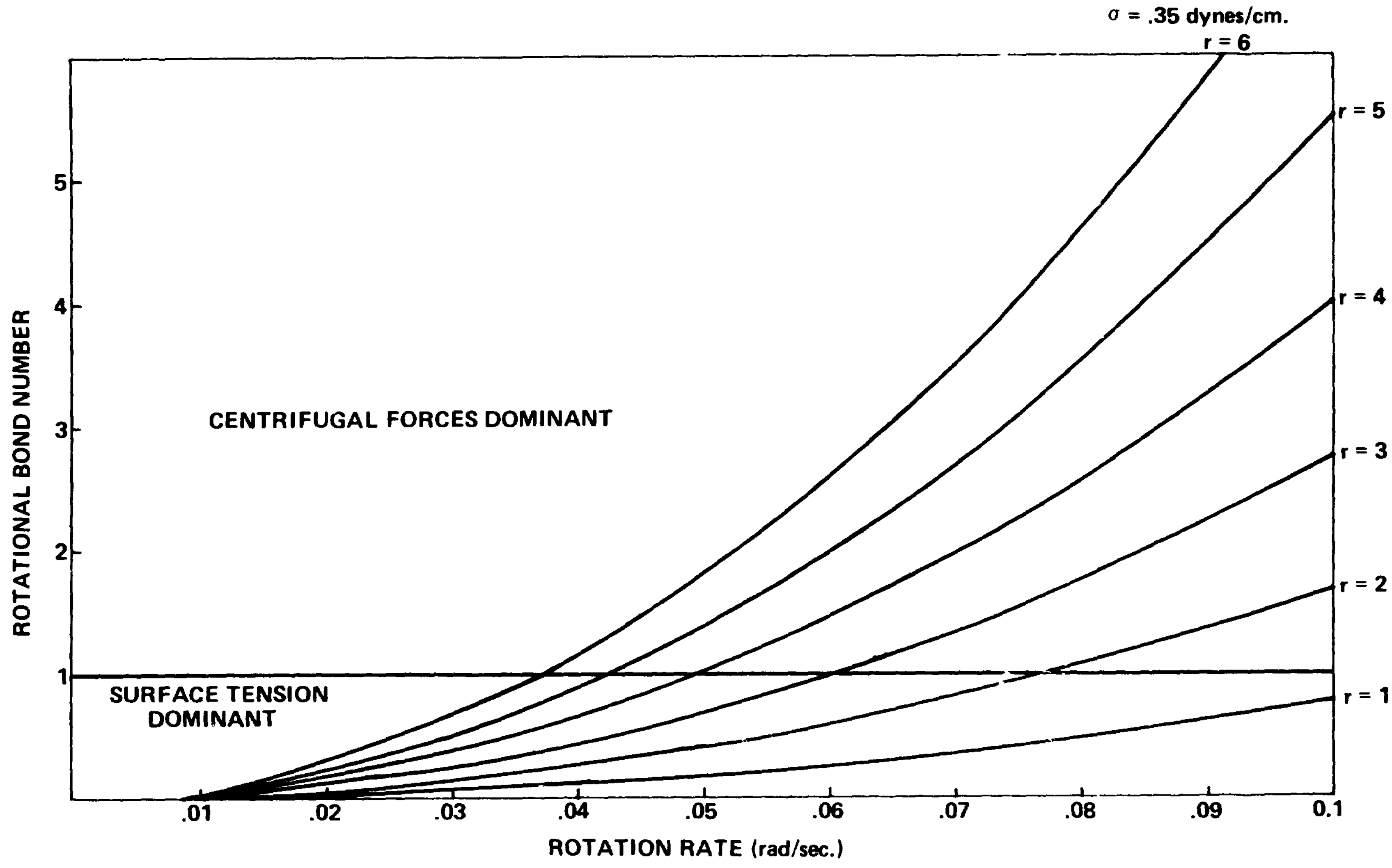

Figure 21. B_r versus ω for bubble positioning.

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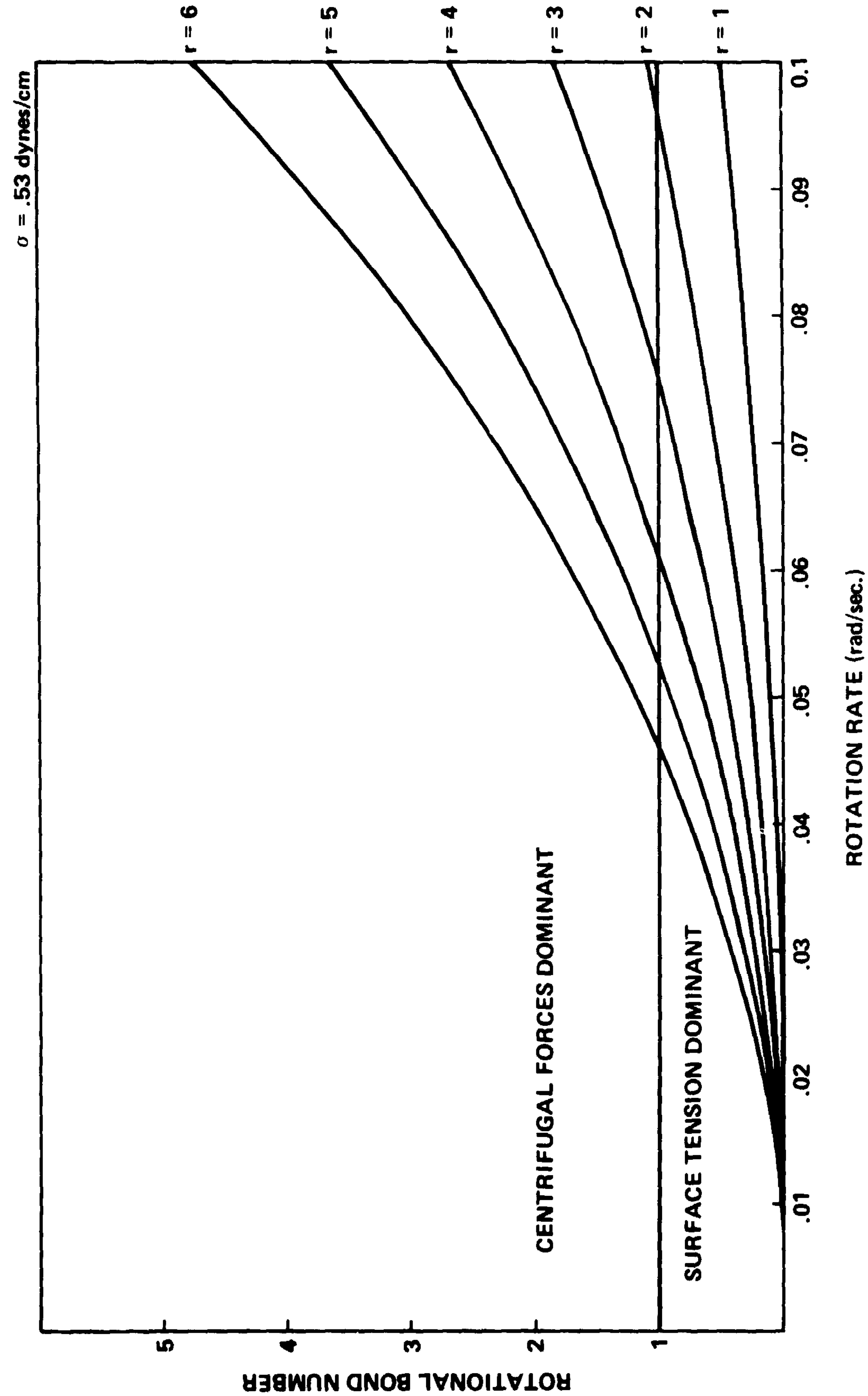

Figure 22. B_r versus ω for bubble positioning.

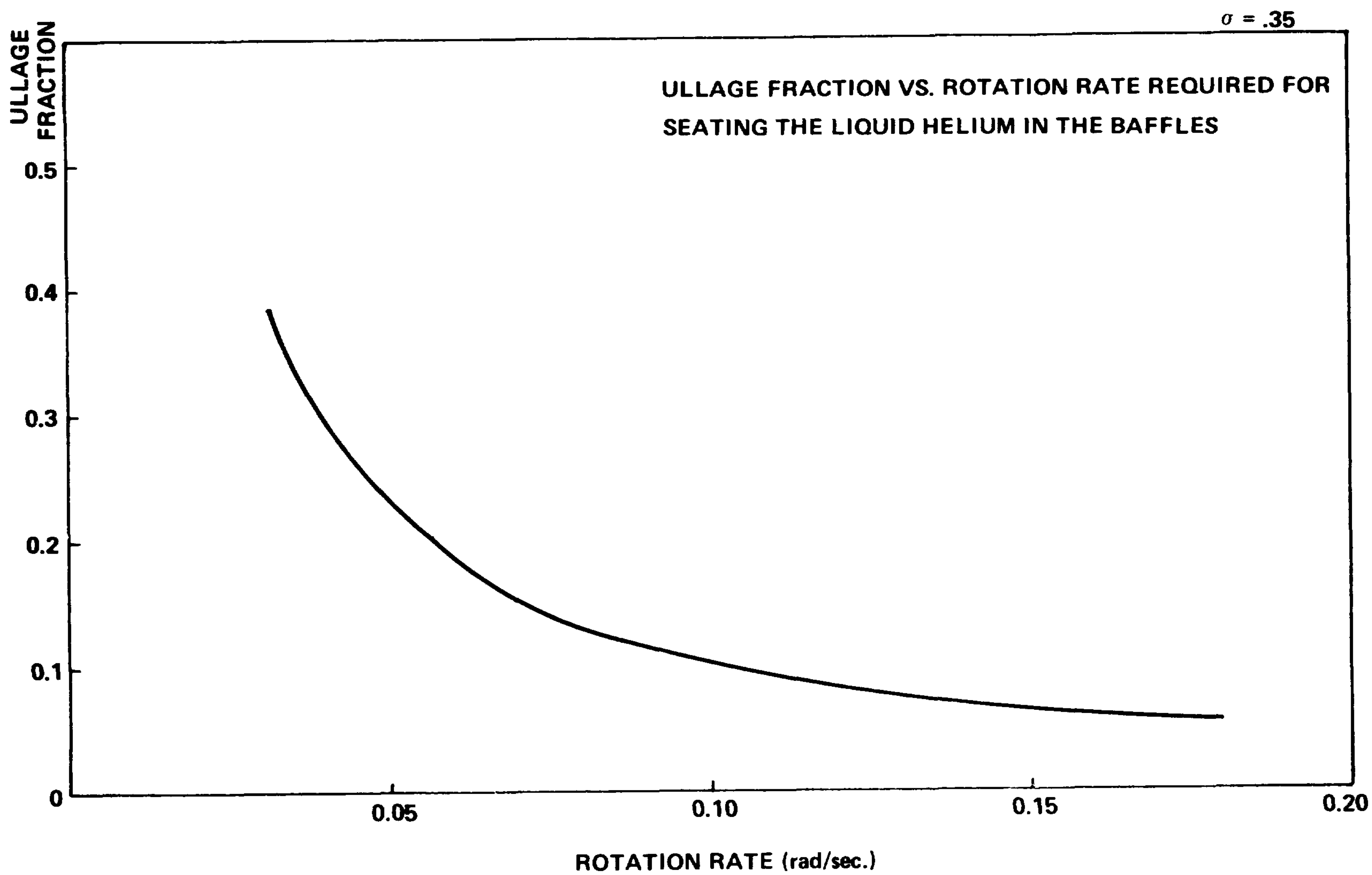

Figure 23. Minimum required ullage fraction versus initial high rotation rate.

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