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# NASA

ZERO LEAKAGE

SEPARABLE AND SEMIPERMANENT

DUCTING JOINTS

by

H. T. MISCHEL

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GEORGE C. MARSHALL SPACE FLIGHT CENTER

CONTRACT NAS 8-28150

WILPAC MANUFACTURING COMPANY

EL CAJON, CALIFORNIA 92120

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# ABSTRACT

A study program has been conducted to explore new methods of achieving zero leakage, separable and semi-permanent, ducting joints for space flight vehicles.

The study consisted of a search of literature of existing zero leakage methods, the generation of concepts of new methods of achieving the desired aero leakage criteria and the development of detailed analysis and design of a selected concept.

The study also explored other techniques of leak detection with a view toward improving this area.

# FOREWORD

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# I

## INTRODUCTION

The purpose of this program was to develop engineering data, designs and conceptual ideas for "Zero Leakage" separable and semi-permanent ducting joints for space flight vehicle application. The range of system criteria which was considered was cryogenic and non-cryogenic media, pressures from 100 to 3000 psi, and long life, reusability and high reliability.

The program was conducted in two Tasks consisting of:

Task I   -   Survey of available information and development of new concepts of ducting joints for future work.

Task II  -   Determine the best analytical approach based on past experience, and develop detail designs and analysis on the concept selected from Task I.

The work during Task I consisted of three distinctive efforts. The survey of the existing state-of-the-art, the definition of the problem and the conception of approaches to solving the problem, and the delineation of the more promising ideas. In addition, the area of leak detection, an item in the scope of work of the contract, was the subject of some Task I effort.

During Task II, instructions were received from NASA to concentrate the remaining effort on one of the concepts generated during Task I. Further definition of some of the other concepts was made prior to this decision and this work is presented in later sections of this report.

The fact that this program was began coincident with the early phases of the Space Shuttle program caused the investigators to move the study effort toward what appeared to be shuttle oriented approaches. By that, the problems associated with Zero Leakage ducting joints were looked at from the viewpoint of potential space shuttle ORBITER and External Tank needs. The investigators, therefore, added to the aforementioned system criteria, the further boundaries of manyfold connections and disconnections namely the ability to verify joint integrity, the cost of replacement parts, inherent protection of critical components and surfaces and ease of connection and disconnection in confined spaces.

STATE-OF-THE-ART

A state-of-the-art survey was made by reviewing liter-
ature, examining joint designs used on the earlier space flight
vehicles and discussion with representatives of manufacturers
of seals which have been used in the past.

An overall conclusion of this survey reveals that most
of the attention in the design of joints in the past has been
directed toward achieving an optimum environment in which a
seal can reliably be maintained when subjected to the dynamic
and thermal levels and variations of space flight. The result-
ing joints could consistently be characterized as heavy, bulky,
difficult to maintain in a leak tight condition and sensitive
to handling induced damage.

Most of the investigative and inovative work in the past
was directed at the seal itself, directed at trying to make a
seal which would be more capable of accepting relative motion
between the flange faces either through deflection or thermally
induced dimensional changes, and more tolerant to less-than-
perfect mating sealing surfaces. These traditional approaches
have been more adequate for a vehicle of one time use, such as
Saturn, but by no means was an optimum design ever achieved.

The most optimum ducting joint is that which exists continuously along the length of the tube. While we cannot categorize a planar section through a tube as a separable or a semi-permanent ducting joint, its other characteristics should be the target of a ducting joint optimization effort. A section of tubing is most often strength limited, in that a reasonable amount of deflection under bending and hoop pressure loading is tolerated allowing the thinnest practical wall and the lightest possible weight. By contrast, a flange joint is, due to the limitation of the seal and the practical inability to uniformally transmit the load from one flange to its mate, stiffness limited, i.e., designed to limit deflection under load to below that which the seal can tolerate.

The literature survey did not uncover any seals which, in the environment of Space Shuttle ducting systems, would permit relaxing the stiffness requirement in the flange design.

In an attempt to return to the conditions inherent in a section of tubing some of the work was devoted to studying homogeneous or nearly homogeneous joint concepts where an unbroken vessel is created by welding, brazing, soldering or diffusion bonding the mating surfaces of the ducting components.

EFFECT ON DUCTING DESIGN

If an entire ducting system could be developed with no ducting joints the problem of designing for the dynamic environment would be greatly lessened. A duct system consisting of just tubing members with fairly constant spring rate and uniform flexibility would result in simple analysis. The location of ducting joints, chosen primarily for installation and practical fabrication limitations as well as conditions created by vehicle structural considerations, presents to the dynamic condition ducting problem localized high mass members which often result in high stress concentrations in other areas of the duct. The desire to limit deflections in the duct flanges compound the problem by creating stress risers due to the rapid transition from a relatively flexible tube member to the extra stiff flange.

NASA Tech Brief 66-10326, entitled "External Linkage Tie Permits Reduction in Ducting System Flange Thickness" presents an interesting method of reducing the flange mass effect when a flexible joint is adjacent to the ducting joint. By bridging the gimbal or pin joint load over the duct joint to an attachment on the adjacent duct, the longitudinal load due to pressure is effectively deleted as a ducting joint requirement permitting

much lighter flange thicknesses.  In order to utilize this idea, however, the mating ducting segments must be treated as a single design problem rather than individually as was often done in the past.

## EFFECT OF TEMPERATURE

The cryogenic environment narrows the designers choice of materials for use in ducting joint structural members and seals. Metallic structural members must be made from families of materials which have adequate ductility at these low temperatures. Unfortunately, most of these materials have fairly high coefficients of thermal expansion (or contraction). The choice of non-metallic materials for use in seals is more severly limited since very few non-metallics retain sufficient resiliency at these temperatures to be useful. The non-metallic materials compound the sealing problem further by exhibiting large increases in yield strength when exposed to cryogenic temperature. This increase in yield strength must be taken into account when specifying the initial seal preload so that when chilldown occurs, sufficient stressing of the seal face occurs to retain the seal. Conversely, over stressing the seal face can result in extruding the non-metallic material out of the contact space. The designers problem, therefore, is that the seal preload sufficient for the cryogenic condition must not fail the seal at ambient temperature.

The transient thermal condition which occurs when the duct is being chilled down creates conditions within the joint which tend to alter the original loads and component positions achieved

during the mating of the joint. Often the joint can no longer be assumed to be leak tight during and after chilldown and therefore must be re-tested for verification. The transient-created problem is primarily due to the relatively poor heat transfer between parts in contact and the differences in co-efficients of contraction. Significant offenders are the tension bolts which are usually relatively far removed from the wetted surface of the duct joint. The maximum contact pressure (and threfore the best heat transfer) between the bolt and the flange usually occurs on the outer surface of the flange, the last area to stabilize at the new low temperature and the area which, when stabilized, will be at the highest temperature of any point on the flange. If the tension bolts do not contract as quickly and as much as the flange material, a lessening of the preload will occur. If this lessening is enough, then a loss of seal will occur. Also, if the contraction rates are different, relative movement of the seal and sealing surface of flange will occur disturbing the initial contact condition.

If an independent seal is to be used, then a means of preventing differences of total contraction and contraction rates must be used. From the earlier remarks, a simple substitution to materials of proper coefficient of contraction

may not be possible. Mechanical means may be employed which will increase the rate of heat transfer. For example:

1. Placing the bearing contact surface between the flange and bolt or nut well inside the flange material by recessing or counterboring. This would also reduce the bolt length which reduces the magnitude of the contraction difference. The flange may get heavier, however, in order to achieve the required stiffness.

2. Tapered bolts and nuts, shown in Figure 1 is a means of increasing bolt (and nut) and flange contact area within the mass of the flange, thereby increasing the heat transfer rate and reducing the lag of bolt contraction.

3. Drilling chill passages from the inner cylindrical surface of the flange radially outward to locations adjacent to the bolt holes.

Arranging the attachments so that various load carrying members are in compression could create the situation where a lesser contraction by the bolts then the flanges would result in an increased sealing load. Figure 2 is a sketch of such a concept. On the surface, it appears complicated but with a concentrated design effort it could be simplified.
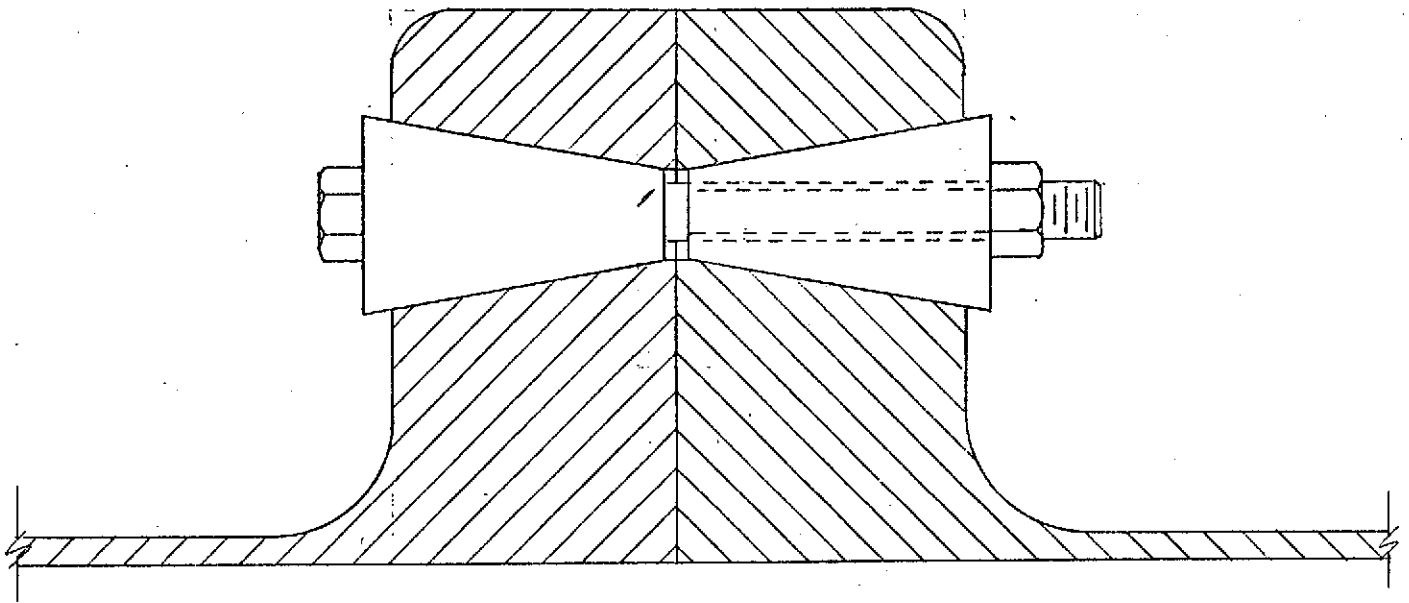
FIGURE 1

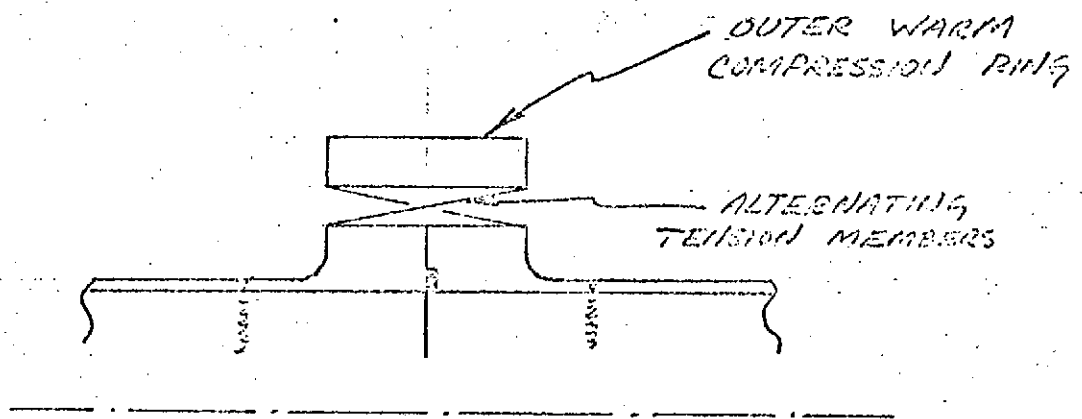TAPERED NUT AND BOLT FOR INCREASED HEAT TRANSFER

FIGURE 2

## SEMI-PERMANENT JOINTS

An area of investigation during the Task I work was ducting joints wherein the seal is accomplished by the welding, brazing, diffusion bonding, or soldering of the joint halves or flanges.

Joining of tube sections by butt or lap joining would be the simplest and lightest weight approach but also the most permanent. To accomplish the sealing requirement of ducting joints does not require much of a metallurgical joint with regards to thickness. If the ducting loads, that is pressure and vehicle induced static and dynamic loads, can be isolated from the metallurgical joint then a high reliability seal can be expected.

In order to achieve the characteristic of separability, it is desirous to utilize disconnectable methods of carrying load and easily opened or removed metallurgical joints. Figure 3 shows a ducting joint which was developed by Solar for use on the Brayton Cycle Gas Radiant Heating System for the NASA/ Lewis Research Center. This joint, a snip open joint, was designed because system temperature and zero leakage requirements exceeded the capability of other sealing devices. The seal was accomplished by fusion welding the outside diameters of washer shaped foils .254 mm (0.010 in.) thick. This allows
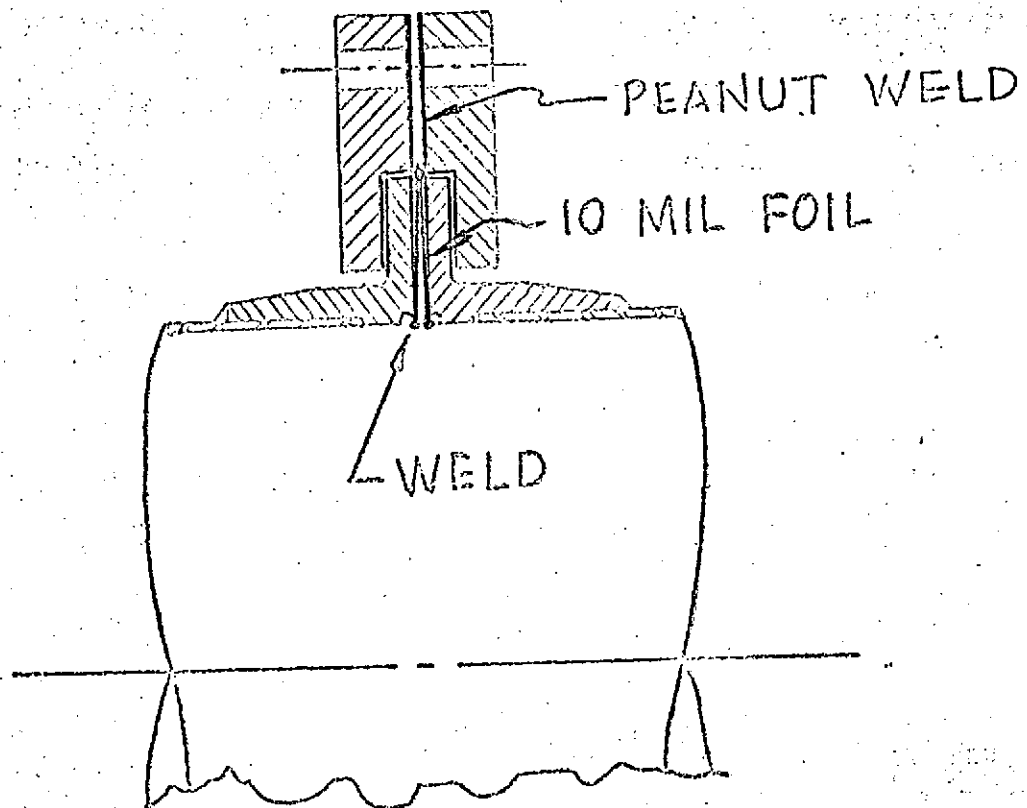
PEANUT WELD

10 MIL FOIL

WELD

FIGURE 3: SCHEMATIC DIAGRAM OF SNIP-OPEN JOINT

the disconnection to be performed using snips or shears which eliminates grinding, filing or sawing and their resultant residues. The joint shown could be re-welded approximately five (5) times before a new foil needed to be attached to the ends.

Since weight and envelope were not critical, bolted floating lap joint type flanges were used as the load carrying members and the means of supporting the foil discs against the pressure load.

The primary disadvantage of semi-permanent joints, wherein a metallurgical bond is created, is the need for special equipment to make the joint. Also, in order to open the seal in a manner designed to assure the best possible conditions for future rejoining and the maximum number of re-uses of the same foil discs, it is supposed that special slitting devices would be required. Finally, the fact that this making-and-breaking of these types of joints would have to be accomplished within the confines of the compartments of a vehicle such as Space Shuttle, adds another constraint to the approach.

The above disadvantages and constraints, however, are all felt to be solvable within the existing state-of-the-art of the required disciplines. The investigation during this work has determined that this capability has been demonstrated in various

applications in the past. The advantages of these types of joints, with regard to being able to achieve "zero-leakgage" within the range of requirements of the program scope of work and the Space Shuttle vehicle suggest the need to further investigate and refine this approach.

During this program, contact was made with firms with the capability to provide the technology required to demonstrate the feasibility of semi-permanent joints made by fusion-welding and ultra-sonic welding. The inherent reliability of welding as opposed to soldering, brazing and diffusion bonding is the reason for concentration in that area. Additionally, while welding requires higher local temperatures than brazing, soldering or diffusion bonding, surface preparations of the mating parts, and the ability to be able to control this heat, is easier during welding. Welding is also a faster process than brazing, soldering or diffusion bonding.

Figure 4 shows a fusion welded type joint with an approximate envelope of the aligning and welding device believed to be within the state-of-the-art.

Ultra-sonic welding offers a method for accomplishing a reliable, leak-tight joint since it is a highly controlled process. This process offers the advantage of easy re-welding if leak checking reveals the need. Also because of the low heat
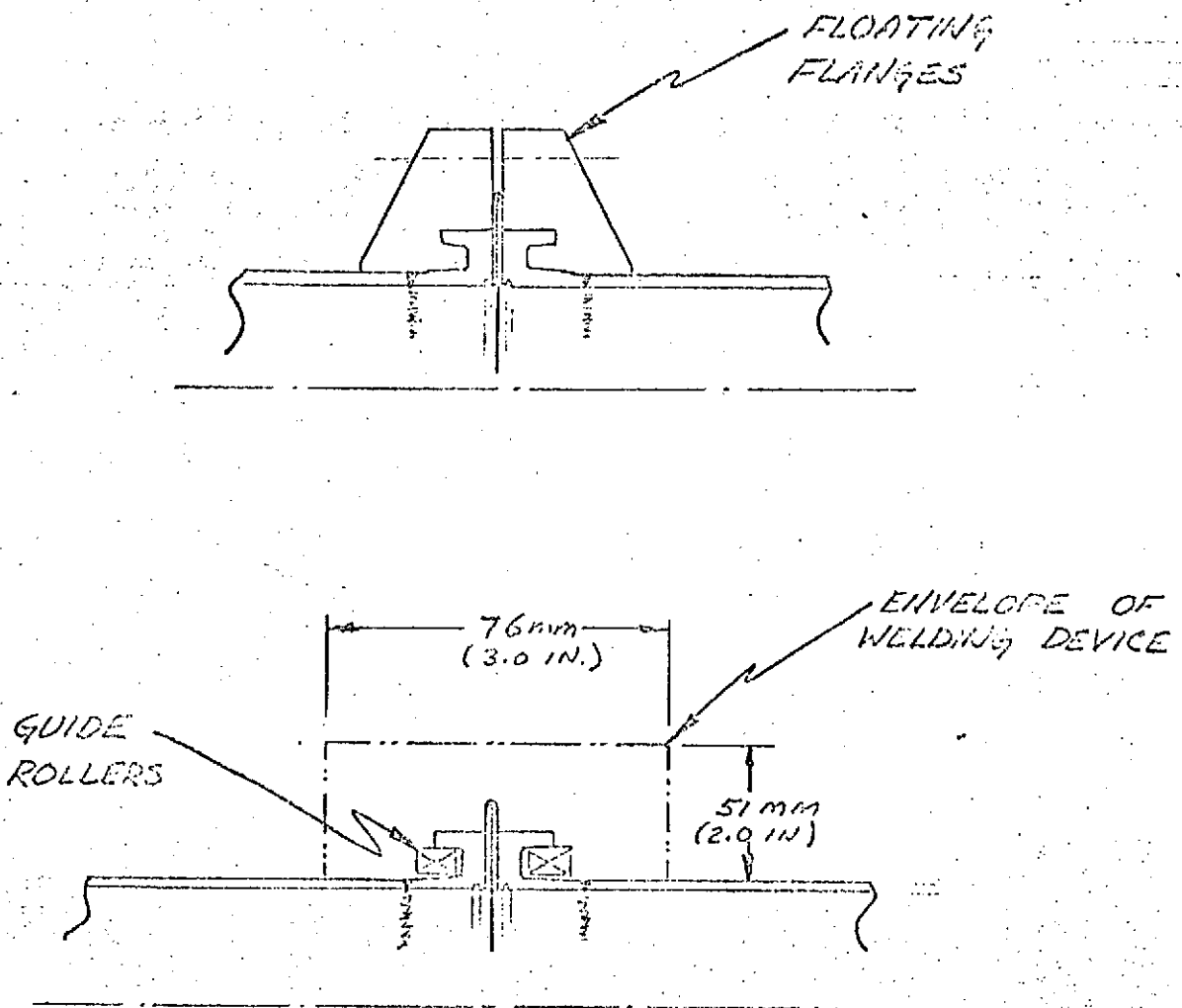
FLOATING
FLANGES

ENVELOPE OF
WELDING DEVICE

GUIDE
ROLLERS

76mm
(3.0 IN.)

51 mm
(2.0 IN)

FIGURE 4

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generated, it is conceivable that ultra-sonic welding can be used to seal joints in areas where adequate venting of gases is not possible.

## THREADED CONNECTORS

Threaded connectors have the potential of being the lightest load carrying joint restraints because of the high shear areas which can be developed within a thin annualar volume.

Since the total seal preload is directly proportioned to the diameter the excessive torquing required for large diameters has limited the use of threads to below approximately 76 mm (3.0 in.). A major portion of the torquing load is due to friction with a large percentage of the friction occuring not in the threads but on the bearing surfaces. Figure 5 presented next eliminates this bearing contact and provides the additional mechanical advantage of a finer thread than can be fabricated inexpensively.

The breech mechanisms of cannons solve another criticism of threaded joints, that of requiring many turns and the danger of thread damage during thread starting. Cannon breech blocks require less than one turn to lock and accept load by the alternate grooving, axially, of the threads on both mating parts. This permits the insertion of the male thread to the almost full depth before rotation.
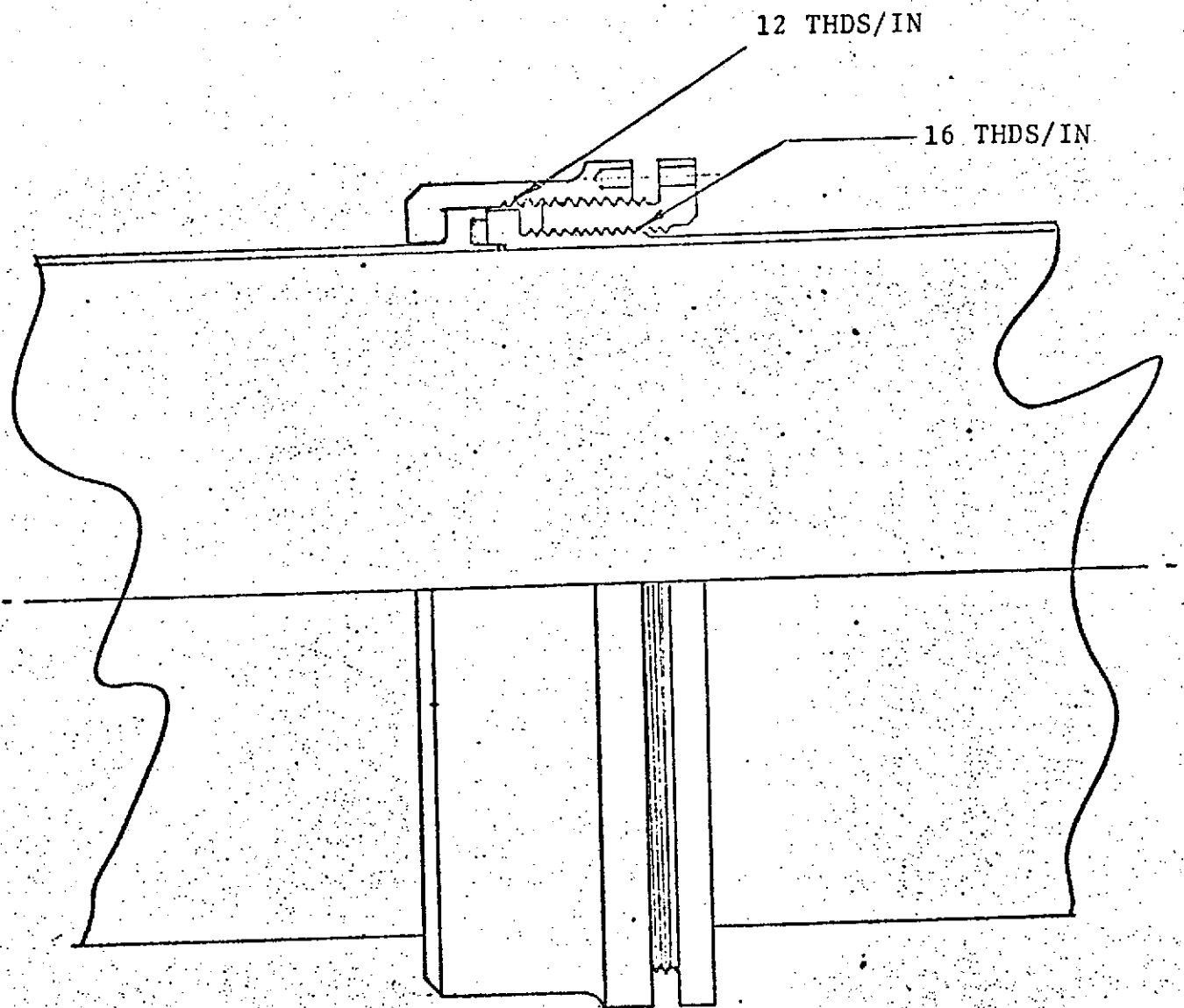
12 THDS/IN

16 THDS/IN

FIGURE 5

Threaded sleeve and collar uses two pitch angles.
Assembly is made by tightening the outer collar until
snug. The seal is then loaded by holding the collar
and rotating the sleeve. By using two different pit-
ches the approach angle is a result of the difference
between pitches (16-12 or 4 threads/in.) with conse-
quent reduction in torque.

Pro - Even load distribution
    - Low profile
    - Loads carried close to duct wall
    - Minimum engagement length
    - Permits threaded couplings on larger diameter ducts

Con - Thread friction coefficients must be very low for
      any appreciable reduction in torque to be obtained.
    - Limited to smaller diameters
    - Difficult to provide secondary seal
    - Difficult to provide for anti-rotation

FIGURE 5: Continued

LEAK DETECTION

To verify the leak tightness of ducting joints, when acceptable leakage is defined as $1 \times 10^{-7}$ cc/scc $H_e$ or better, the helium mass spectrometer has been the most often used tool. Disadvantages of the helium mass spectrometer are:

1.  The need to achieve a high vacuum on one side of the joint being tested.

2.  The need of the reference gas (helium) on one side of the joint being tested.

As an "on the vehicle" verification system, such as between flights of the Space Shuttle Orbiter, the above requirements of the mass spectrometer made its use almost impratical or at best, extremely costly.

An Ion Mass leak detection system developed and manufactured by Industrial Dynamics Corporation, Beach Grove, Indiana, was reviewed. A discussion of this method is included in the following review of the strengths and weaknesses of current leak detection methods in use by industry:

A.  SUBMERSION

The part ot be tested is pressurized with air and submerged under water for some period of time. Leaks are detected by an operator watching for bubbles. The advantages of the submersion method are:

1.  Low initial cost.

2.  No special training for operators or maintenance personnel.

3.  Leak locations can be identified.

Disadvantages of the submersion method are:

1.  Low productive rate--test times of one minute are common.

2.  Possibility of human error--small leaks often are not found.

3.  Difficulty of sealing parts under positive pressure.

4.  Parts are contaminated by water, often causing housekeeping problems. Where wet parts or rusty parts are intolerable a considerable investment and expense can be required to dry the parts.

B.  DIFFERENTIAL PRESSURE

One of the first attempts to automate leak testing utilized a device known as a differential pressure transducer (D/P cell). The D/P cell has two (2) airtight chambers separated by a movable diaphragm. In operation, the test part is connected to one (1) chamber, then both chambers and the test part are pressurized. When a stabilized pressure has been achieved, one (1) chamber is isolated from the test part and the other chamber. Any loss of pressure

in the test part then causes movement of the diaphragm, indicating a leak.  The advantages of this system are:

1.   Removal of human error in evaluating test result.

2.   Leak test can be automated.

Disadvantages of the differential pressure method are:

1.   Instability of apparatus, requiring frequent calibration.

2.   Inaccurate tests--drop in temperature of test part gives the same reading as a leak.

3.   Low production rates due to relatively long times needed to stabilize system pressures.

4.   Special training is required for calibration and maintenance personnel.

5.   Leak location is not identified.

C.   HELIUM MASS SPECTROMETER

In this method, the test part is evacuated, connected to the spectrometer, and placed in a helium-rich atmosphere. The helium will enter the part through any existing leak path and be detected by the spectrometer sensor.  Advantages of this system are:

1.   High sensitivity.

2.   Removal of human error in evaluating test result.

3.   Leak test can be automated.

Disadvantages of the mass spectrometer method are:

1. HIgh initial cost.

2. The basic sensor used requires the use of diffusion pumps to achieve the hard vacuums required.

3. System requires use of liquid nitrogen or a mechanically refrigerated cold trap.

4. System cleanliness required necessitates use of extremely clean test parts, and usually much maintenance.

5. Calibration and maintenance personnel require training.

6. Handling and expense of tracer gas required.

D. ION-MASS TECHNIQUE

The test part is evacuated to a moderate vacuum level and connected to the test unit. The test unit ionizes all air molecules in the detector chamber and reads the concentration of these ions at a given point in time. The test unit electronically and automatically establishes this ionization level as zero, then reads any increase in ion concentration as a function of time. If, after a predetermined test time an increase in ion concentration due to air leaking into the part exceeds established limits, the part is rejected. The advantages of the ion-mass technique are:

1.  High accuracy--more sensitive than submersion or differential pressure methods.

2.  Can detect leaks as small as 0.000005 cc/sec.

3.  Rapid production rate is possible because of the soft vacuum required.  High sensitivity allows extremely fast test times with most test cycles as short as five (5) seconds.

4.  Total automation of the leak test is possible to remove human error in test result evaluation.

5.  The ion-mass technique is insensitive to temperature changes in test parts.

6.  The ion-mass technique is readily compatible with current machining or assembly operations.

7.  Test accuracies approaching mass spectrometers without the need for cold traps, diffusion pumps, lengthy pump-down times, and without the use of tracer gas for production leak testing operations.

Disadvantages of the ion-mass technique are:

1.  Leak location is not identified during normal production testing, however, the test unit can be tuned to detect a tracer gas and this approach can be used in a repair operation to locate leaks.

CONVOLUTED SEAL

The concept selected by NASA for study in Task II was a combination of the convoluted seal, commonly found in the Saturn ducting joints, and a conical disc seal. Figure 5 shows the original concept. The sealing mechanism occurs by achieving mechanical advantage through toggling at the flange seal groove edges. The desirable characteristics of such a joint concept are:

1.  Lower initial sealing forces.

2.  High pressure induced sealing force component.

3.  Low cost sheet metal seal construction.

4.  Protected flange sealing edges and surfaces.

5.  High seal elastic deflection capability to compensate for flange deflection.

Initially, deflection analysis of the convolution portion of the seal was performed by standard bellows expansion joint technique. However, the free inner edges of the seal member was felt to make the analogy less accurate than desired. The method now being used is to divide the seal into a series of parts and analyze them separately. Figure 6 shows that the seal is divided into three (3) different types of members:

Item 1 - Semi-toroidal cap

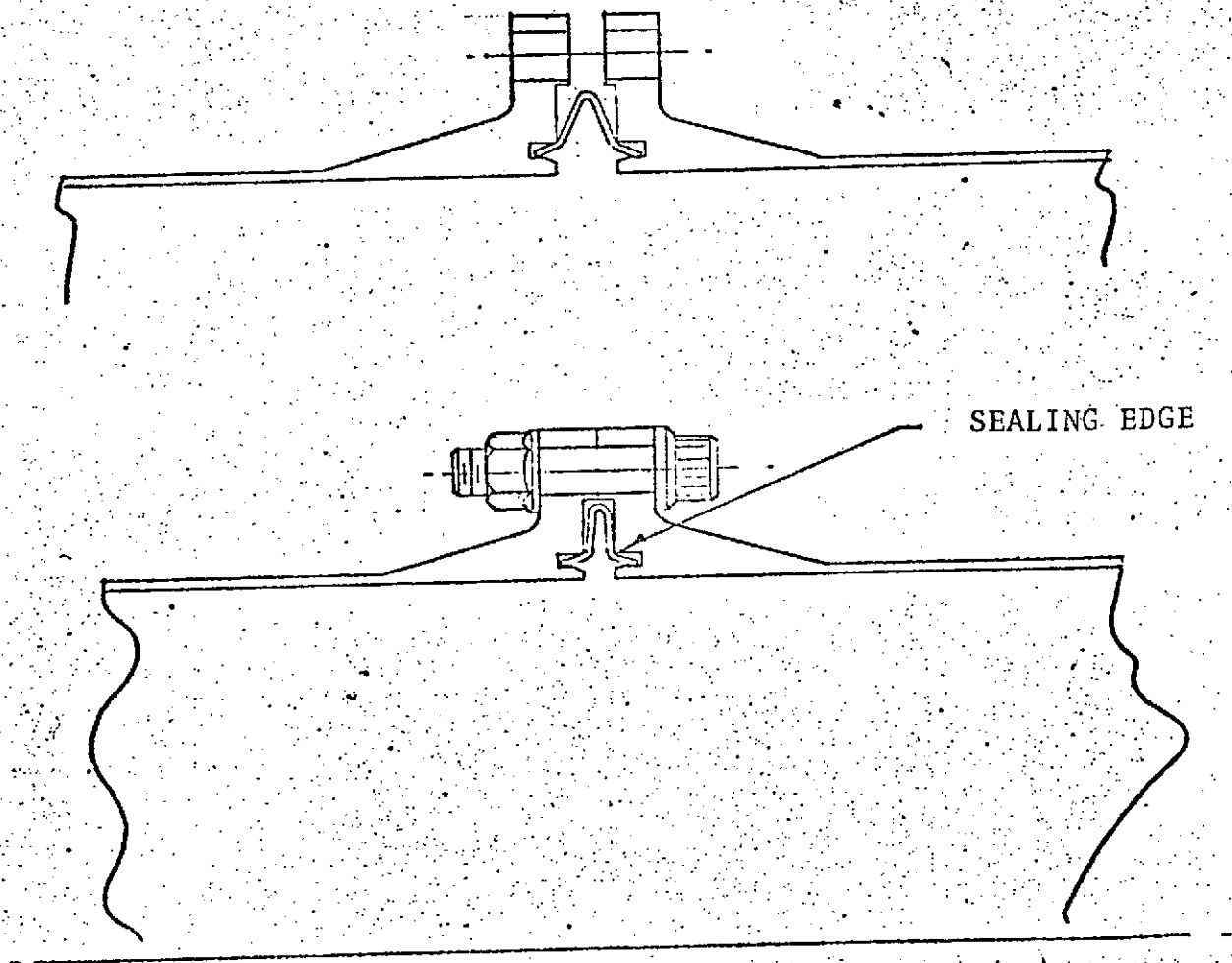Item 2 - Washer sidewall (2)
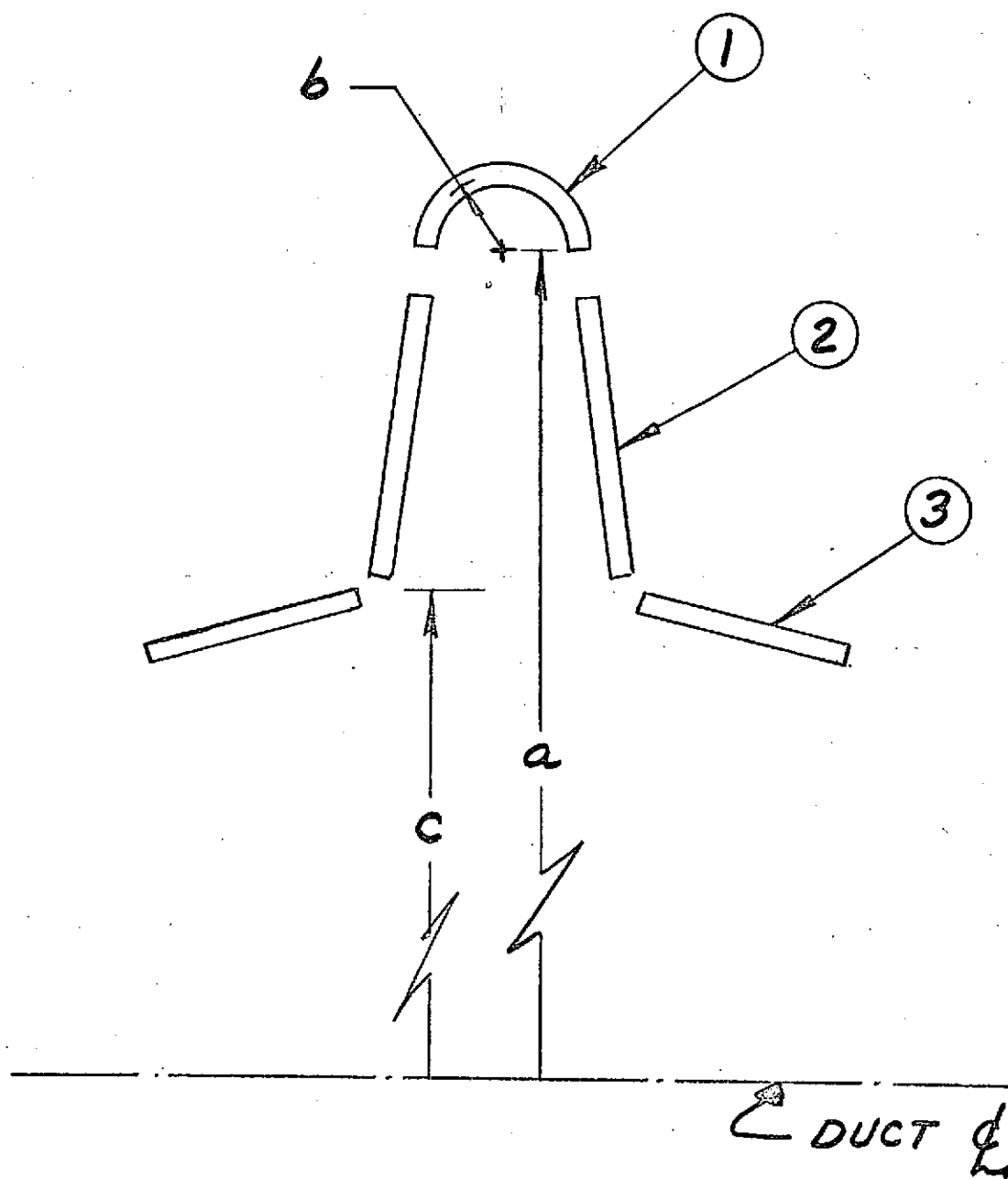
Item 3 - Conical disc (2)

SEALING EDGE

FIGURE 5

FIGURE 6

## ITEM 1 - SEMI-TOROIDAL CAP:  ANALYSIS

The axial (along duct centerline) deflection ($\delta$) of the semi-toroidal cap member can be determined by the following equation:

$$\delta_1 = \frac{1.813 \ Pb \sqrt{1-\gamma^2}}{\pi \ Et^2} \tag{1}$$

where P = total axial load

b = near radius of outer cap (Ref. Figure    ).

The meridional bending stress due to deflection can be determined by the following equation.

$$\sigma_{m_1} = \frac{1.63 \ P}{2\pi \ ta^6 \sqrt{1-\nu^2}} \sqrt[3]{\frac{ab}{t^2}} \tag{2}$$

For practical purposes, the deflection of the toriodal cap should be a minor component of the total seal deflection. The bending stress calculation is important, however since plastic deformation of the cap will result in a major re-duction of seal spring back and resulting sealing force.

## ITEM 2 - WASHER SIDEWALL:  ANALYSIS

The washer sidewall has been analyzed as a washer with both outer and inner edges fixed.  The axial displacement of the inner and outer edges is felt to be so small, rela-tive to the diameter, that a bellville spring analogy may not be representative.  The axial deflection of each washer sidewall can be determined by the following equation.

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$$\delta_2 = -\frac{3P(m^2-1)}{4\pi m^2 E t^3}\left[a^2 - c^2 - \frac{4a^2 c^2}{a^2-c^2}\left(\ln\frac{a}{c}\right)^2\right] \quad (3)$$

$$m = \frac{1}{v}$$

The seal is assumed to axially deflect by such as bolt unloading, flange shrinkage, etc., in the Item 1 and 2 members only since the loading of the seal by the flanges occurs at the intersection of the Item 2 and 3 members. Also, because of its almost parallel orientation to the duct centerline, it can be assumed that Items 3's contribution to the axial deflection is negligible. The maximum deflection induced stress (occuring at the radius C edge) can be determined by equation 4.

$$\sigma_{2_{MAX}} = \frac{3P}{2\pi t^2}\left[1 - \frac{2a^2}{a^2-c^2}\left(\ln\frac{a}{c}\right)\right] \quad (4)$$

## OTHER CONCEPTS

During Phase I, a number of concepts were generated, some of which were presented for NASA review. The development of concepts continued into Phase II whenever an idea occured to the investigators that could logically be extrapolated into a definitive mechanism.

Examples of the earlier concepts, which were presented are shown in Figure 7 through 13 with a description of their advantages and disadvantages. Later concepts included a water filled metal O ring, rotating bi-metal locking seals and covered bolts to reduce flange mass.

FOIL SEALS

PEANUT;ROLL;
OR ULTRASONIC
WELD
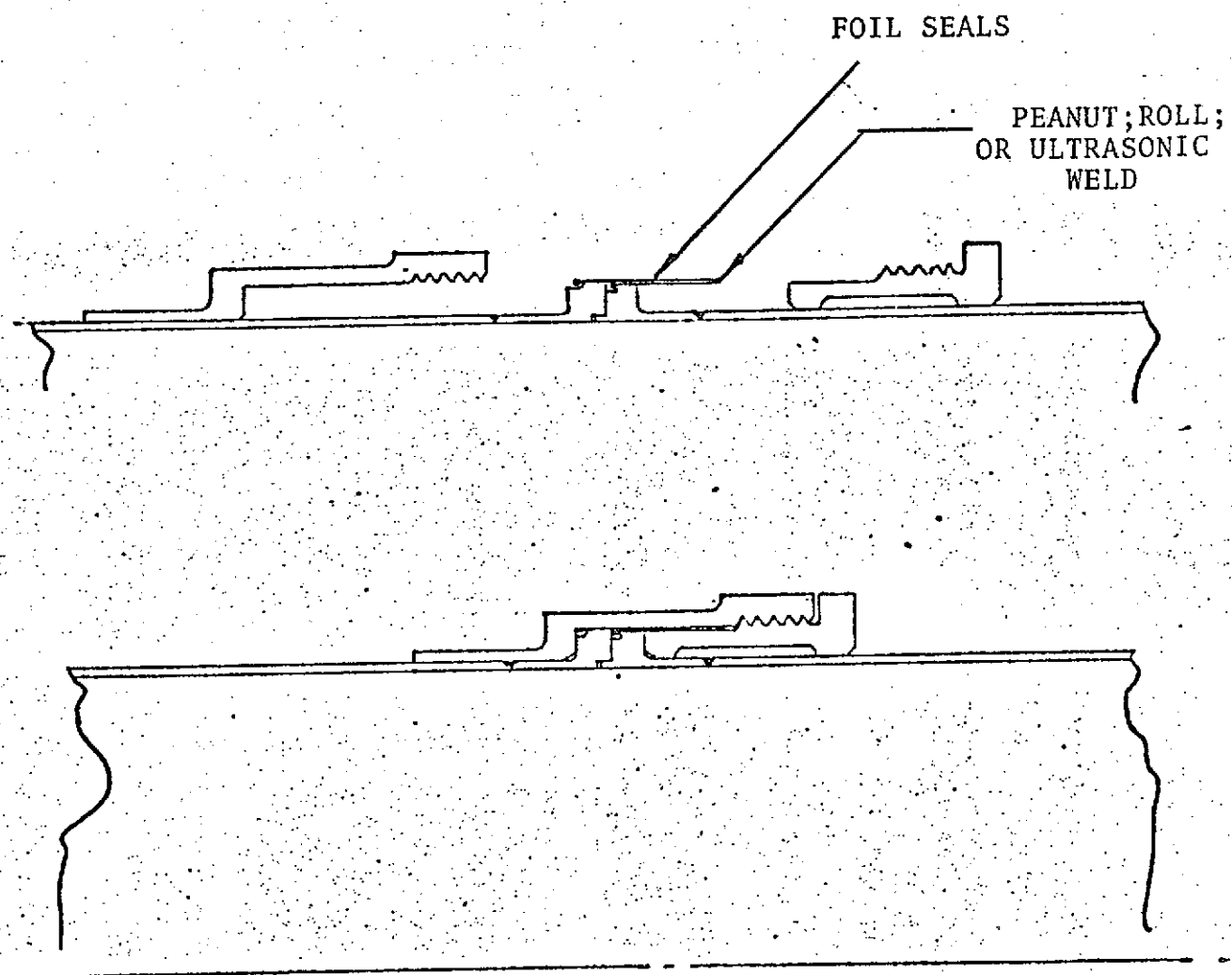
NOTES:  1.  Sleeve nut used to align duct sections during engagement.

2.  Seal weld may be trimmed off for disengagement. May be rewelded several times prior to replacing seals.

FIGURE 7

Semi Permanent Connection - Welded foil seals parallel
to duct C.  Seals may be reused several times by trim-
ming and rewelding.  Seals are supported by collar and
sleeve when pressurized.

Pro - Zero leakage
    - Seal is insensitive to minor deflections caused
      by thermal or structural variations
    - Attachment structure at a minimum as no sealing
      loads are involved
    - Elimination of sealing loads permits use of threaded
      connectors on relatively large diameters as tight-
      ening is limited to snugging down the mating halves
    - Low profile
    - Pins may be used to prevent rotation

Con - Care required during assembly to avoid seal damage
    - Considerable length of engagement
    - Difficult to provide secondary seal

FIGURE 7 (continued)

FOIL SEALS

PEANUT;ROLL; OR
ULTRASONIC WELD
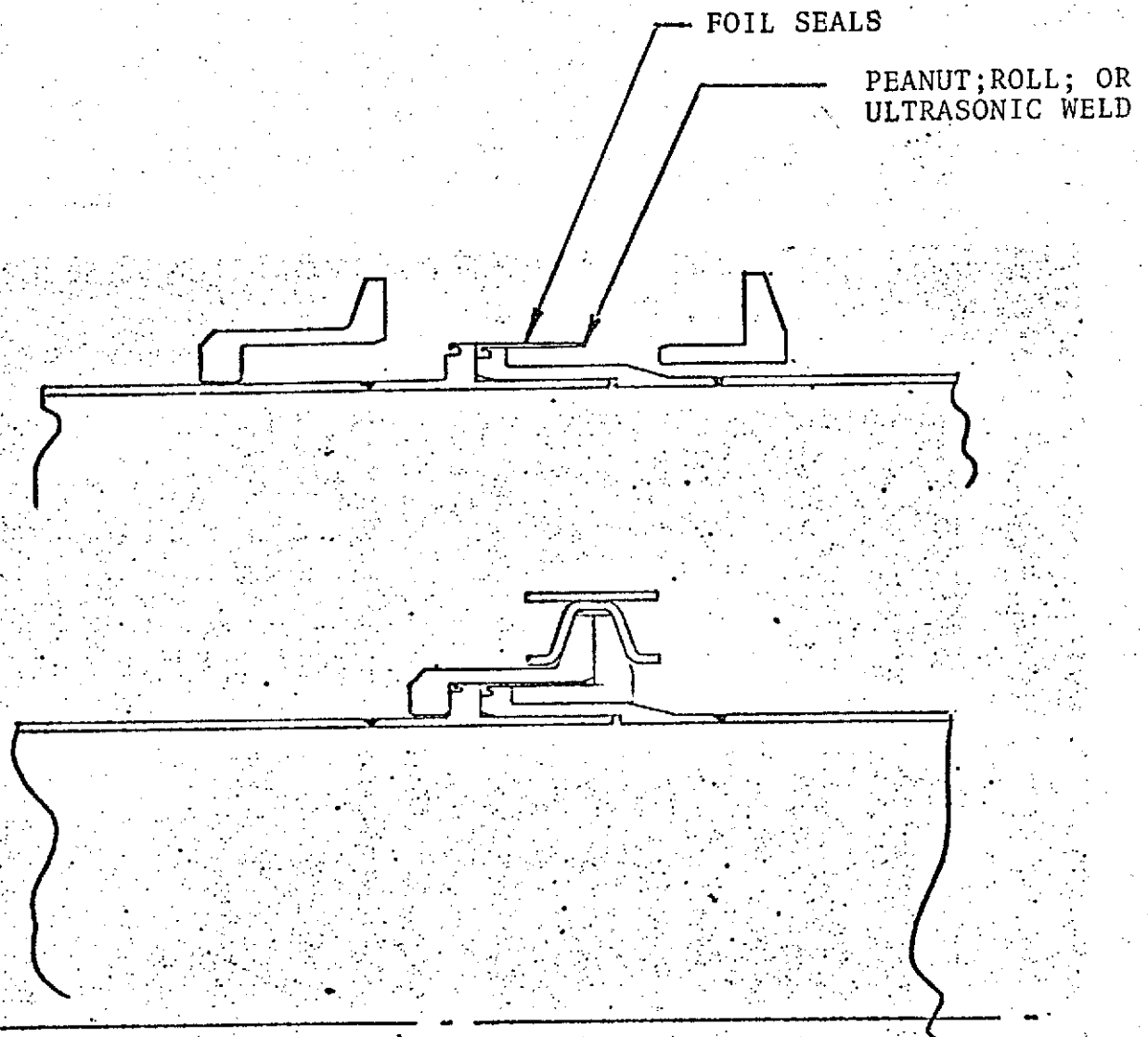
NOTES:  1.  Seal Weld may be trimmed off for disengagement.
            May be rewelded several times prior to replacing
            seals.

Similar to Fig. 7 except better alignment capabilities through
use of rigid internal support.

Higher profile than Fig. 7 but eliminates threaded collar and
sleeve and is therefore capable of use with larger diameters.


FIGURE 8

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SEALING MEMBRANES

PEANUT; ROLL OR
ULTRASONIC WELD
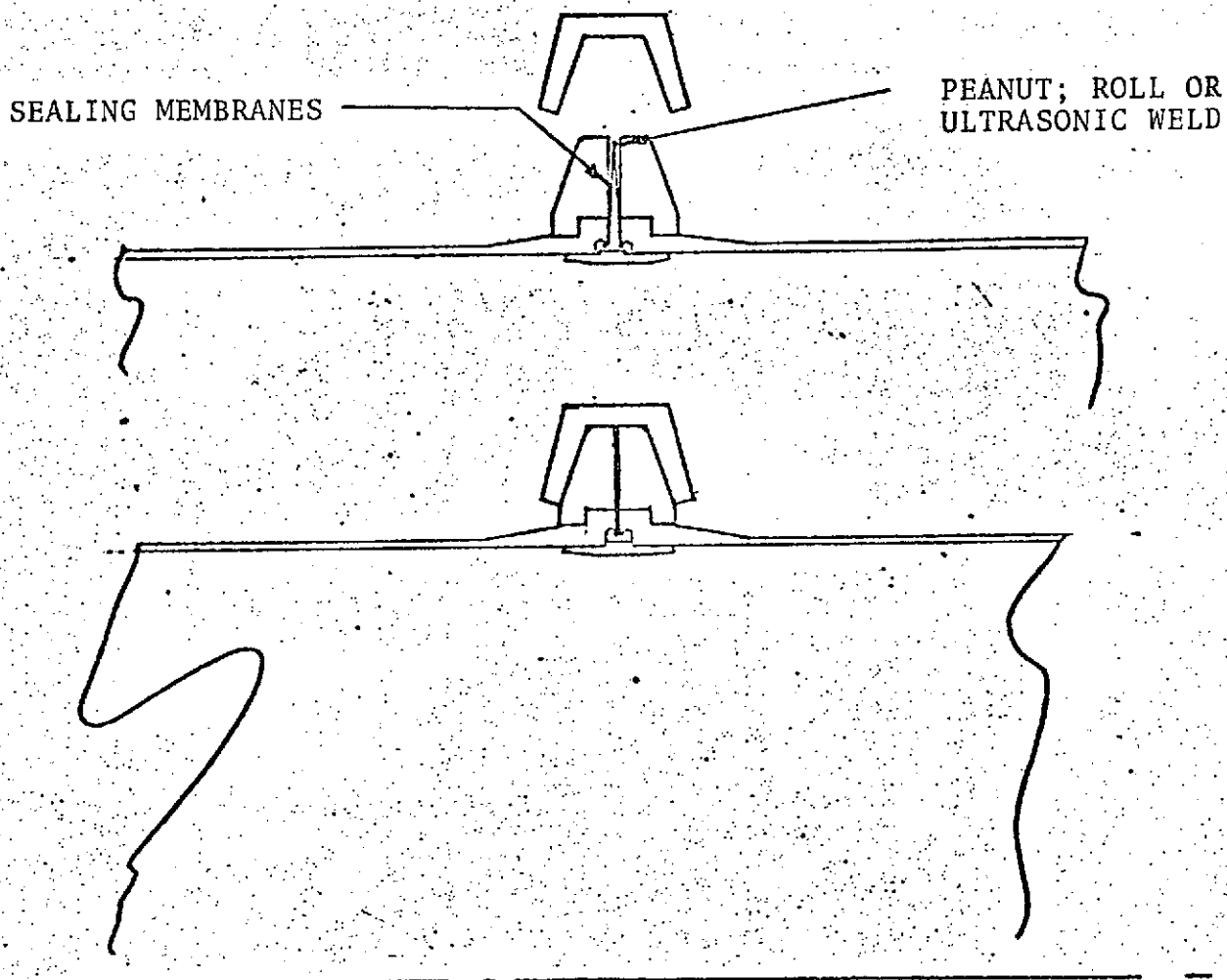
- Semi permanent using foil seals perpendicular to duct $\mathcal{L}$.
- May be reused several times by cutting and rewelding seals.
- Well suited to " " band but may also be bolted.
- Aligned laterally by internal indexing ring.
- No sealing force required - only structural loads
- Diaphragm action makes seal independent of minor deflections
  and permits minimum of joining structure.
- Suitable for large diameters.
- Short engagement length.

FIGURE 9

STAINLESS SEAL
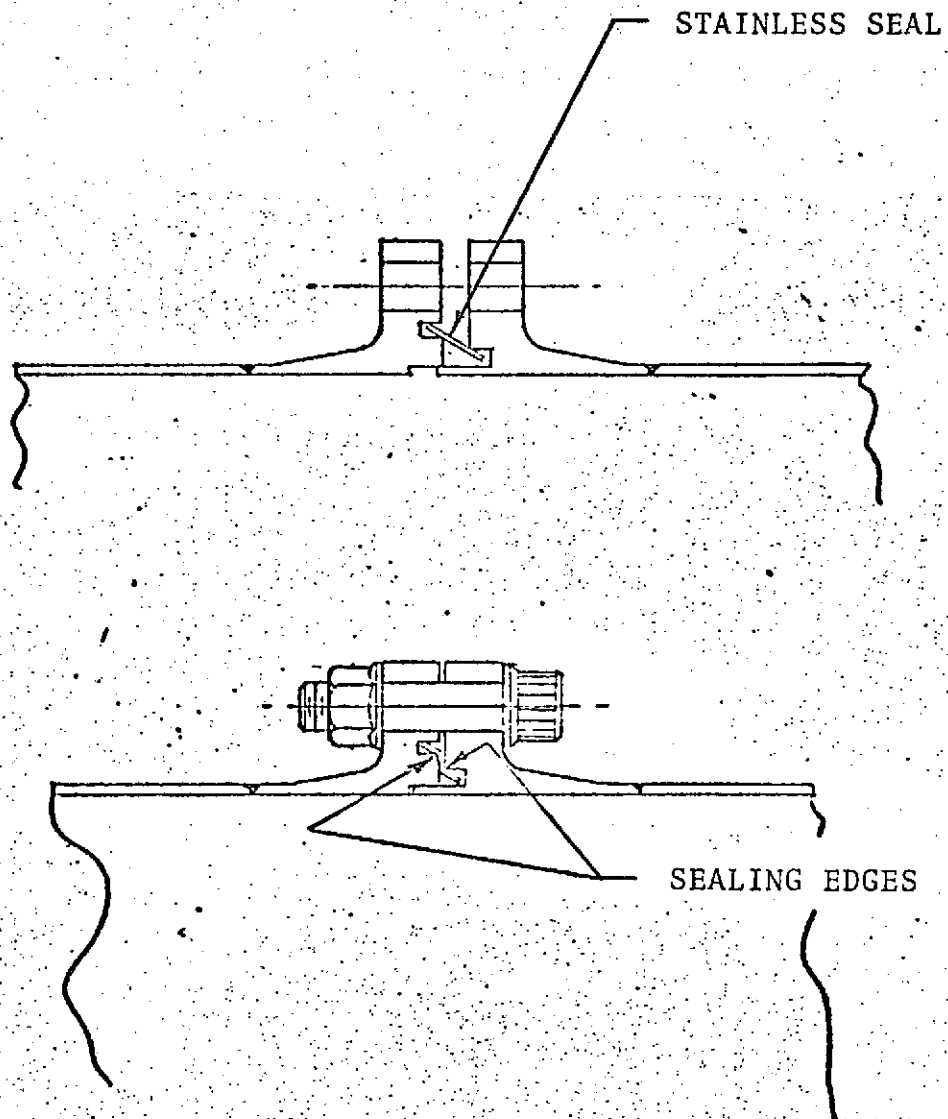
SEALING EDGES

Toggle action seal formed by crippling a conical disc, the seal being accomplished by yielding at the slot edges.

Pro - Low Sealing forces
    - Sealing edges reasonable well protected
    - Relatively compact
    - May accept slight deflection through springback
    - Bolted - no rotation
    - Low overhang

Con - As shown toggling action may tend to reduce the load at the sealing edge
    - Secondary seal can be provided at the expense of increased height

FIGURE 10

Flange machined and slotted to provide engagement and clamping action with mating flange.
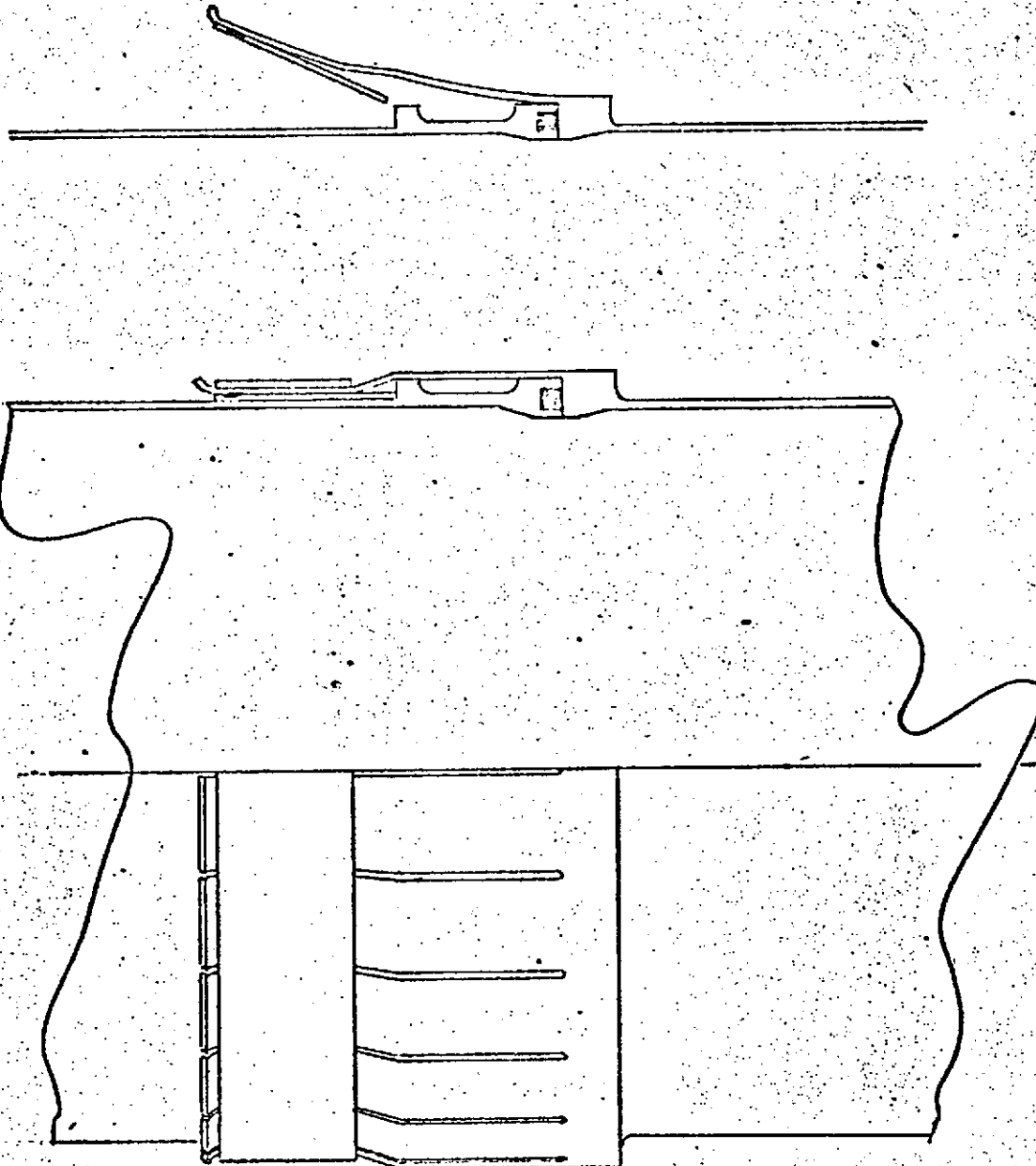


Pro - Extremely low profile depending on seal used
    - Low weight
    - High and uniform flange loads for low force

Con - Very long engagement
    - Requires tool for complete disengagement
    - No anti-rotation although friction force may be adequate
    - Difficult to provide secondary seal

FIGURE 11

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COPPER SEAL

SPLIT RETAINER WIRE

CLAMPING TOOL

SEGMENTED RETAINER RING

BAND CLAMP
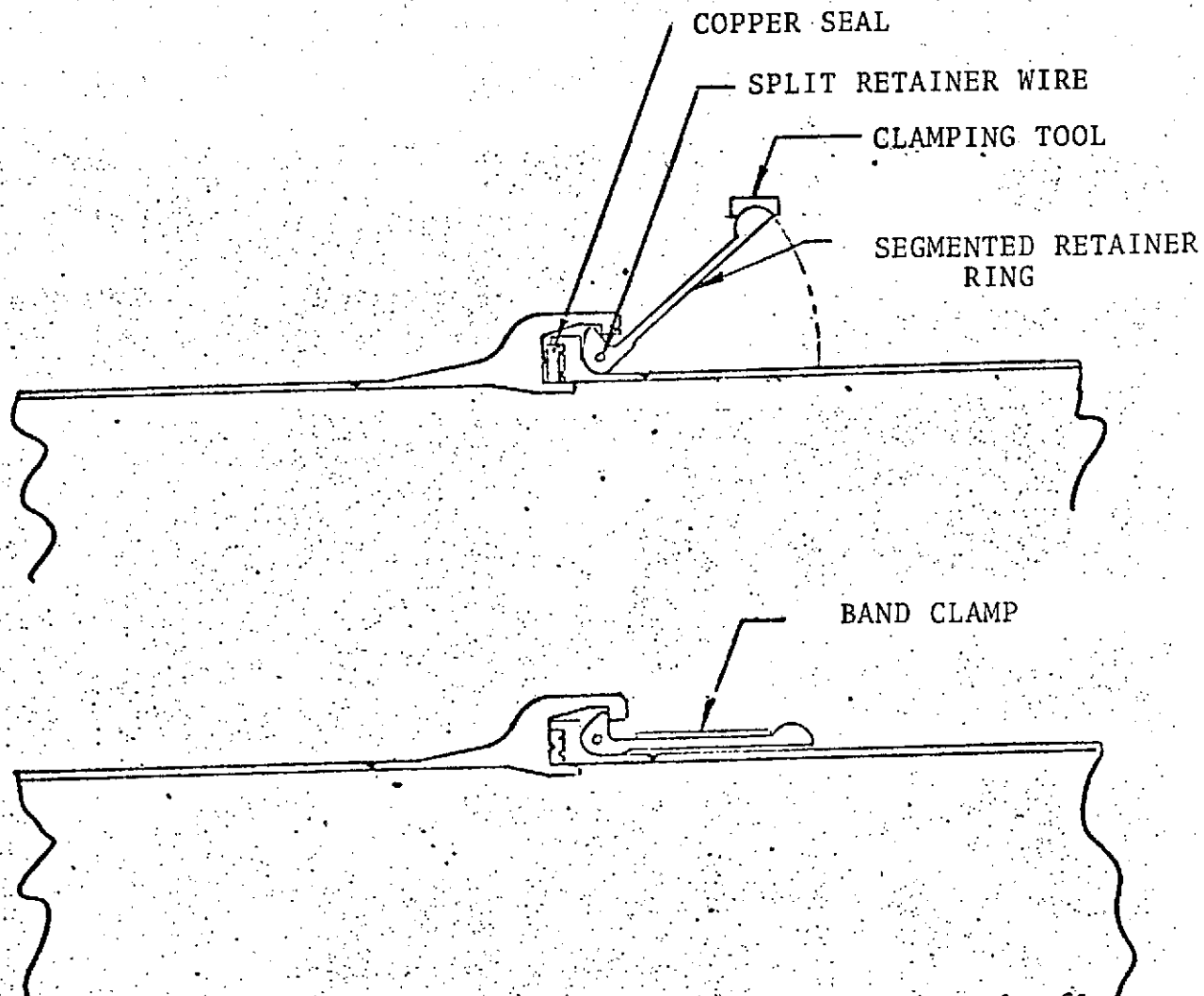
Segmented ring used to provide high sealing forces by toggling the flanges together. A retainer wire is passed through each segment and formed to the duct diameter. This merely acts to assemble the segments for ease of handling and being split the ring may be expanded to pass over the flange. On mating the retainer segments are perpendicular to the duct. Once engaged they are brought to approximately 45° by hand, and a clamping tool used to provide the sealing force as they are brought down to the duct wall. A band clamp retains them in this position. As shown a simple copper seal is used as this has demonstrated excellent sealing properties in vacuum systems when evenly loaded.

Pro - Low profile
    - Even loading
    - Lightweight
    - Reasonable engagement length
    - Retaining forces are close to being in line with the wall.

Con - Difficult to provide secondary seal although leakage is unhibited by inner flange butting against outer.
    - Difficult to provide anti-rotation.

FIGURE 12

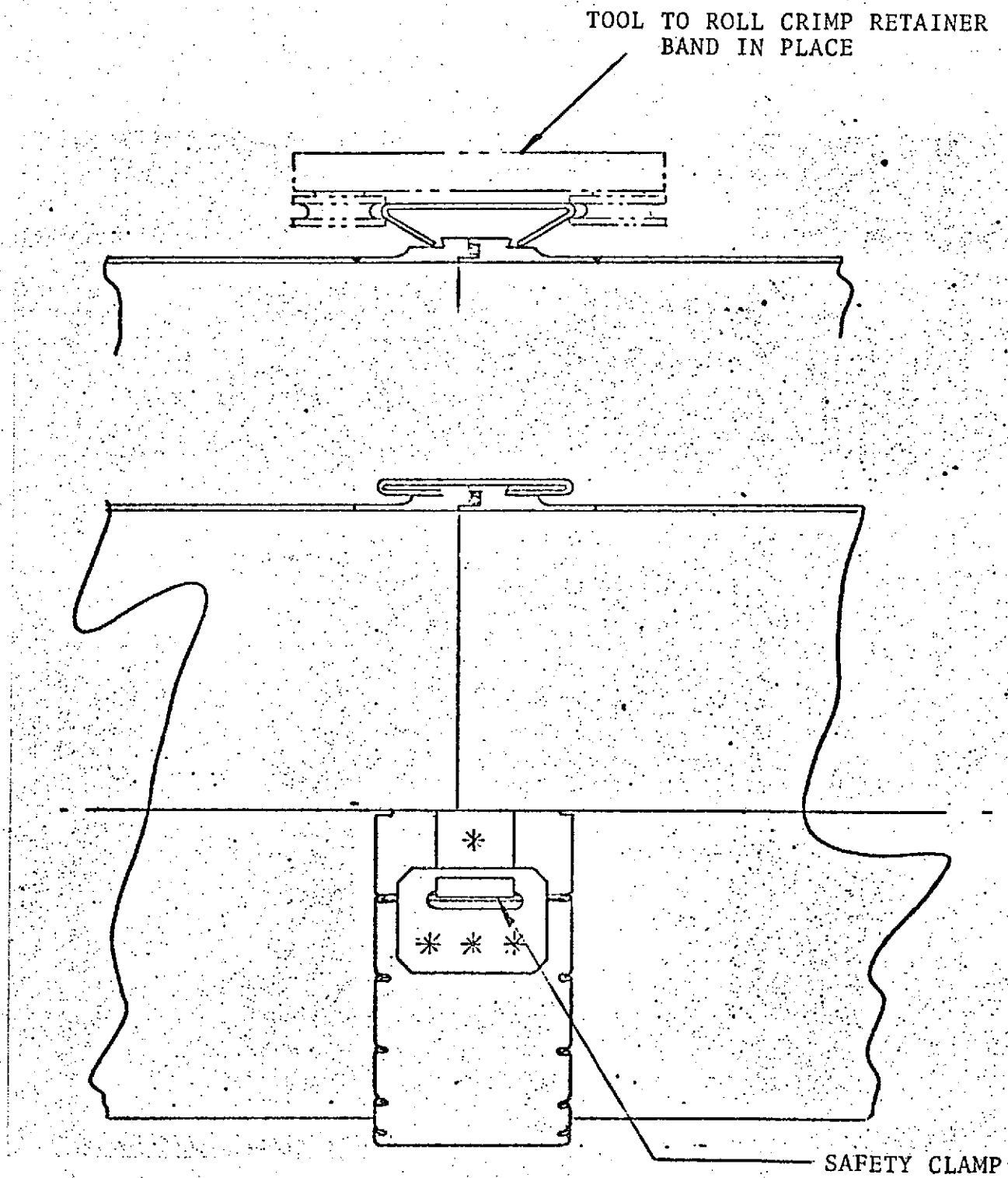TOOL TO ROLL CRIMP RETAINER
BAND IN PLACE

SAFETY CLAMP

FIGURE 13

Slotted strip formed in place by yielding the edges locally using rolls or other means. As the tool progresses around the flange the height reduces and the toggling action provides the clamping force. The ends can be locked together for safety. Removal can be accomplished by peeling the strip off the flange.

Pro - Very flow profile
    - Clamping force almost in line with duct wall and evenly distributed
    - Low cost and weight
    - Clamping force applied by removable tool and is not part of the flight hardware weight.
    - Very low overhang.

Con - Limited to smaller diameters except for low pressure applications
    - Not reusable.

FIGURE 13 (continued)

## WATER-FILLED O-RING

The problem of preventing the loss of seal preload due to flange shrinkage suggests to the designer a device which can expand as temperatures are reduced. The unique characteristics of water offer the basis for such a device. Some years earlier, the author experimented with cold working pressure vessels at ambient and cryogenic temperatures by freezing water into ice. The method used was to seal water in the vessel at ambient temperature and submerge the vessel in liquid nitrogen. A thin walled metal O-ring would permit the contained water to quickly give up its heat and rapidly freeze and expand before the effects of chilldown occurred in the flanges.

To explore the concept, some analysis was performed and is contained in the following discussion.

In order for a water filled O-ring to work, a number of basic conditions must be achieved and a number of assumptions must be made.

1. It is not desirable to design the O-ring to contain or resist the expansion of the water.

2. The design must satisfy two conditions of duct operation.

    a. Zero leakage at ambient temperature.

    b. Zero leakage at low temperature.

3. Bearing pressure during expansion must not compressively fail the seal and flange surfaces.

4.  After freezing the ice will contract as a function of its own coefficient of contraction.

Figure 14 shows the three (3) conditions to be considered in the analysis.  Condition I is the unloaded seal, Condition II is the seal loaded on installation (slightly compressed) and Condition III is the seal after the water is frozen.  Using subscripts equivalent to the three (3) conditions, we can state that the crossectional areas of Condition I and II are equal:

$$A_1 = A_2$$

The incompressibility of water makes this assumption valid.  And

$$A_I = \frac{\pi d^2}{4}$$

$$A_{II} = \frac{\pi d_i^2}{4} + 2 a_i d_i$$

If the crossectional areas do not change from Conditions I to II, then the circumference of the section must change and this change in circumference is a deflection in the metal O-ring skin.  Therefore.
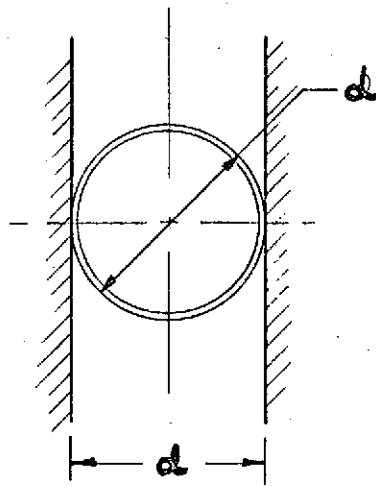
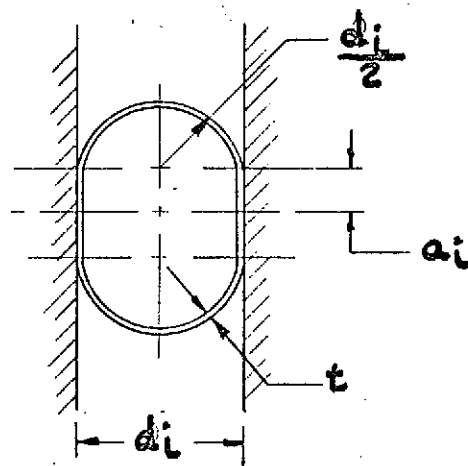$$C_I = \pi d$$
$$C_{II} = \pi d_i + 4 a_i$$

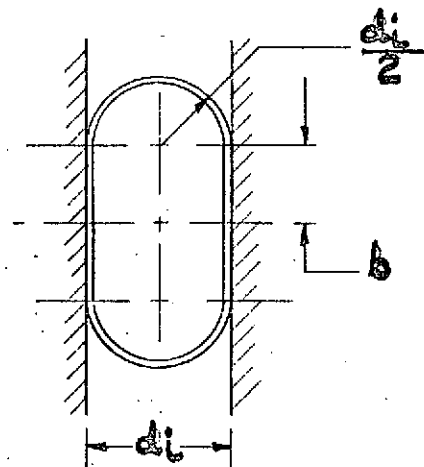From the above it can also be stated that

$$C_{II} = C_I + \delta$$

where $\delta$ = the deflection in the O-ring skin

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FIGURE 14: Water Filled O-Ring

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The strain($\epsilon$) in the metal O-ring skin can be stated as:

$$\epsilon = \frac{\delta}{\pi d}$$

Therefore, solving for $a_i$ from the above equations yeilds

$$a_i = \frac{\pi}{4}\left[(1+\epsilon)d - d_i\right]$$

The stress in the metal O-ring skin produced by the strain($\epsilon$) is proportional to the pressure produced by the water when the round O-ring is deformed. Multiplying contact area of the O-ring (approximately: $\frac{\pi d_m^2}{4} \times 2a_i$ ) and the water pressure will determine the total bolt preload. The designer must select a di (compression) and an elastic strain($\epsilon$) for the O-ring material and solve for Ai. Then again using the strain($\epsilon$) and the elastic modules($E$) of the O-ring material to solve for the stress($\delta$) the water pressure ($P_{II}$) in condition II can be determined as

$$P_{II} = \frac{2t\delta}{d_i}$$

where t = O-ring skin thickness

The reader will notice in the above equation that the O-ring surface in contact with the flanges does not enter into the calculation since it is assumed to be fully supported and does not in itself resist the pressure by skin tension. The water pressure will equal the O-ring to flange face bearing pressure and this pressure must be high enough to effect a seal. For low bearing pressures, and therfore low bolt preloads, coating the metal O-ring outer surface with a material such as teflon would be recommended.

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For Condition III, when the water freezes to ice the change in circumference is directly proportional to the change in volume. Here again, it is important that the resulting strain be carefully considered so that the elongation limit of the material is not exceeded.

The O-ring will attempt to grow in all directions with the resulting flange separation load being determined by the tension resistance of the toroidal surfaces of the O-ring. If the bolts are reduced by flange chilldown, the O-ring will grow to fill the gap until bolt load exceeds the strength of the O-ring material.

By a close examination of the geometry involved, it can be seen that a minimum practical preload to make the seal in Condition II is the most desirable condition since the O-ring would be stressed the least when subjected to Condition III. Furthermore, bolt relaxation to the degree that the O-ring remains nearest to fully round in Condition III is again the most desirable state for the O-ring.

The techniques of fabrication filled metal O-ring are fully developed. The unique characteristic of being able to increase seal force on chilldown makes the concept interesting enough to justify suggesting that further work be encouraged.

# XI

## CONCLUSION

The program was primarily design and analytically oriented with a major emphasis on generating concepts which could provide the basis for future zero leakage ducting joints.

The double convoluted seal offers an interesting combination of proven seal components such as the belleville washer and the convoluted seal. Because of the size of the seal the joint diametric envelope becomes large, however the projected increased ability of the design to accept flange deflection may permit a total flange joint weight reduction over existing designs.