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Mechanical Considerations and Design Skills

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Mechanical Considerations and Design Skills

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Abstract

The purpose of the report is to provide experienced-based insights into design processes that will benefit designers beginning their employment at Sandia National Laboratories or those assuming new design responsibilities.

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FIGURES

1. Acknowledgements

Much of what I have included is the result of my experience and work at Sandia National Laboratories (SNL), the many people I have worked with on projects, manufacturing, assembly, and facilities. There were physicists, material researchers, and engineers from other laboratories from whom I have also gained experience and knowledge outside the system design groups. I am grateful for all their assistance, and excellent working relationships.

2. Purpose

The main purpose of this document is to provide engineers with the practical aspects of system design. The material discussed here may not be new to some readers, but some of it was to me. Transforming an idea to a design to solve a problem is a skill, and skills are similar to history lessons. We gain these skills from experience, and many of us have not been fortunate enough to grow in an environment that provided the skills that we now need. I was fortunate to grow up on a farm where we had to learn how to maintain and operate several different kinds of engines and machines. If you are like me, my formal experience is partially based upon the two universities from which I graduated, where few practical applications of the technologies were taught. What was taught was mainly theoretical, and few instructors had practical experience to offer the students. I understand this, as students have their hands full just to learn the theoretical.

The practical part was mainly left up to “on the job experience.” However, I believe it is better to learn the practical applications early and apply them quickly “on the job.” System design engineers need to know several technical things, both in and out of their field of expertise. An engineer is not expected to know everything, but he should know when to ask an expert for assistance. This “expert” can be in any field, whether it is in analyses, drafting, machining, material properties, testing, etc. The best expert is a person who has practical experience in the area of needed information, and consulting with that individual can be the best and quickest way for one to learn.

If the information provided here can improve your design skills and save one design from having a problem, save cost of development, or reduce difficulty in manufacturing, then my writing effort will have been worthwhile. It is also my hope that you will freely provide others with design information that you have found beneficial to the less-experienced engineers. The result will be that as a whole, the designs will improve, and the development time will be shortened from start of the design to full system operation or deployment.

3. Structural Joints of Cylindrical Thin Wall Sections

The assembly in Figure 1A is a typical bomb case assembly. It is fabricated in sections because sections are necessary for system subassembly purposes. The sections are mechanically joined together to complete the system by 36 radial-oriented bolts located around the circumference at each section joint.

Comments on Joint Design

The cross-section of the cylindrical joint is shown in Figure 1B, and it is an outer overlap joint as shown in Figure 1C. The bolt has a countersunk head and threads into a floating nut plate. The bolt size is determined by the diameter of the thin wall structure cylinder and its thickness. The head is required to result in a relatively smooth surface, yet have enough material left under the countersink to provide the required strength. The floating nut plate assembly provides ease of assembly by not requiring a wrench to be inserted inside to restrain the nut and to allow maximum tolerance for ease of manufacture.

This assembly has a good history, but let us look at some of the design concerns. Each section has 36 countersunk holes radial-drilled to the correct countersink depth. The mating holes must be drilled correctly, and the nut plates must be assembled correctly. This involves several machining operations, each of which has a risk that it will be defective and ruin the floating nut assembly. If the countersink is not at the correct depth, the holes will not be perfectly aligned, a bolt may be cross-threaded, or a nut may break loose and result in an unwanted repair/replacement expense. If a problem occurs at assembly with one of the bolts, the bolt and floating nut plate can be relatively inexpensively replaced. This design has desirable qualities.

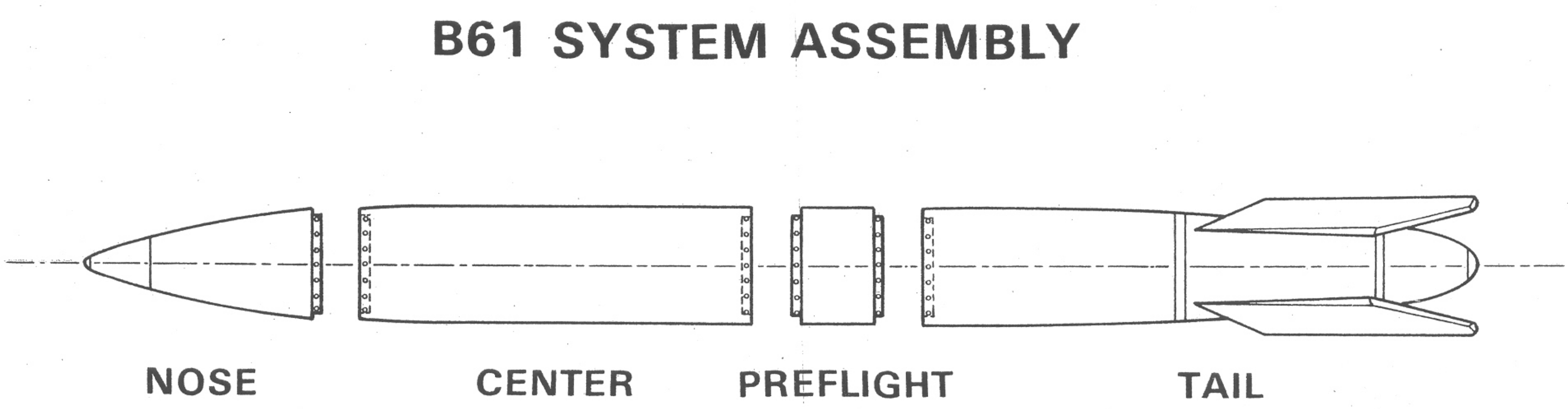

Figure 1A. Typical Bomb Case Assembly

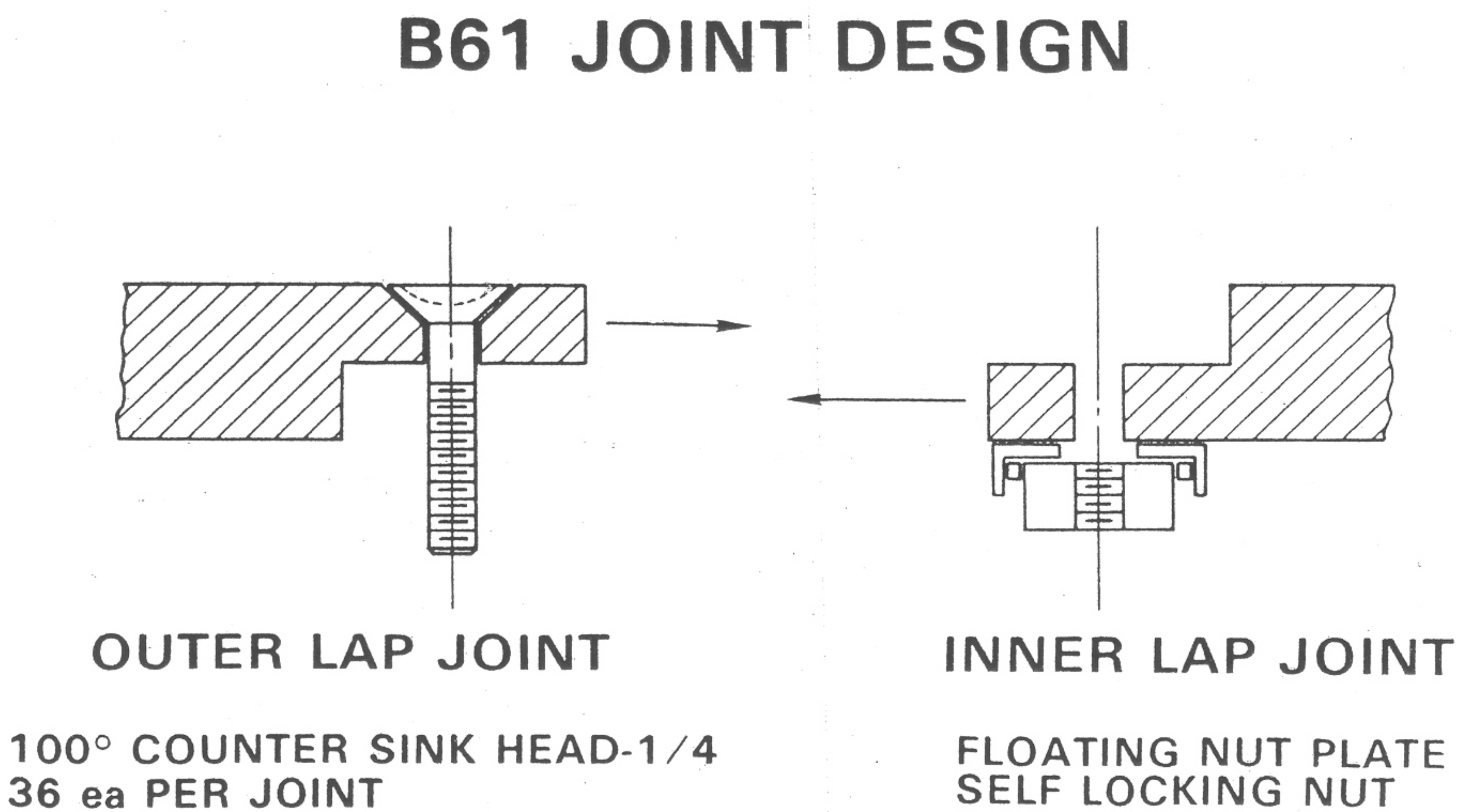

Figure 1B. B61 Joint Design

4. Typical First Joint Design Approach

Figure 1C shows a typical first design approach. The bolts screw into an expensive and high-risk item. Because the bolts are screwed into a structural member of the part to be joined, it may require a whole new section assembly to correct one bolt cross-thread, over-torqueing and stripped threads on the mating assembly, or inadequate tolerance alignment for proper assembly. The lesson here is to always thread a bolt into a member that can be easily and inexpensively replaced, which will prevent scrapping the expensive part. What is not evident is that tolerance build-up can be a serious problem and an added fabrication expense.

5. Structural Joining at Higher Strength Requirement

If a new or modified design was required for the above structural joint because of increased load requirements to the one shown in Figure 1A, one might modify the design as shown in Figure 1D-1. To accomplish this requires extra strength, so the bolt heads are moved closer together so that more bolts can be used. This approach did not work as the failure mechanism moved from the bolts to the cylinder material between the bolts. To gain the strength needed, another row of bolts was added. Figure 1D-1 shows the double row of bolts, with maximum possible spacing between them. Still the failure occurred between bolts heads in the thin cylindrical member.

The concept, for this and other reasons, had reached its limit on strength. This design would have had fabrication problems even if it had been able to carry the required load. The tolerances of the assembly became very difficult and significantly increased the problem for manufacturing. Second, commercial floating nut plates were not available for this design, and a new design for them was needed. The 80 bolts versus 36 bolts presented the new assembly risk that one or more bolt assemblies might have had defects in them, and that was unacceptable. There were other approaches to the design, but the associated weight and size were unacceptable. Another approach considered was to thread both members, but large diameter and thin wall tubing do not have high strength capability because the threads tend to jump over each other. A new type of design was needed (necessity is said to be the Mother of Invention). This resulted in the invention of the Alvis/Tape Joint shown in Figure 1D-2 for comparison purposes.

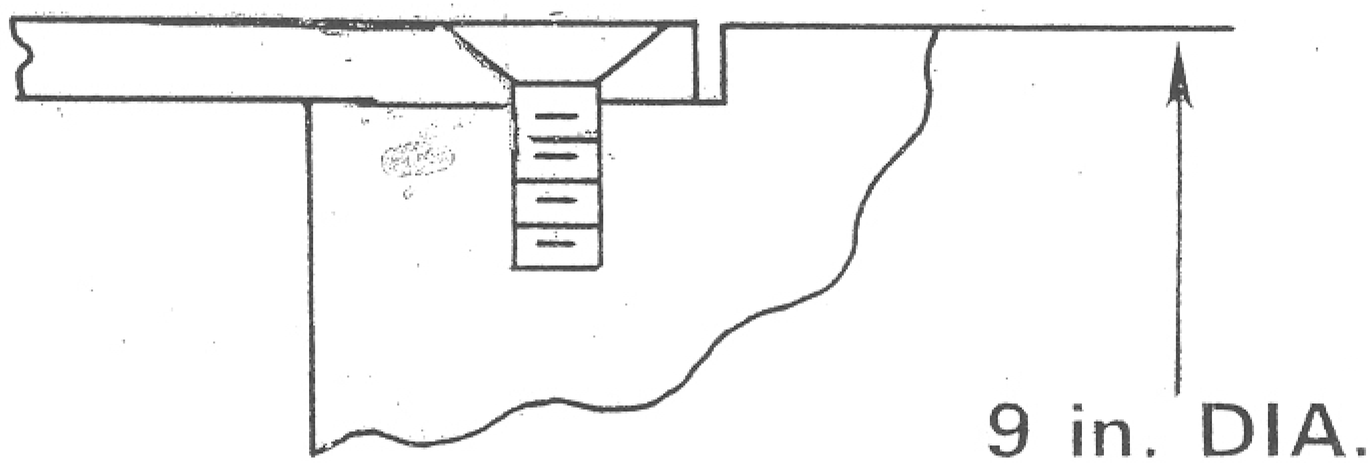

Figure 1C. A Typical First Bolt Design

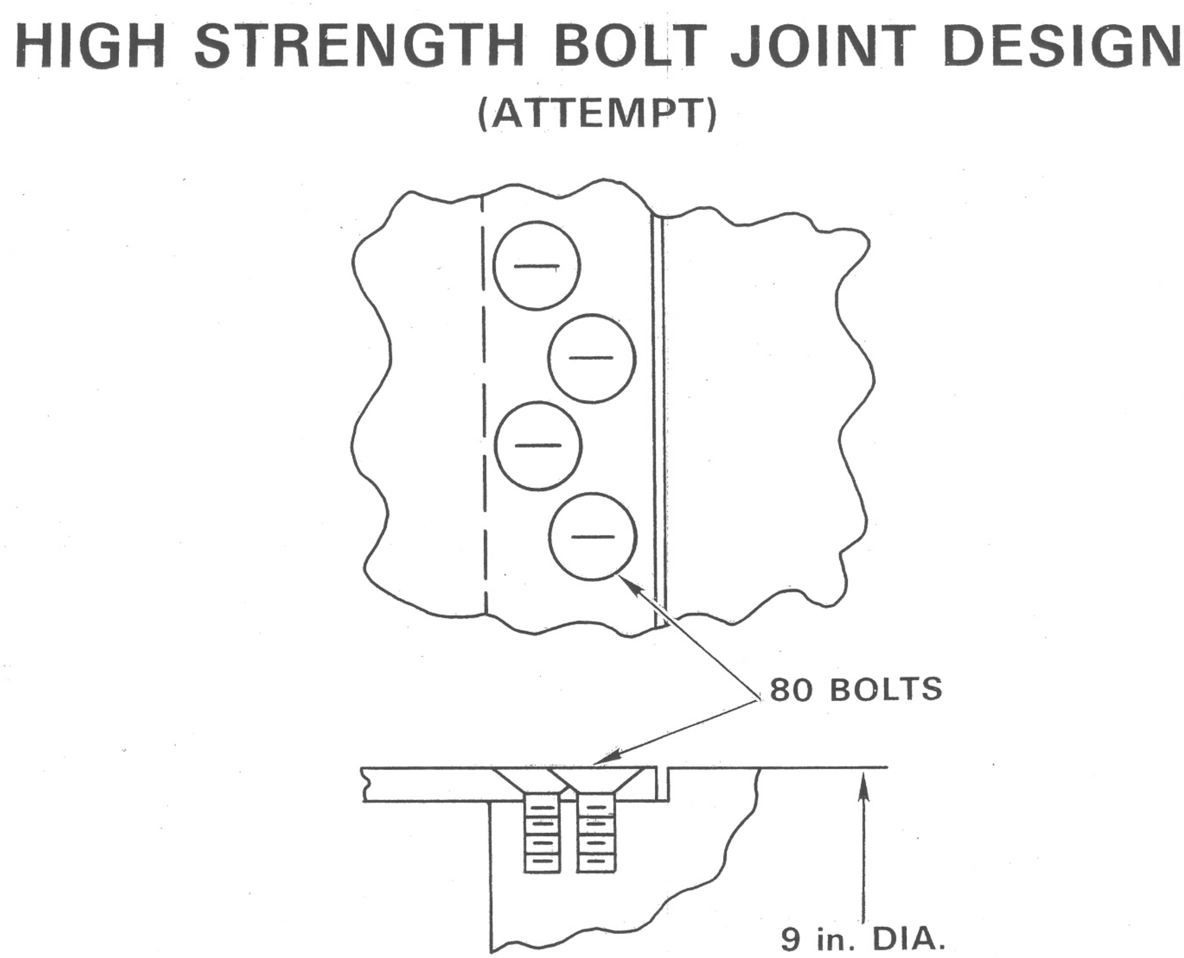

Figure 1D-1. High Strength Bolt Joint Design

HIGH STRENGTH BOLT JOINT DESIGN
(Attempt)

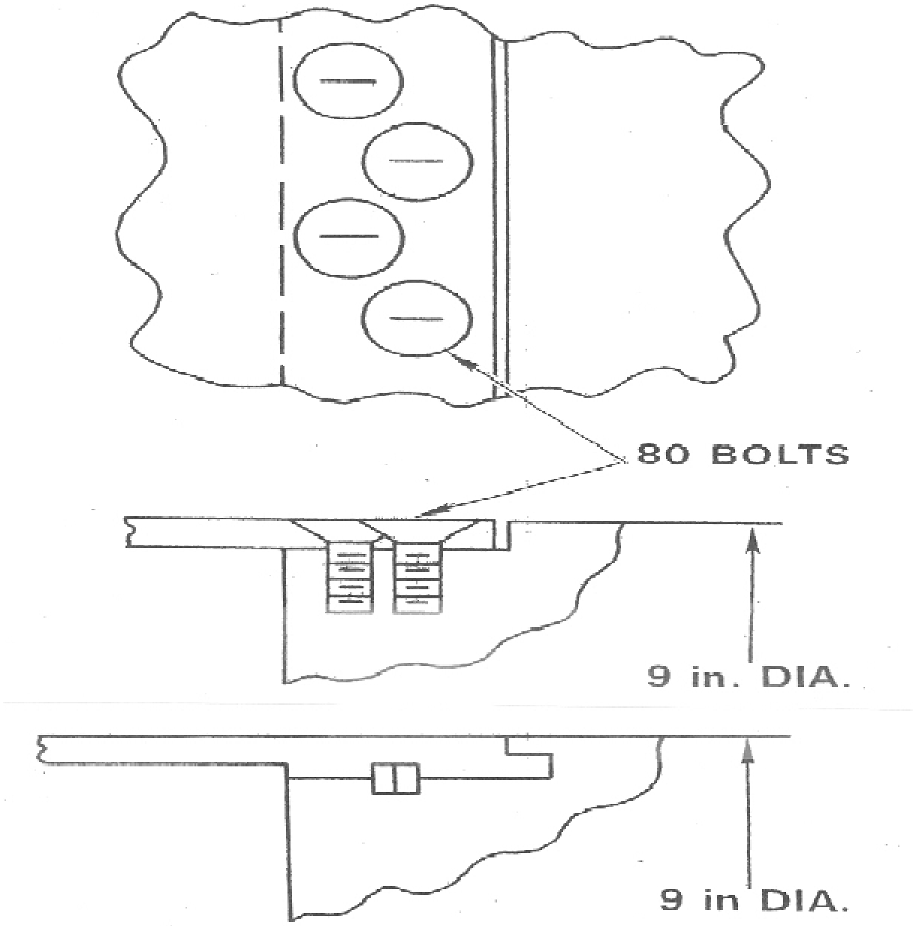

Figure 1D-2. Possible Typical Tape Joint

The simplicity of the Tape Joint can easily be seen. It offers ease of assembly, small relative size for the same load requirements, and potentially less cost to fabricate. The Alvis/Tape Joint and other commonly used joint designs will be discussed later in this report.

6. Mounting Plate Design Considerations

Figure 2A shows a mounting plate used in a compact mechanical subsystem. It is small compared to the weapon assembly, but it has some of the same design/fabrication concerns. It requires 60 machine operators to manufacture. Therefore, there are at least 60 possibilities for a machine operator to cause an error that results in rejection of the part. Allied Signal Co. reportedly manufactured this part, and it took about three years before a part was made without a single flaw. There are practical design lessons to be noted from the examples above that should be applied where practical.

- Design should require that all machining operations be done on one plane and on one side of the material. Changing the part orientation and setup during machining can add machine time and fabrication errors.
- Select the best material that is acceptable for machining and then review the design for possible stamping to obtain outer sides and contours, as a minimum. Usually, the outside is not as critical as the rest, and many parts with essentially the same tolerance can be produced from one die.
- Minimize machine operations of any one part. Possibly multiple assemblies could be used, and the risk of scrapping any one part could be reduced. Reducing any part loss would reduce cost.
- Do not design the part such that datums are machined away during manufacture. This complicates part inspection and acceptance, and increases the cost of the item.
- When requiring small holes to be drilled and threaded, as in this plate, attempt to keep the hole diameter to be drilled no less than one-half of the material thickness or depth. This can save a lot of drill bits from being broken during use and possibly ruining the part. This problem becomes more prevalent with smaller holes, and other methods of fabricating the holes need to be researched.

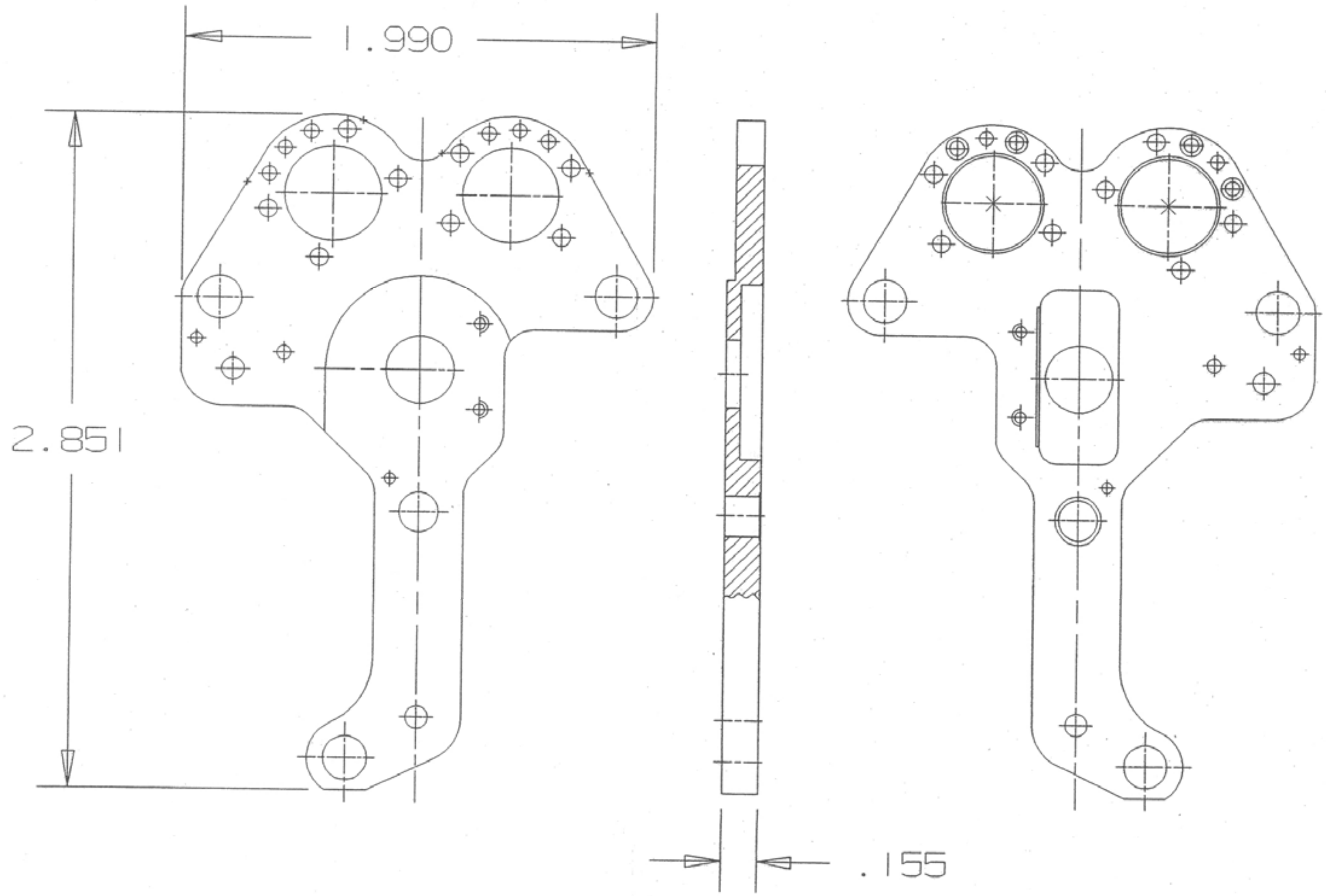

Figure 2A. Mounting Plate

- When dimensioning the part, use a minimum of datum points. Then use dimensions from these minimum datum points to each item. This will eliminate or at least diminish tolerance build up and acceptance testing time.
- The complexity of dimensioning can be found on Sandia Dwg. AY373613. Sides 1 and 2 of this part are shown in Figures 2B-1 and 2B-2.

The above items are good practices for any size part. They can guide you to the minimum production cost.

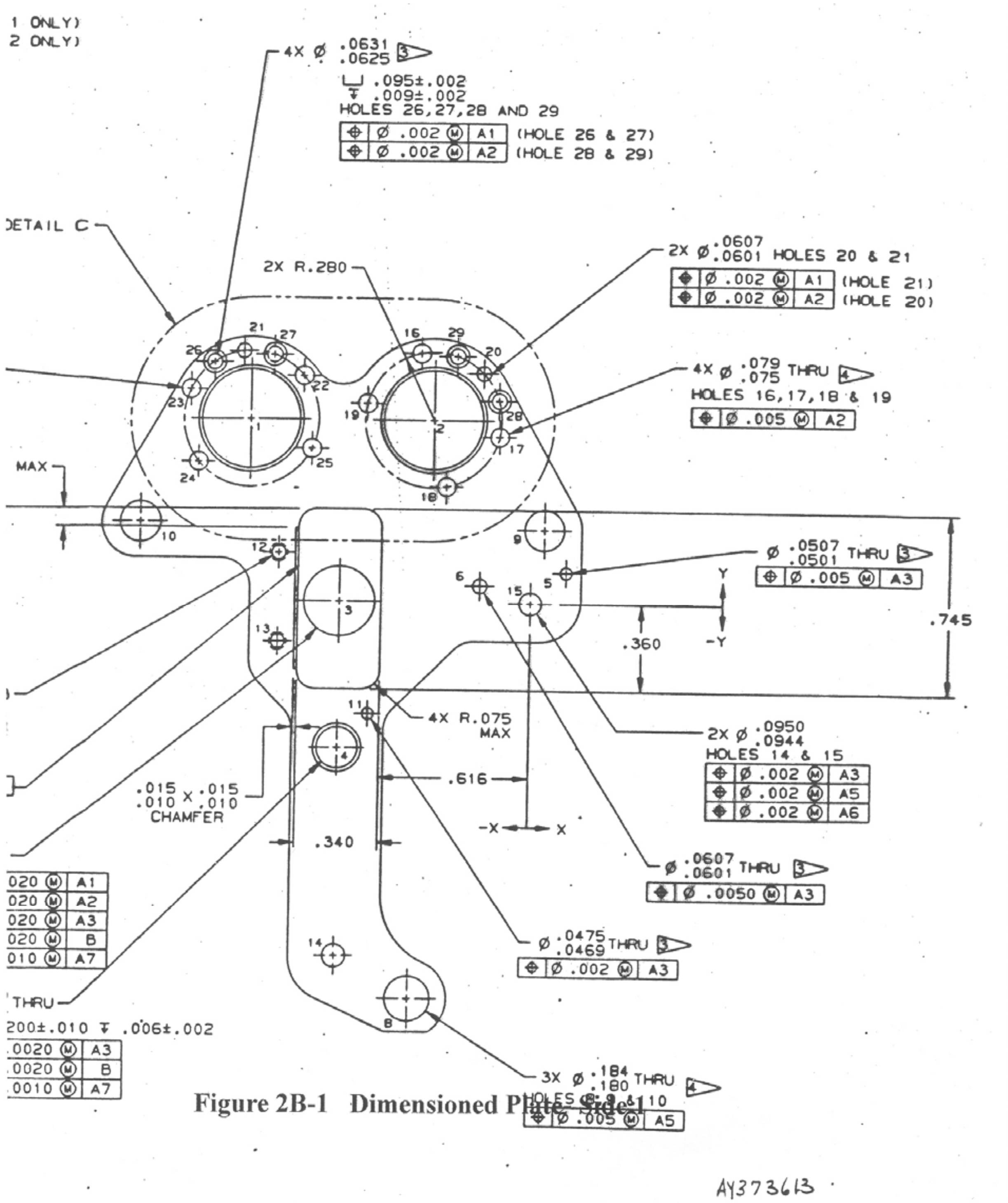

Figure 2B-1. Dimensioned Plate – Side 1

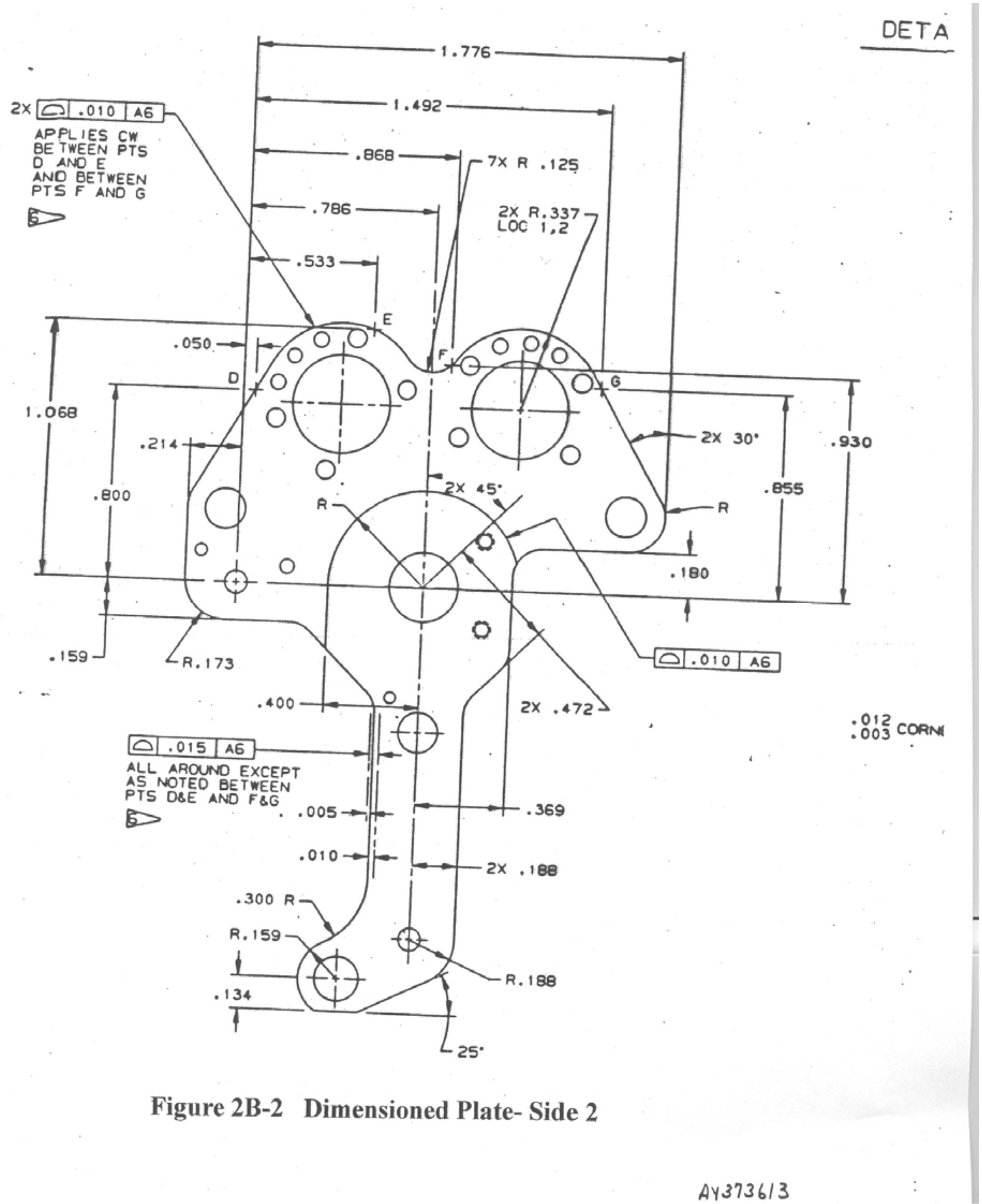

Figure 2B-2. Dimensioned Plate – Side 2

7. Joint/Attachment Considerations

Mechanical Joint Design Sealing Consideration

In joint designs, there are other mechanical considerations. Figure 3A shows three possibilities that may result in a bolted design as discussed above. First, for two cylinders to slide easily together at assembly, there must be a gap between them when assembled. This is the result of necessary tolerances of the two members. The worst-case dimension situation of assembly is when the parts are line-to-line. The CONCENTRIC ASSEMBLY, shown on the left side of Figure 3A, shows this gap as a band between the two concentric circles. It is exaggerated to make this point, but it will always be there for a noninterference fit.

The center view, BOLTS DEFORM STRUCTURE, exaggerates again what happens when the radial oriented bolts are torqued. The larger cylinder is considered to be structurally weaker than the inner one, just for this discussion. In reality, both inner and outer would be shown as scalloped in shape. The bolts pull the weaker member to the other member, creating large gaps between the adjacent bolts. If the design used an O-ring for sealing, it could present a sealing problem. It is my experience that if "something can happen, it probably will." Therefore, you can expect leaks to occur in these assembly designs. The sealing problem, as well as other system design concerns, can be exacerbated by the assembly process. This is shown by the figure on the right entitled NON-CONCENTRIC ASSEMBLY. If the assembler starts to torque the bolts on one side and continues around the assembly joint, the result will be as shown, plus there will be even larger scallops of the thin member. As a designer, you need to specify the assembly process. One can request that the torque process on the bolts be in a cross-star shape and only torque to small progressive amounts each time a torque sequence is made. This will tend to keep the members centered, but the assembly quality is now in the hands of the assembler. At best, it will result in a final condition as the center figure indicates.

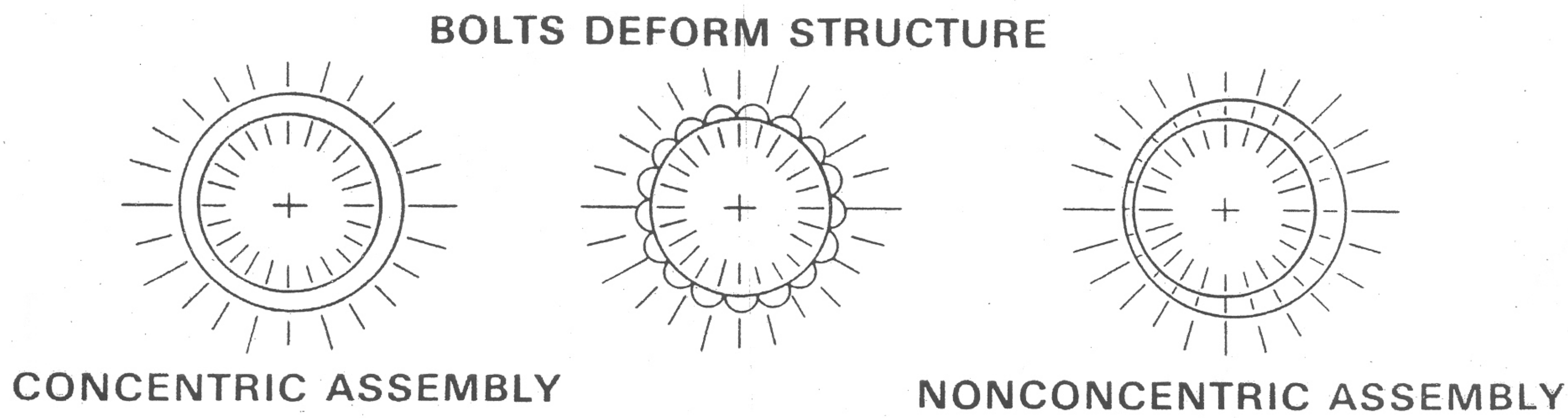

Figure 3A. Cylindrical Joint Assembly Configuration

8. Sealing Structural Sections of the Assembly by Membrane Technology

If joint sealing is a high priority in your design, you may want to consider sealing each section and not the total system. To have an efficient design, one should consider a membrane-type closure member, as it may be less weight and less expensive than sealing at the structural joint. This is, however, dependent upon the pressures that you must seal against. If the system only has to be sealed against normal atmosphere environments, then the overpressure of the system to the atmosphere will be small, say, a couple of atmospheres. Figure 3B shows how this has been designed for, and with just a little increase in weight, much higher pressure can be handled with relatively little added weight. The greater the pressure, the more efficient this design can become.

The higher system environment pressure must be on the concave side so that the seal cover membrane is always in tensile stress. The thickness of the membrane can be tapered by chemically machining to be compatible with the allowable stress at the outer radius of the seal. This process is not all that expensive if several units are being produced. The bolt size and number can be limited to a small number by adding a lip to the seal cover outer radius as shown. The bolt is mainly to hold the lip in its groove. It is best that the groove for the lip is continuous so that the groove can be fabricated like an O-ring groove. The lip takes all the load of the membrane. The bolt holes are into blind holes in order to preserve seal quality of the structure. Experience has shown this design to be superior to a flat plate bulkhead design. The seal, possibly an O-ring, must be inside the bolt circle location for a good seal. The groove and O-ring groove may be machined on the same setup as the lip groove, which also minimizes fabrication cost.

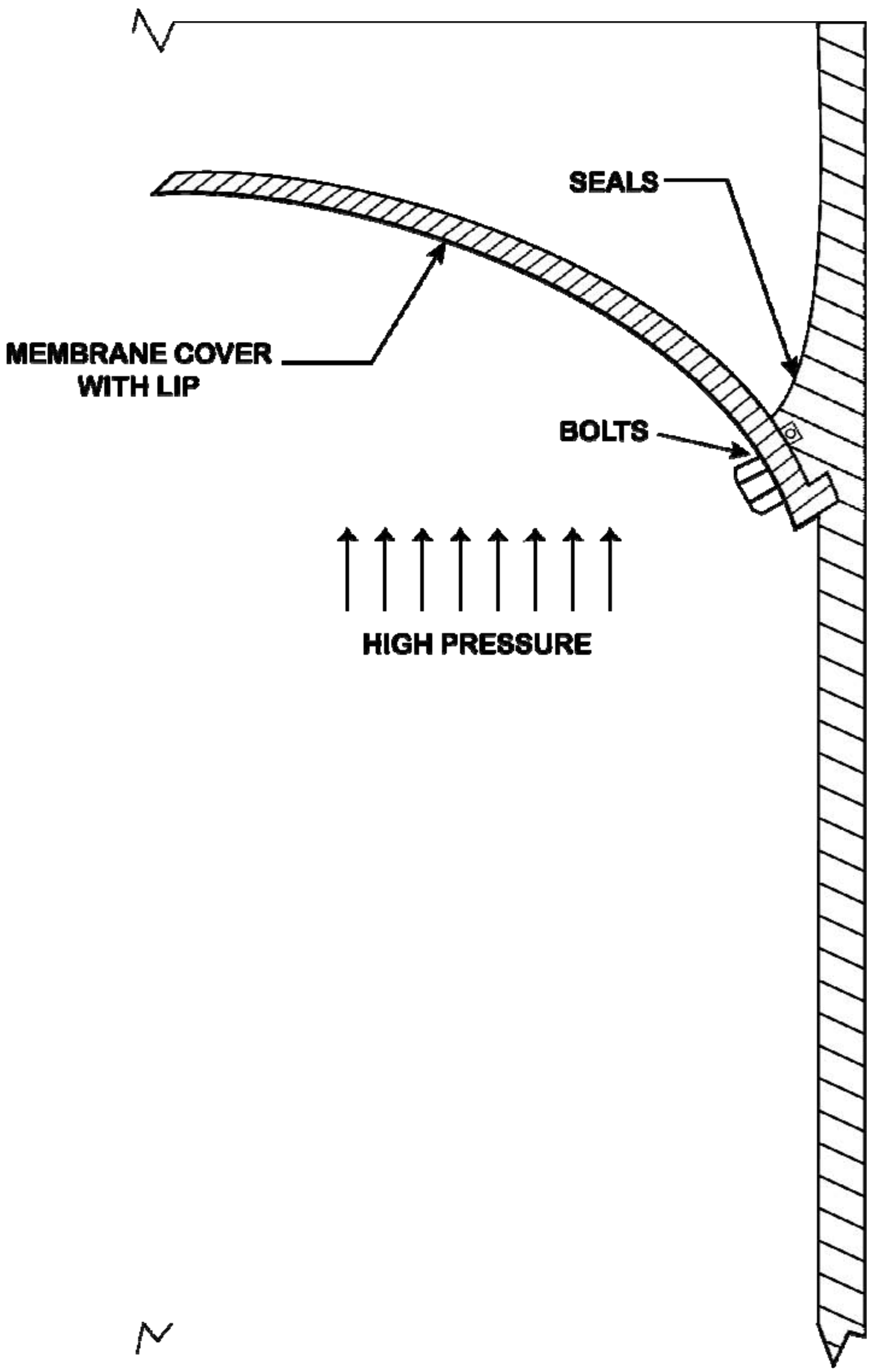

Figure 3B. Membrane Seal

9. Shortcomings of the Previously Discussed Designs

Problems Experienced

Joints that are made by bringing together the two cylindrical members by the use of radial row/rows of bolts will almost certainly result in a difficult joint to seal (such as that shown in Figure 1D). If the diameter of the two members is large, then the problem just gets larger. If the assembled system has to be true to the center line and/or be mechanically balanced about the center axis, the previous bolted joints exacerbate the problems. Bolts are only designed to be used in tension. So, for a structural member, one must torque the bolts to a high value for structural reasons, and this increases the seal problems because all the previous problem conditions will be larger.

The additional bolt design generates problems that may not have previously been considered. One is the number of repetitious processes and the probability of a serious risk in the manufacture. One bolt failure can cause a catastrophic failure as the bolts adjacent to the failed one can also fail due to the extra load placed upon them. Bolted assemblies fail like a zipper fails. Another type of failure can occur if high-temperature fluid or gas leaks past the seal during operation. This hot fluid or gas may cut the seal material and possibly result in a catastrophic failure. This is especially a concern on rocket propellant case seals.

Then there is the design consideration of assembly weight. If the system is to be shipped or flown, and most are, weight should be minimized. There are several other design options available, but most are bulky as described later. They have their place in systems, but not necessarily in ones that are flown and/or ones that must survive large structural deflections.

10. Solution to the Design Concerns – The Tape Joint Design

An improved joint design was needed for higher strength, lower weight, good structural stiffness, and improved sealing capability while under severe tensile, bending, and sealing capability. As stated earlier, necessity is the mother of invention. To solve some of these problems, it was recognized that some of the individual design problems already had solutions. It simply required putting them together in a complementary way. Figure 4A illustrates the thinking involved in developing the solution.

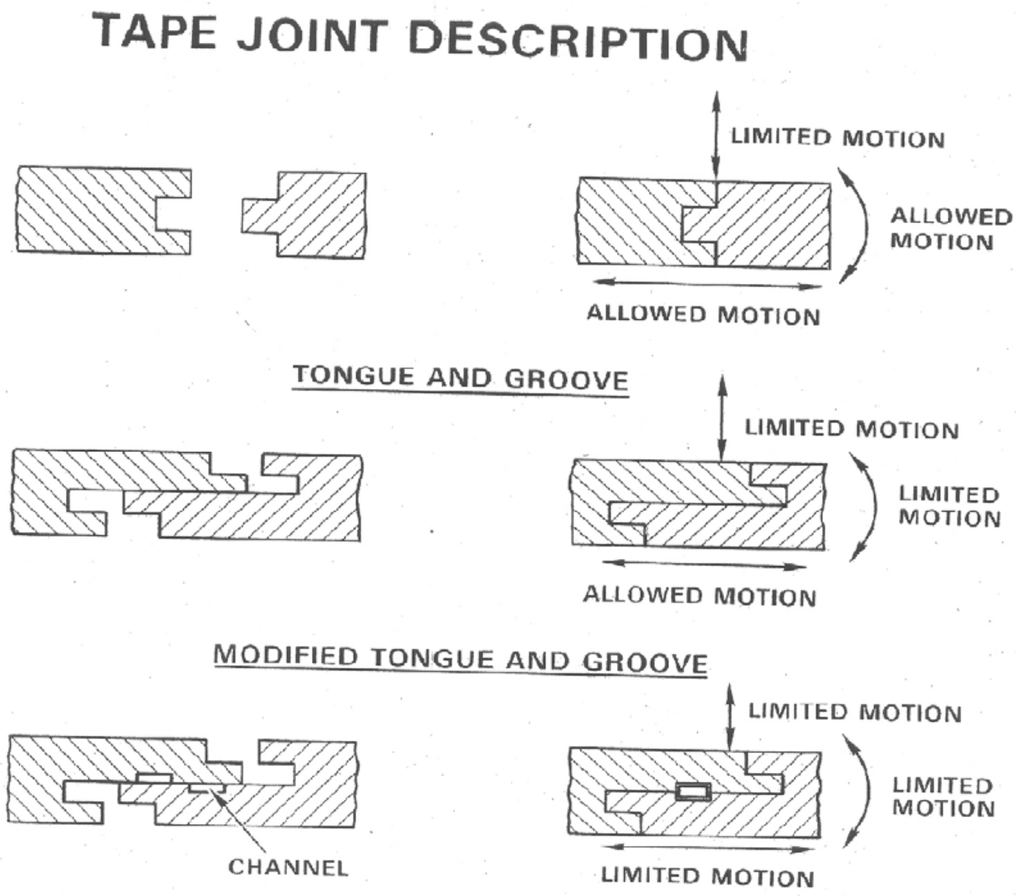

Figure 4A. Tape Joint Description

The top of Figure 4A shows how a tongue and groove joint, similar to some wooden boards, incorporates a mechanism that will maintain vertical relative alignment. When it is fully joined, it somewhat limits the relative movement adjacent to each member. The close fitting can also keep them in alignment with each other, even when being flexed or bent. Therefore, the tongue and groove concept needs some provision to keep it from pulling apart to provide tensile strength and prevent bending. To accomplish this, two tongue and grooves were developed as shown in the middle cross-section view. The result is that the joint can be very structurally stiff in bending. Still, it needs a method to keep the joint tightly pulled together. The bottom cross-section view indicated this was accomplished by adding a channel between the two tongue and groove members when the two members are joined. Approximately one-half of the groove is formed in each structural member as indicated. A small slot is formed in the side of the assembly, on the outside if the joint is cylindrical in shape.

Two wedge-shaped tapes that contain parallel outer sides and a matching taper on the inside are then placed into the channel through the slot. The wide end of one tape is inserted first into the channel assembly, followed by the second tape (narrow end first). As the second tape is inserted, the two tape assembly width grows due to the wedging action of the tapes. With the proper sizing of the tapes width to the channel, the wedge-shaped tapes will fill the channel in the structural axial direction. It is necessary that the outer and inner tape grooves be slightly offset to provide for manufacturing tolerances so that the load path of the tapes is always pulling the two members together, forming a tight joint. Due to the small angle of the wedge tapes, a slight assembly force or tap by a small hammer on the end of the tape is needed to set it in place, and will provide a strong, tight joint. This wedge angle should be small and should be much smaller than any bolt thread angle, and it will not come loose due to vibration or thermal cycling when the compatible materials are used. Therefore, no locking mechanism requirements have been found necessary.

Disassembly of the joint is both easy and quick. First, it aids the disassembly effort if no other loading than at assembly is present during this operation, such as a bending load on the structure. A notch may be added to the thick end of the tape that is inserted last. Hooking a tool to catch the notch makes it possible to pull it out by hand. Sometimes, a small tap on the tool will loosen the tape, making pulling it out easy. Any small amount of tape movement during the initial disassembly will result in a loose condition and easy joint disassembly. If the tape insertion hole needs to be made smooth, a cover can be used that is the same shape at the insertion hole and the same curvature as the outside surface. As the cover will be relatively small, only one small screw will be needed.

Adding a seal to this design is quite simple. A groove has already been added for the tape assemblies. In the same manufacturing operation, another groove can be inexpensively added to each structural member for the O-ring, or it can be added at the end of one of the tongues, similar to the one shown in Figure 4B. It is recommended that a groove be added for the O-ring in the structural member because dimensions on it can be more easily controlled than an O-ring at the end of one of the tongues. The seal must be placed between the tape insertion slot and the tongue side to be sealed.

Some Uses of the Tape Joint

The use of this joint is not limited to outer radii tape insertion types. One of the uses was for a tape insertion on the side of a membrane-like cover. Another is the cover shown in Figure 4B. The concept works just as well. Also, for inexpensive use, it has reportedly been used on plastic pool water filter containers with a V-type seal at the lip/cover end of the container, and only one tape or tube was used to hold the two members due to the very small angle of the wedges. These manufacturing techniques allow for cost savings. It has also been used to hold two very strong flat structural members together during both very high transient tensile and compressive loading.

The key advantage of the design is that the load is fully distributed by the continuous tape/groove, and the loading is in shear on the tapes and not in tensile as in bolts. Shear strength is strong and predictable to analyze. The wedge shape allows the two members to be pulled very tightly together. This joint design is very strong and structurally stiff in structure bending for its size. Large radial deformations have been shown not to damage the structural integrity or seal quality of this joint design. It has been used in several weapon systems, as well as in solar and commercial items. The first fabrication of the tapes was expensive, but Allied-Signal developed a fabrication technique that resulted in approximately 90% cost reduction. Both flat and cylindrical structural members are easy to fabricate, and it is easy to conduct acceptance measuring/testing on them.

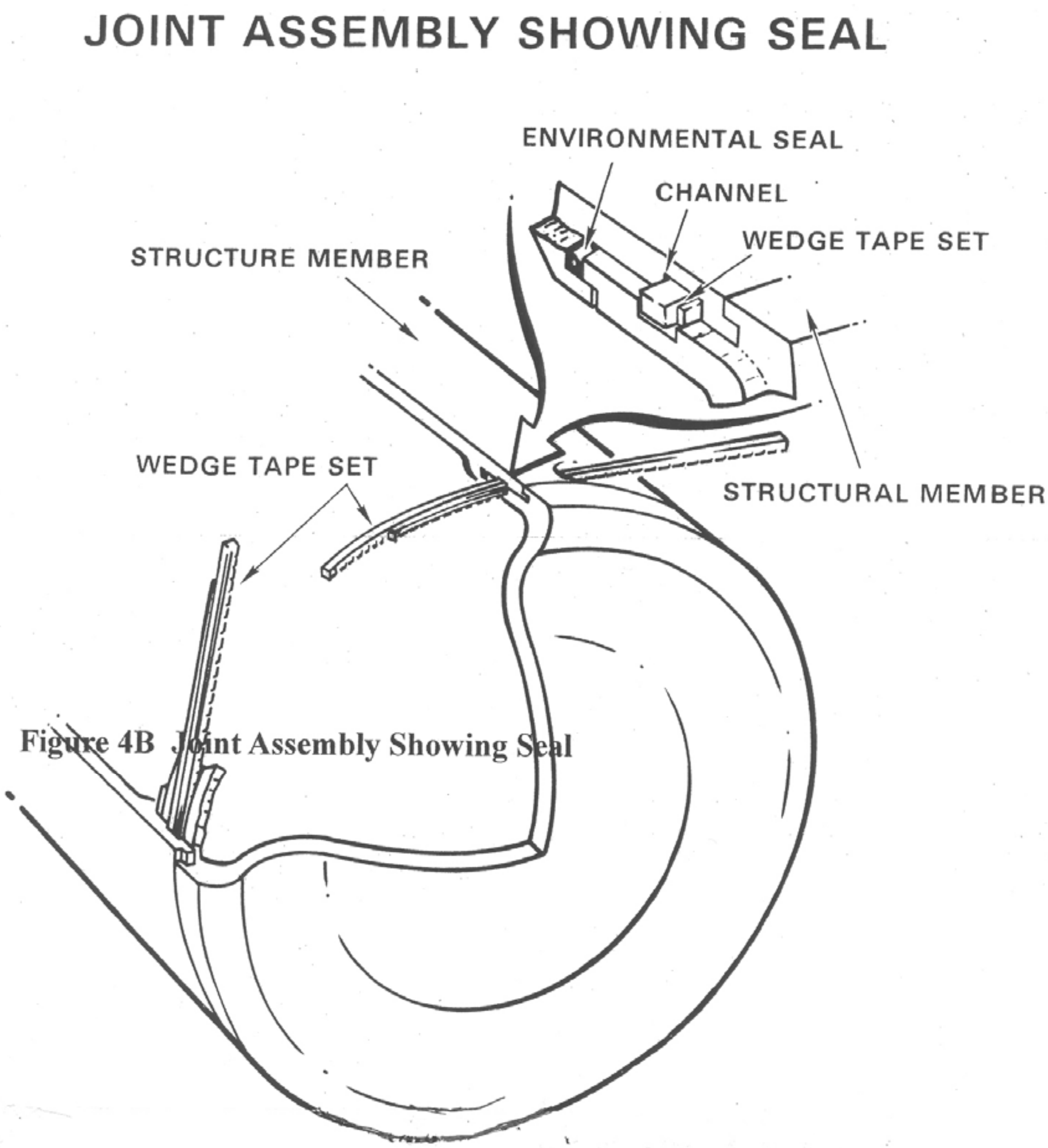

Figure 4B. Joint Assembly Showing Seal

Note that from Figure 4B, one can see that the tapes have slots in the inner radius side. This is necessary for assembly of fairly large metal tapes so that they will easily conform to the diameter of the groove. This even aids assembly for small tapes of, say, an eighth of an inch or less to prevent them from attempting to twist or buckle in the groove. Pre-forming the tapes to the diameter of the assembly will also assist in assembling it the first time. Reuse of the tapes, in general, is a satisfactory operation. The width of the slot and the number of slots will be determined from the radius of tape groove in the assembly members. For flat member assemblies, no slots are needed or desired. Radii are designed into the grooves to reduce stress concentration of the structure. The tape's outer edges are broken to prevent interference during assembly in the grooves because of the groove radii.

More information can be found on this joint design from the U.S. Patent Office for Patent #3600011. Design information concerning loading and stress concentrations of the design can be found in Sandia Laboratories Development Report No. SAND76-0166 and others from SNL's Technical Library.

11. Some "Lighter" Design Considerations

Special Bolts for Common Situations

Figure 5A shows a series of these special bolts. Their individual application is listed below each "cartoon." Most engineers, especially assembly people, have experienced each one of these in their careers, and at the time, these situations were probably not funny. They were not funny to me. Some have been experienced more times than we want to admit; the designer must always be on alert against their use. The source of these cartoons is unknown, but there are several similar versions available. Although the situation for the need of such bolts may occur, the attempt to use any one of them is not a good or practical solution.

Swing Design

Figure 5B-1 shows a simple swing design, which many fathers have constructed for their children. However, in this design, the easy fabrication/assembly approach was taken without regard to the functional ability. The swing, moving outward from the tree would be fine, but the inward swing travel would impact the tree trunk. The swing would probably survive, but the user would probably be hurt, or at least upset.

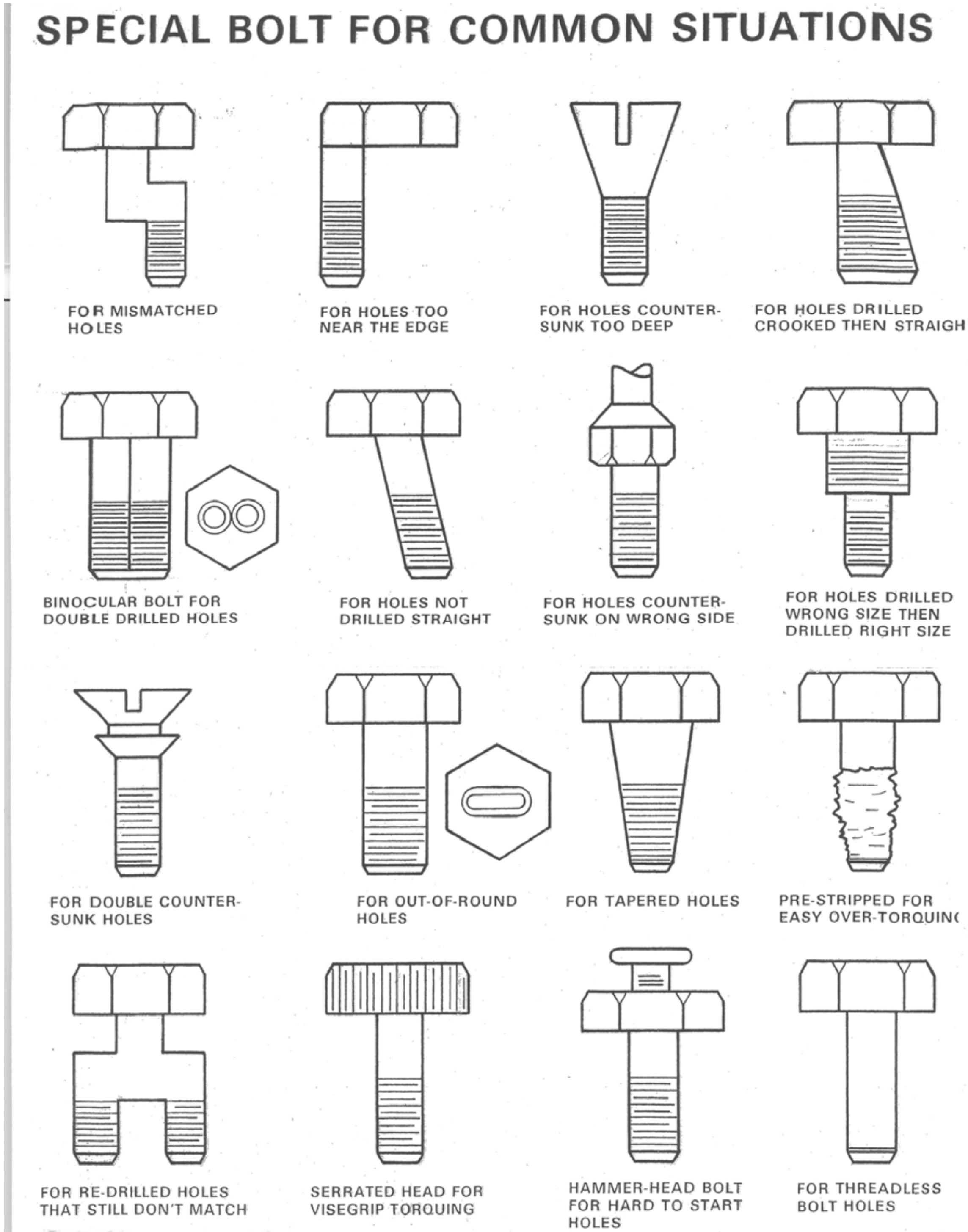

Figure 5A. Special Bolts

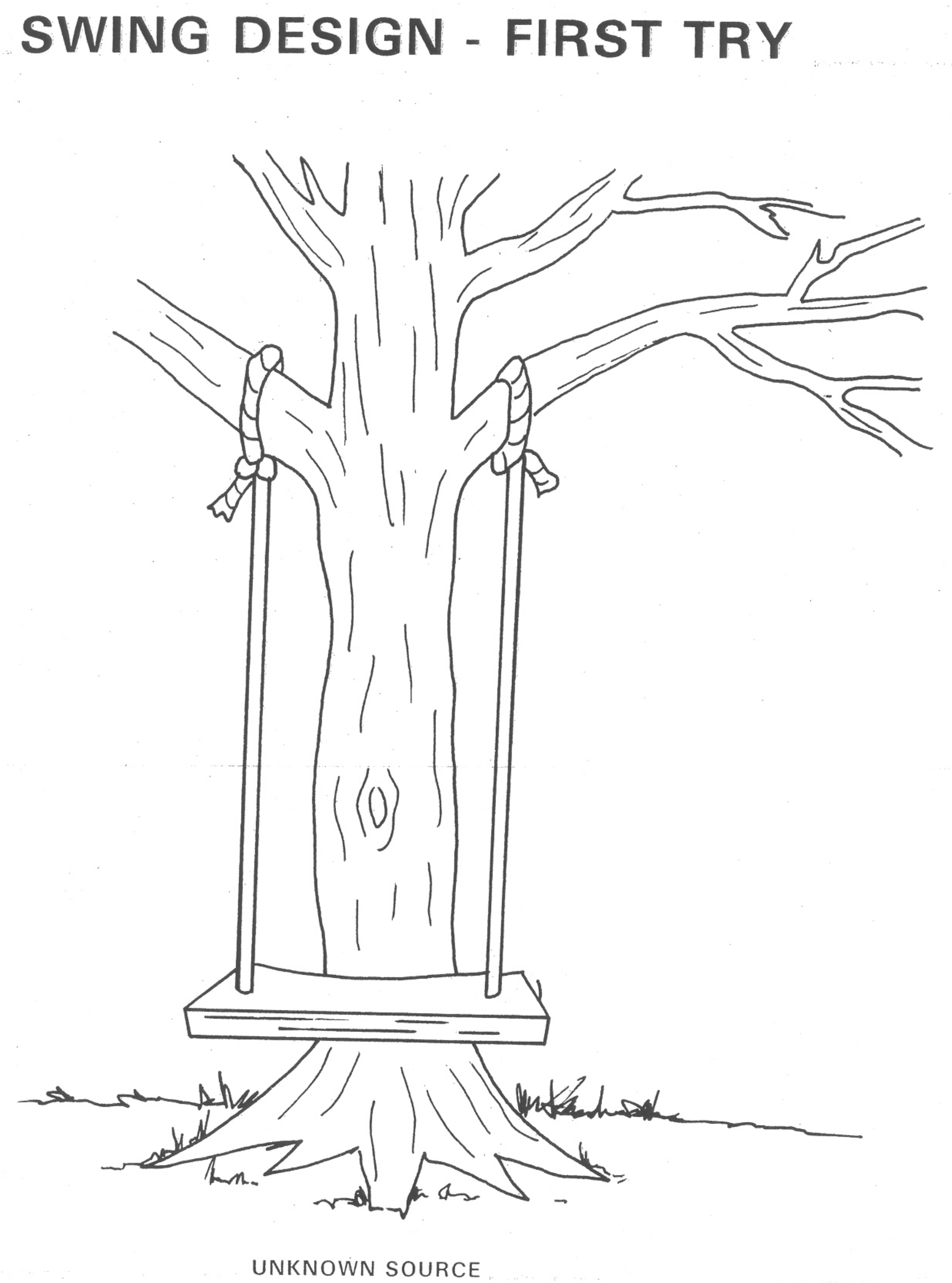

Figure 5B-1. Swing Design – First Try

Figure 5B-2 shows the redesign. It was easy to recognize that the tree trunk was the problem. So, one could remove the problem by cutting off the tree trunk. However, the consequences could be even more severe. First, the "fix" would kill the tree. Second, the supports for the tree are not reliable, and third, the tree and the supports could fall upon the user causing even more and possibly severe damage.

Now for the more serious side of these two "lighter side" designs. It is obvious that neither of these is considered good designs. But to an experienced designer, they immediately show that the designer is either inept or trying to do a minimal job on the design. His reputation is seriously damaged, and this damage could spread to his co-workers. Not a smart move! Designs should be open to review, and comment received should be seriously considered for improvement with the present and subsequent designs. Design reviews can serve as a teaching tool and technology transfer. Both of these are valuable to the organization's designers.

12. Other Joint Designs

Marmon Clamps

The Marmon clamp design has been commonly used for cylindrical structures for a number of years. Figure 6A shows a couple of cross sections of a Marmon clamp. The Marmon clamp is a modified V-clamp that uses two slanted surfaces to pull the joint structural members together. The members are forced to be concentric, usually by a small lip/tongue on the adjoining surface. The clamp must be a minimum of two pieces to enable assembly. The bolts tend to pull the members together, mainly at the clamp's slanted interfaces. Usually a hammer is used to tap the clamp to get it to seat uniformly around the whole structure flange. This design can provide high strength, but it is usually heavy and not as stiff as the tape joint due to the flange springing open during loading. It has been used in several of the older weapon systems and in many common pressure vessels where weight of the joint is not a prime consideration. When used in vibration and bending environments, special design and assembly care must be used to keep the joint from loosening due to friction wearing of the sloping contact surfaces, and it is not recommended for large radial deflections of the joint.

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SWING DESIGN - DESIGN FIX

SOURCE UNKNOWN

Figure 5B-2. Swing Design – Second Try

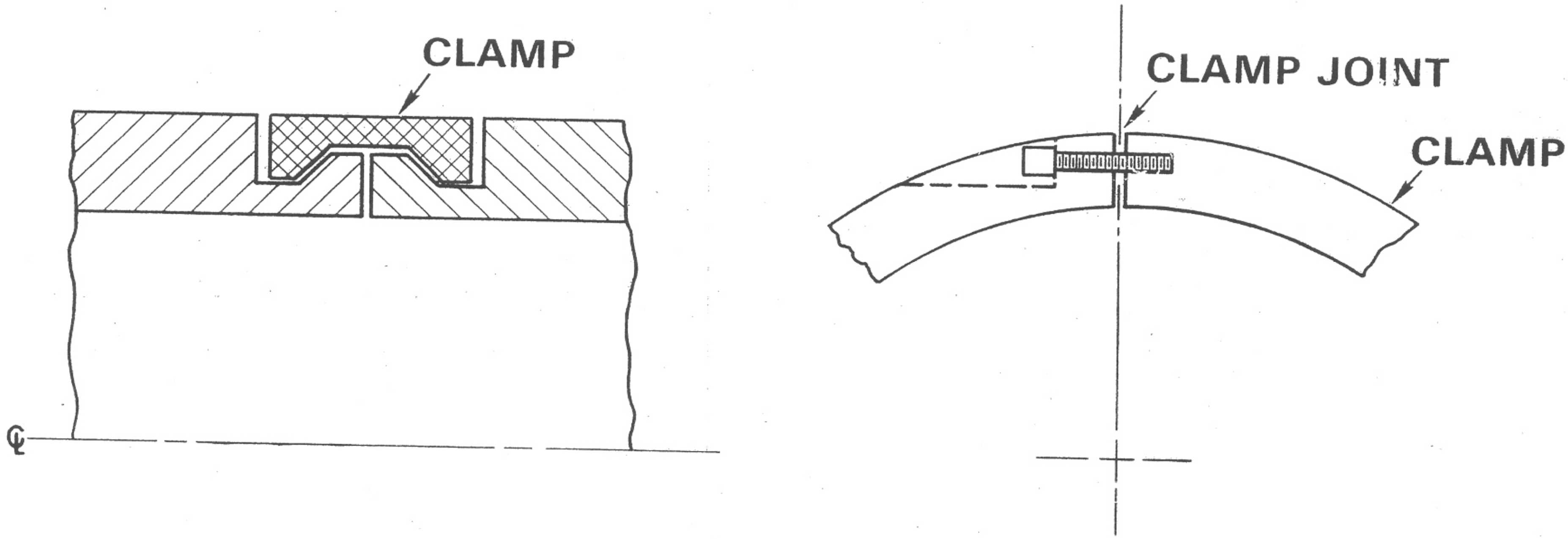

Figure 6A. MARMON Clamp Design

Hermetic Seal Design Approaches

A hermetically sealed flange joint is shown in Figure 6B. The design uses a butt weld to both seal and mechanically hold the two members together. It is my common experience that the flange and weld are designed so welds can be removed by machining and the two members reassembled a few additional times. The weld depth must be controlled so that a known amount of weld bead can be removed at each disassembly. In my experience, it was designed to be disassembled and reassembled two times after the first assembly.

Due to the load path, the design is not to be used for highly stressed structural members. Vibration environments or high loads can rapidly initiate cracks in the flange and/or weld. To prevent this, the flange design approach is best used for sheet or other light-weight assemblies and only for hermetic sealing requirements.

Cap/Plug Design Consideration

In designing a plug seal for a hole or tube, a good rule of thumb is to have the working pressure help make the seal better instead of defeating it. In Figure 6C, three possible approaches are presented. All have been observed in practice.

At the upper left is a cross-section of thin-walled tube with a plug inserted, either by threads, solder, or interference. The pressure to be contained is inside the tube. In a cross-section, it is easily seen that the pressure is acting to create a leak between the inner wall of the tube and the plug. This pressure can work against the seal, and failure is probable. Stress concentrations are in play and will significantly aid in fracturing or opening the seal to leak.

The center design is a better design in that it contains a hollowed plug that allows the plug to be forced by the inner pressure toward the tube’s inner wall and helping the sealing action. The problem is that it does not take much stress to propagate a crack in the seal area, and eventually it could cause seal failure. The tube wall and the plug mechanical thickness and strength are not usually the same, and a stress crack between them can develop.

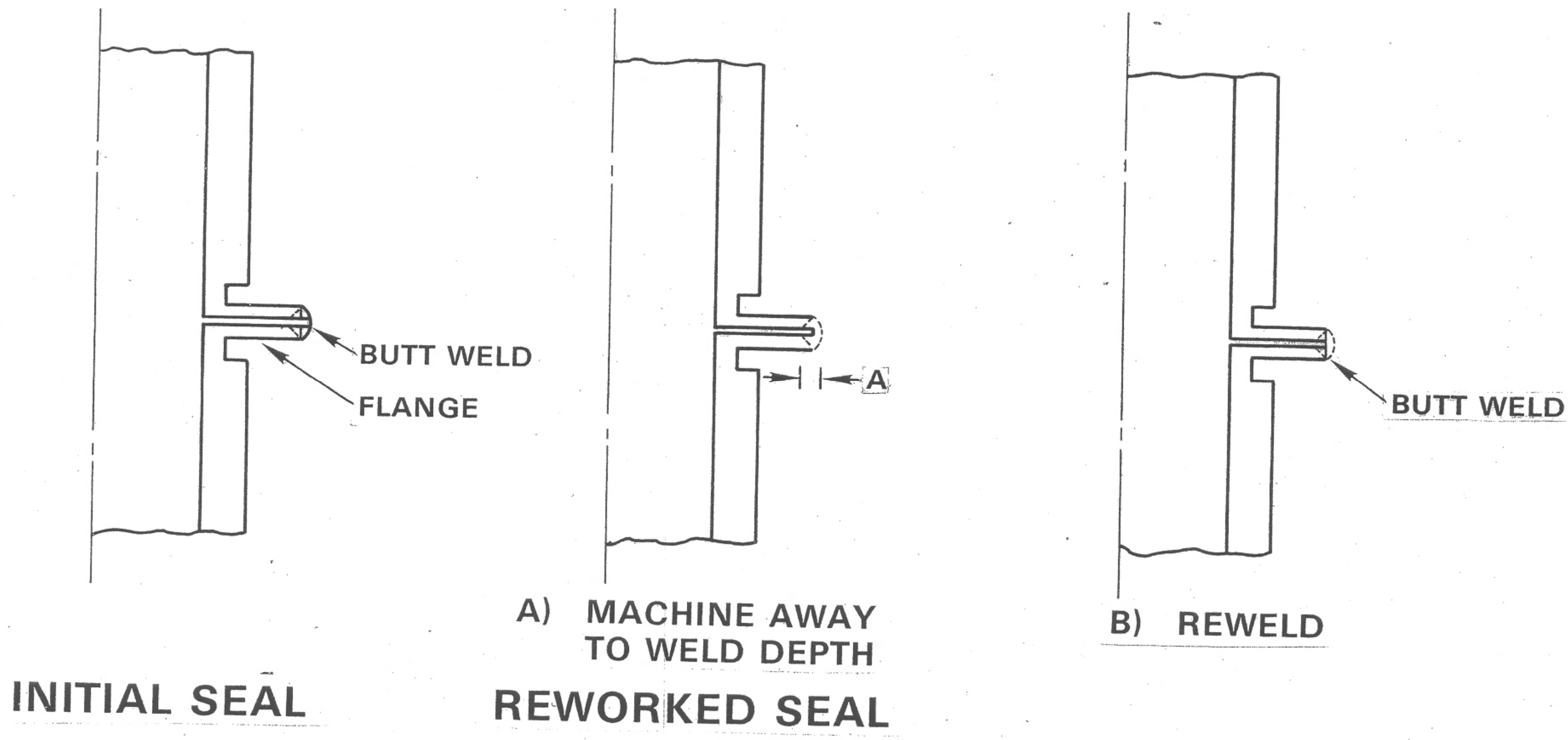

Figure 6B. Hermetic Seal Design Approach

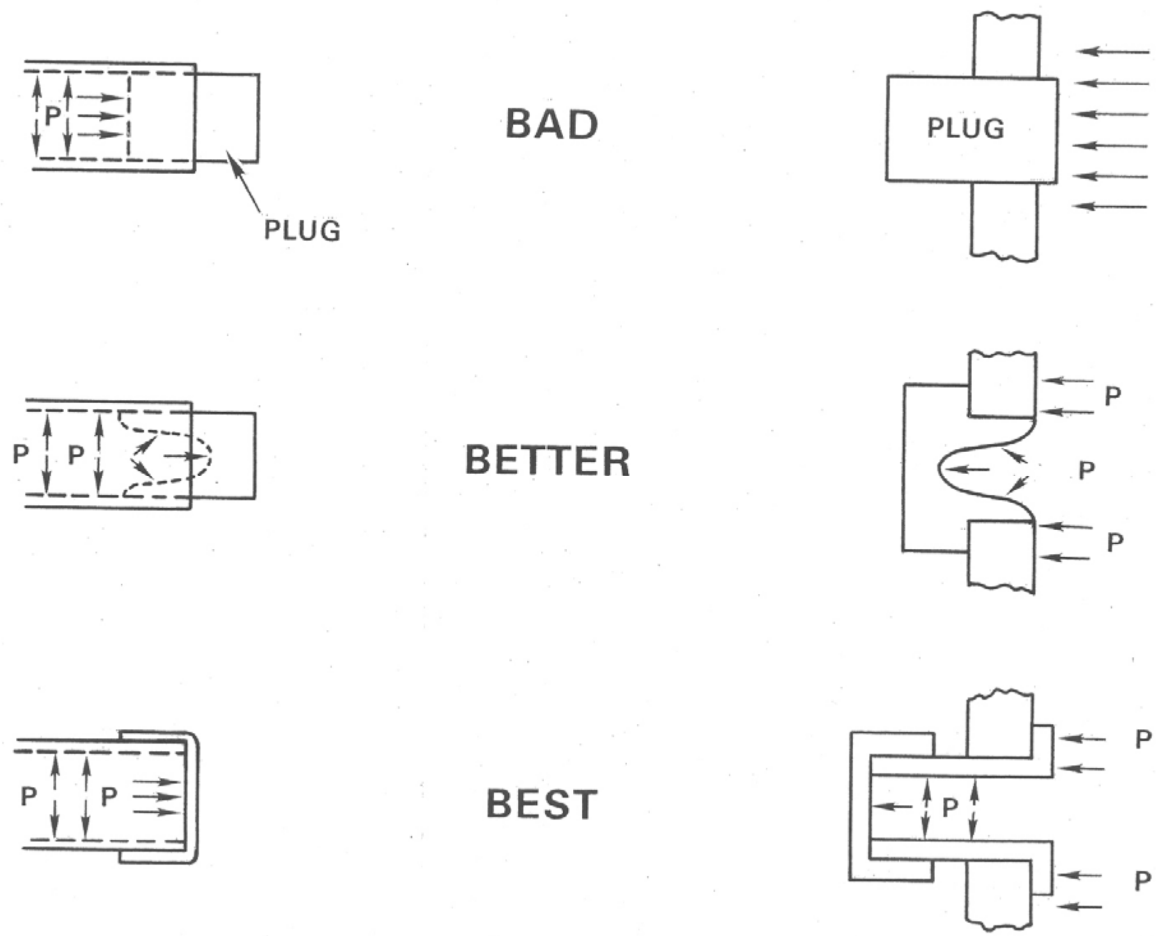

Figure 6C. Cap/Plug Design Consideration

The lower left cross-section shown is the best of the three design approaches. The cap surrounds the tube, and the internal pressure on the tube tends to improve the sealing quality. Either threads, solder, or brazing can be used. However, threads need a sealing compound to prevent them from leaking. The cap can be equal or thicker than the tube, as the tube is sufficient to hold the pressure and the cap just increases the joint pressure holding capability.

On the right side of this figure are some approaches for plugging a hole in a plate. At the top right is a plug essentially placed in a flat plate. The pressure force as shown will tend to flex the flat structural member. First, there is a sealing problem. A constant diameter plug must be threaded into place. Without a shoulder on the plug, the threaded plug will not tighten until it uses all the threaded area and seizes due to the unthreaded part. The flexure of the plate, depending on application and pressure, will eventually cause a leak.

A better design is shown at right-center of the figure. Like the tube the hollowed plug attempts to allow the pressure to help seal. However, the higher the pressure, the more flexure of the plate will occur. This can destroy the quality of the seal. Some improvements can be made for this approach. First, a backing plate could be added and welded to the backing plate around the hole. Second, the hole, with backing plate of proper thickness, can be threaded to accept a shouldered bolt. Third, a washer seal can be added to the bolt, just under the head on the bolt plug. This design with seal works well and is how most, if not all, drain plugs on a car engine oil pan are designed. One potential problem is that the plug can be over-torqued, and the thread either stripped or partially stripped. Do not allow anyone to use an impact wrench on this type of design because it will almost assuredly strip the threads. I have experienced this first hand, unfortunately, at my automotive dealership.

At the lower right side of the figure, the best solution is shown. A flanged tube is welded in place. This creates a good seal and reinforces the plate. Then apply a cap over the tube to take advantage of having the pressure work for you as in the best tube-capping approach. All of these designs must be protected by locating them in an orientation or place where they will not be inadvertently impacted by something that could crack or loosen them.

Seal/Structure Design Considerations in Bending

Figure 7 shows the exaggerated effect of bend moments on a sealed joint. The left side of the figure, a flange joint is shown in bending and pressure. First, the pressure will add to the assembly strain on the bolts and is a concern when the pressure becomes high. When this occurs, the seals will not be in the original quality state. Therefore, the flange and bolt design must take into account all loading so that the working pressure does not degrade the seal quality. Bending of the members does the same thing, with one side being loaded more than the opposite side. The design must account for these loads or design mountings for the pipes on each side of the flange to elevate this condition.

On the right side of Figure 7, a cross-section of a possible hydraulic cylinder is shown. The bending effects are exaggerated for observation of the results. The cylinder rod is usually solid in construction, but the bending is still possible. The concern is the loss of sealing ability of the cylinder. One could design in multiple seals, but the underlying problem is still there, both at the piston and the cylinder rod/cylinder interface.

The solution is to mount the cylinder on a mounting bracket and pins. This will prevent bend moments on the cylinder and rod assembly. A loose pin can be used in some applications, while others may need a tight-fitting assembly to remove any play/slack in the system control. On the rod, one can use tie-rod end designs to accomplish the minimum play. Both of these type mountings are commercially available. Let other types of guides be used to keep parts in alignment and prohibit any bending of the rod/cylinder.

Some Commercial Seal Designs Available

Figure 8 shows a cross-section of three types of O-ring seals. The bottom left shows a cross-section of a flat plate sealed assembly. These are a stationary type seal design. The open ring, commonly called a C-ring, in the top left of the page is made of metal or rubber-like material. The design allows the pressure of the fluid or gas to be sealed to aid in the sealing process. The metal requires, in general, a higher polished sealing surface. Metals have the capability of being used at high temperatures, but the surface finishes are critical.

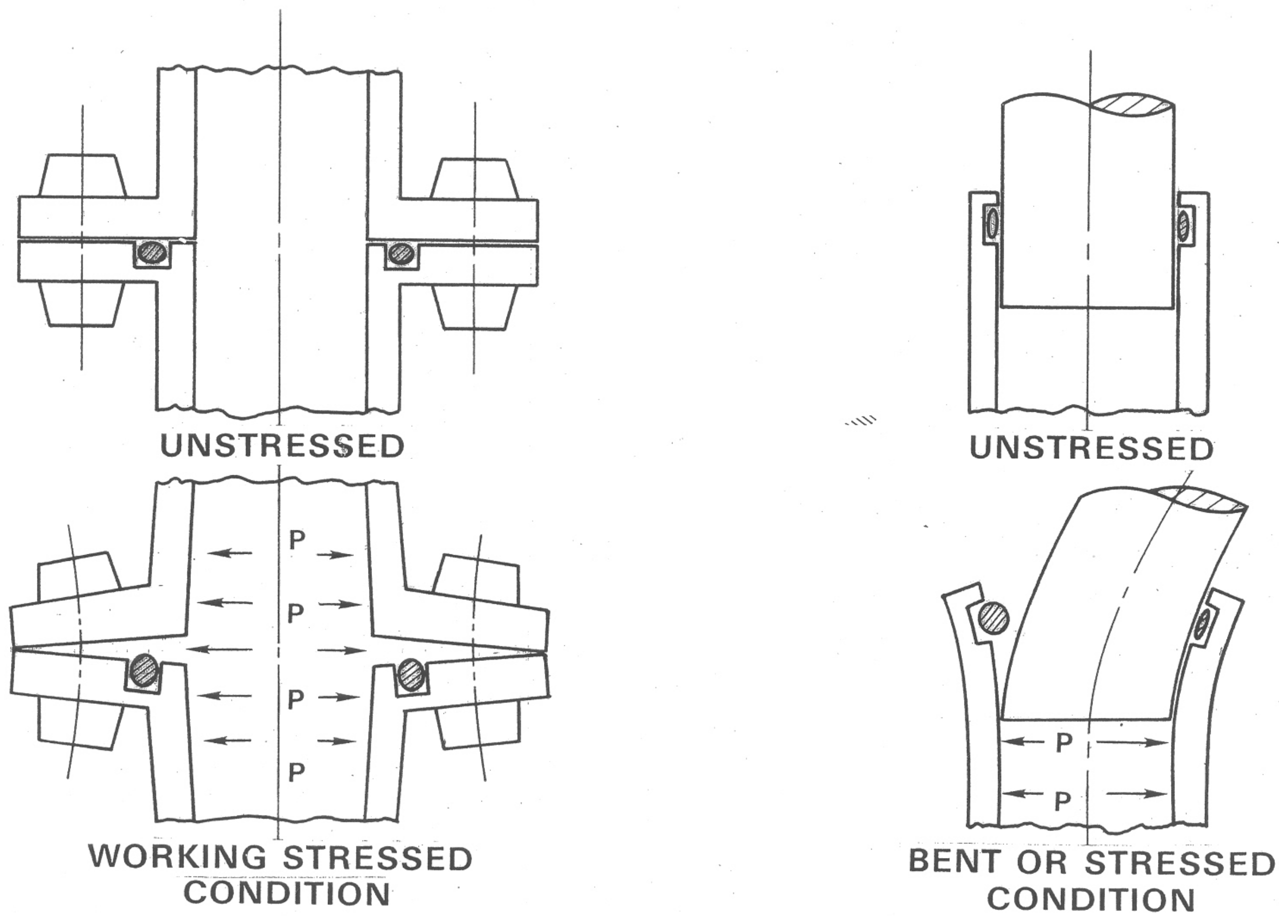

Figure 7. Seal/Structure Design Considerations

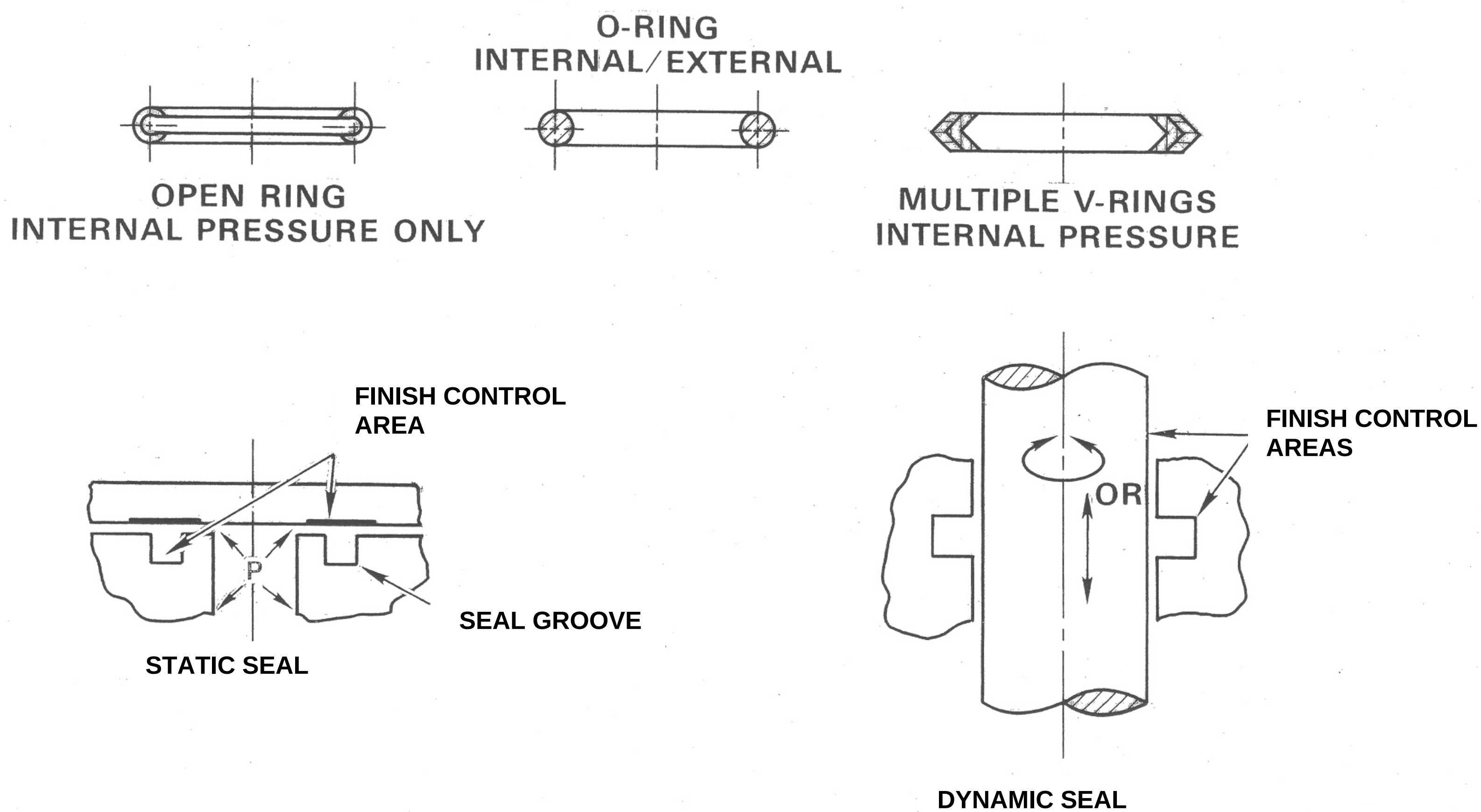

Figure 8. Environmental Seal Types and Design Approaches

The center O-ring, made of rubber or other pliable material, can be used both in stationary or dynamic sealing applications. They are commercially available in several different materials. Research the material that is best for your application. Each supplier, to my knowledge, will supply design information for its product. Many fluid suppliers also have recommendations for seal material use. This information has been tested for reliable use, and designers should avail themselves of this information. Hollow, rubber-like O-rings are available with vent holes to the inner radius. These act the same as a C-ring. However, the regular O-ring has met all my design requirements. A rule for all of these seals is that the cross-section area of the groove must be larger than the cross-section area of the seal. Do not try to use the seals at a higher pressure than recommended. For instance, rubber-type seals will extrude through the smallest crack at very high pressures. Some manufacturers recommend backing rings, etc., for high pressure use, but anything over 5K psi can result in problems. Also, reversible pressure on the seals is not good for long life because the seal is being moved in the groove by each change of pressure direction upon the seal. Multiple seals should be considered to take care of this potential problem. All seals require a smooth finish in the seal area to work properly. The sealing surface must be free of lint, hair, scratches, etc., to work properly. You must require this condition in your specifications for assembly.

V-rings are good for high-temperature use where metal is best suited. The sealing occurs at the edges of the Vs. They can, however, deform the seal surface, so rework of the seal surfaces is usually required after each disassembly, and a new V-ring should be installed.

The dynamic seal design potentially has more requirements. One is the reversing of the activating pressure. Another is that the sealing surface is large enough for the sliding cylinder rod and piston parts. Sometimes the environment is so severe that dust shields are needed to maintain a clean rod surface, while others may require a scraper ring on the moving part to prevent feeding grit, etc., into the primary seal and accelerating degradation of its sealing property. The figure shows the surface that needs good finishes for a seal. Make sure your design and assembly procedures include efforts to protect these surfaces.

The most likely result of joining two cylindrical structures with radial bolts is the nonconcentric joint. When applying moderate amounts of cross-bolt torque in sequence, this will usually be the result. Again, it has all the problems of the other two conditions, plus it creates a nonalignment of the two structures. These conditions show how a simple appearing structural joint can lead to design deficiencies. Flanges are added to many cylindrical structures to circumvent this problem. Other types of cylindrical joints exist, and some will be discussed later that can handle these joint problems better.

Bolts Are to be Used in Tension Only

Bolts are never to be used in shear. Rivets are normally used in this type application because the rivets completely fill the holes, as well as pull the two members together by the assembly process. Bolted joint load transfer is due to the friction between the bolted parts from the resulting compression force on the parts from the bolt tension. Bolts should not be located more than one bolt diameter from the edge of a part. If closer, the bolt may not be in pure tension, and in addition, the drill bit used to make the hole may tend to walk toward the edge of the material during fabrication. The bolt head should be loaded uniformly. If the hole is large with respect to the bolt head (not a good design), one can use a thicker washer under the head to distribute the load. If the bolt head hangs over an edge of the material part, it is a poor design. One thread of a bolt holds approximately 90% or more of the total load. However, it is good practice to use one bolt diameter of thread length in the nut. If the assembly is to be used in a high moisture environment, it is a good practice to have the bolt extended slightly through the nut, perhaps one thread thickness, so that a water reservoir in the nut is not created. Bolted joints tend to fail like a zipper. That is, when one bolt fails, and all are loaded approximately to the maximum, the adjacent bolts become overloaded, causing them to fail until all have failed.

Bolt thread tolerances are qualified in classes. A Class-1 thread has the largest tolerance and a Class-3 bolt and nut can go to zero line-to-line tolerance, or is commonly called a line-to-line fit. Be sure and specify the class fit you desire. If you do not, the part will usually be made to a 50% thread contact, and it may not give the strength that most manufacturers claim or that you require.

Some bolted assemblies may require retorque after a period of time. This can be the result of material creep. Titanium material should be reviewed carefully for necessary retorque. Always check the torque of an assembly, first, by adding more torque until the proper value is obtained or it tightens more, but not by loosening and re-torqueing. Titanium material is prone to creep in an exponential decay in stress. Make sure that the requirement of the design is less than the long term creep stress potential. If steel bolts, for instance, become loose, then they need to be reviewed for proper load, vibration, etc. If loose, the bolt is shear stress and probably will soon fail.

Threaded assemblies tend to cross-thread occasionally for several reasons. The oil field industry uses a square-tapered acme thread design for its drill bits and drill tubing because it is the least prone for this to occur. These assemblies are so heavy that a feel for the correct position of the coupling is out of the question. Large torque values are then applied for a satisfactory assembly. Many times this assembly is done when the two parts to be joined are not in line and possibly in a situation where one cannot even see the assembly. The treaded rotation direction is the same as in use, so in use the joint is naturally being tightened. For assembly of smaller bolts and nuts, it is common practice to turn the nut backwards on the bolt until one feels a slight detent and then turn the nut forward. It will usually start threading correctly. Do not force the nut to start on the bolt or apply large torque when running the nut to final location. If this occurs, remove the nut and inspect it for damage, etc. It could even be that the bolt or nut is not the correct number of threads per inch, or a burr has occurred on the threads.

Some ideas about bolts to keep in mind for better results: Slotted heads for blade-type drivers make it difficult to keep the driver from slipping. This wrench slippage can damage your assembly and/or can cause personal injury. Many bolt head designs are wrench self-centering and are commercially available to prevent slippage (Phillips, socket, hex, half-moon slot, etc.). Most of these are not designed for high torque.

When bolted assemblies become loose, shock-type loads are the normal cause, and the bolts are being loaded in shear mode. The bolt shank in this situation will begin to flatten due to the bolt and member hole edges hitting the bolt(s) and will raise the stress level in both the bolts and member holes. The more flattened it becomes, the weaker it will be, and failure will soon occur. As a minimum, if a loose assembly is detected, all bolts need to be replaced. My experience is that the loads were not properly selected, and a requirements review should be done.

13. <u>Environmental Seals and Common Practices</u>

Environmental seals are used in many component and system designs, mainly for manufacturing joints, access doors, and electrical feed-through. There are many different types of seals, and one should review the literature regarding the different types and their design guides (see Figure 8). Some are liquid until they chemically react and form a gasket. There are hollow metal C-shaped rings and hollow O-rings with communication to the gas or liquid they are attempting to seal, that use the pressure they are attempting to seal to give an added sealing force to the sealing surface. These are useful for some high pressure applications. The disadvantage for the metal O-ring is that sealing surfaces must be very smooth and clean when assembled. My experience is that it is usually difficult to get a good seal at the first assembly try. To aid in solving this problem, this C-ring could be made from a softer material if it will hold the pressure to be sealed. The metal design is only practical for sealing when the high pressure is always going to be on the inside radius of the seal and/or the working temperature is high.

The standard O-ring is shown in the center of the figure. It is usually made from a soft material, like a hydrocarbon material, butyl rubber, silicone rubber, or other plastic. They can be used up to approximately 5000 psi working pressure, but added care to design detail is required at the higher pressure to prevent O-ring material extrusion and failure. See the manufacturer's recommendation for design practices for applications at the higher pressures.

14. A Few Design Approaches to be Aware of

a) The O-ring groove cross-sectional area must be equal to or greater than the cross-section area of the O-ring. Solid rubber is incompressible (Poisons ratio is 0.5), and one does not mechanically tighten against rubber, as it will creep with time and degrade.

b) O-rings will move in the groove when under pressure. Only pressurize the assembly during leak test in the same direction as it will experience in use. Otherwise, the results may not be applicable.

c) Do not require the O-ring to be assembled over sharp edges. The sharp edges may cut or scratch the O-ring. This will almost always result in a leaky seal. Do not stretch the O-ring during assembly more than is absolutely necessary, as it may not regain its original configuration. Assembly tools, similar to the tools for putting rings on an engine piston, may be necessary to prevent O-ring damage during installation.

d) O-rings seal better if a lubricant is used during assembly. A fluorine hydrocarbon grease or silicone greases are commonly used. The selection will depend on the compatibility of all other materials being considered for the joint. The fluid or gas being sealed should be thoroughly considered for contamination.

e) Lubricate the O-ring by rolling it in the palm of your hand with the lubricant of choice. Never pull the O-ring between your index finger and thumb, for instance, as this will tend to stretch the O-ring.

f) Never reuse an O-ring. They may contain certain defects from the previous groove, such as inclusions or ridges. They are inexpensive to the point that you would not want to run the risk of them not working the first time it is used when the system is tested.

g) The multi-V-ring seals are a family of seals that uses the ring edges to create the seal. Some are arranged to allow the working pressure to aid in the sealing while others use the multiple rings for reliability. The material of these seals can be metal or plastic. V-rings allow the ring edges to bite into the surfaces to be sealed and are, therefore, one shot items. The plastic V-seals can be used over again if the sealing surfaces are hard and not damaged by use. Always, rework the sealing surfaces before reassembly.

15. Some Good Design Practices to Keep in Mind

a) Any scratch or foreign material must be removed from both the groove and the seal surfaces before assembly. A human hair can create a large leak, for example.
b) A lead pencil eraser can be used satisfactorily to remove many defects, such as small scratches, discolorations, hard to remove foreign material, etc., on the sealing surfaces. Rouges may .also be used, but the pencil eraser is usually handy and works quite well in most cases. After use, make sure the total sealing surface is thoroughly cleaned.

16. Design for Quality

The previous “light story” indicated a design approach and then a “fix,” which resulted in a dangerous and low quality design. These designs are usually easy to notice, even by the unexperienced people. However, some are not obvious until the design has been developed into a product or system.

Design quality and relative value of components are closely related. The engineer has the decision of how to partition system into subsystems to produce a satisfactory total design. As discussed in the bolted joint versus the tape joint design, each required manufacturing process and assembly has associated risks. Statistically, the greater the number of operations, the more probable it is that a defect will occur. See the example in Figure 9.

Some risks include a hole that is drilled in the wrong location and wrong direction and that is tapped with unacceptable threads and can be cross-thread at assembly. The higher risk of a defect should be assigned to the least expensive part. This will allow the least expense to rework for maintenance and often save scrapping the part. Consider an automobile engine block. The block is an expensive part due in part to the many operations required to manufacture it. The block is cast, surfaces machined, and then drilled and tapped for bolts to be inserted into it. The bolt “studs” are required to hold the engine head assembly tightly to the block and inlet and exhaust manifolds, to name a few. The holes can be drilled too deep into the block material and cause a coolant leak, and as they are blind holes, cuttings may not be thoroughly cleaned out of the blind hole after drilling and tapping, the threads may not be correct, and then it may be assembled wrong. However, this risky procedure has to be done only once during the life of the engine. The studs slide through clearance holes in the head and nuts on the protruding threaded part of the studs to secure the head and block together. These nuts can be removed several times without putting the block or head at risk of ruin. The studs may require replacement, but they are relatively inexpensive. The gasket seal between the head(s) should be replaced every time it is disassembled because they are relatively inexpensive. The studs also act as location guides for the gasket and head.

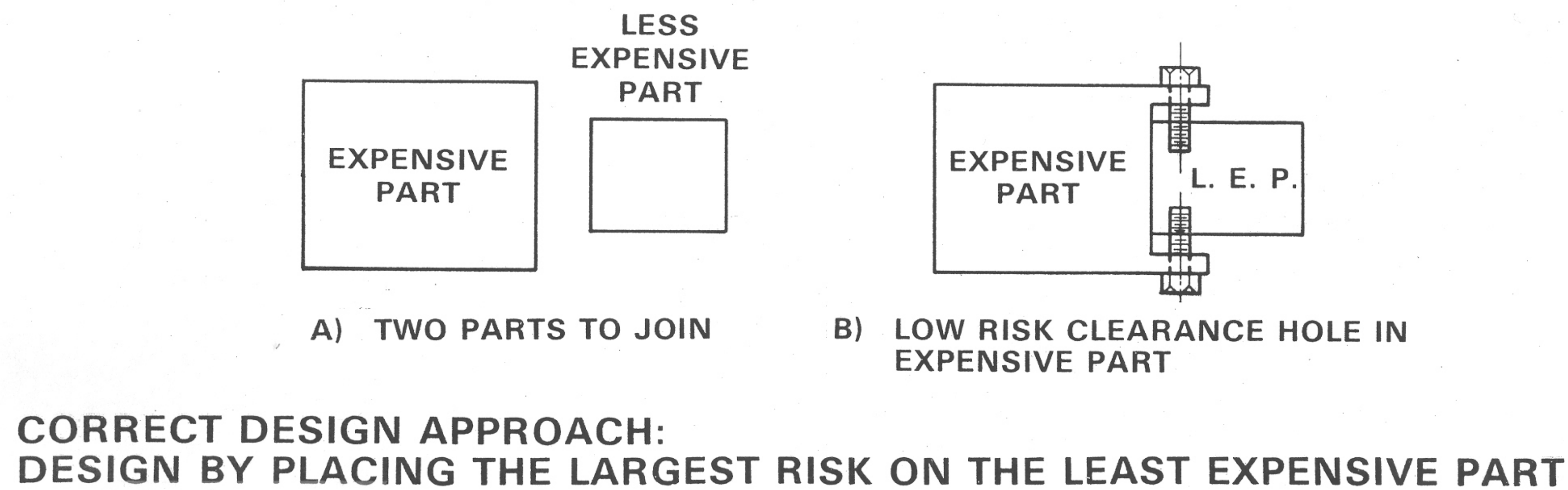

Figure 9. Relative Value Considerations in Design

As an example, several years ago, an American-made luxury car engine had the power steering pump assembled onto the engine crankshaft. One advantage of this design was, probably, to make the engine compartment less crowded. My experience has been that the engine is more reliable than the power steering pump, so the pump had to be replaced, possibly several times, during the life of the car engine. Where the pump was mounted added extra expense to the pump replacement. Therefore, this pump is now mounted as an accessory on the engine and is driven by a belt running off the crankshaft. The replacement is now simpler and less expensive. I know of no automobile engine that now has the pump on the crankshaft. The same can be said for the alternators, air pumps, water pumps, etc. This same risk assessment should be used, say, in mounting the accessories on or in a system. Brackets are designed to be attached to more expensive items with mounting clearances formed into them. The component is designed to have clearance holes with bosses on it so that the mounting bracket and component connect at the bosses. Then a bolt is assembled through the bracket or brackets and the component clearance hole or holes. The risk of assembly, removal, and possible reassembly is on the bolt and bolt nut. The bolt and nut are again the inexpensive parts and usually located where they can be easily accessed, which aids in obtaining a satisfactory assembly and inexpensive replacement.

17. Other Component Mounting Considerations

Figure 10 shows the mounting surface of a component. It has three bosses for mounting that contact with the next assembly part. Why three? From plane geometry, a plane is defined by three points. These three points will be the surfaces of the bosses. The bosses can be relatively easy to fabricate, and the surface location tolerances can be more easily fabricated and controlled, as they are small. The mating part needs to have matching surfaces.

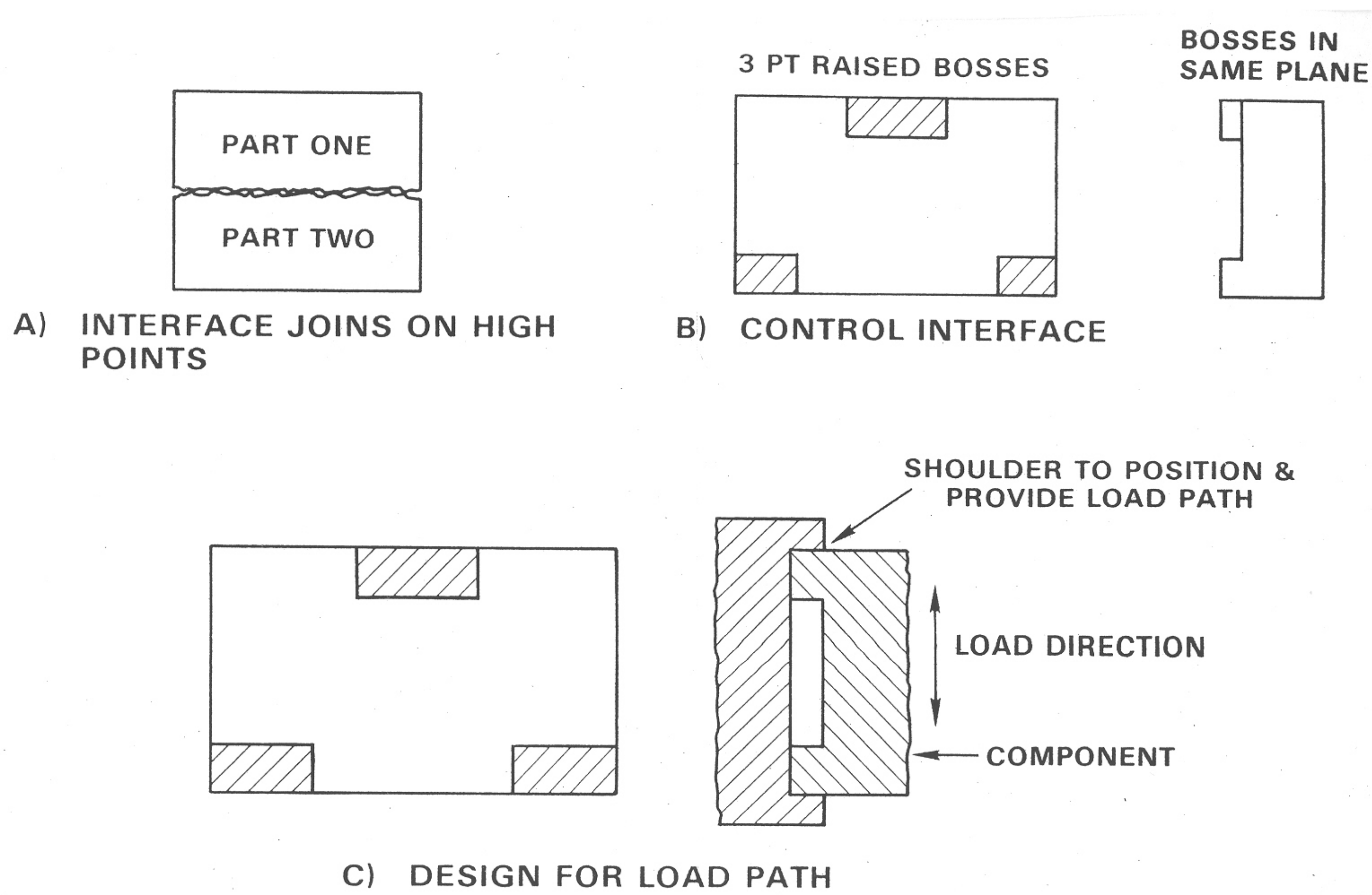

Figure 10. Component Mounting Design Considerations

The usual design approach is to make the whole mounting surface, say, flat, to a given tolerance. The mating surface, if it also has a flat surface, has a tolerance to contend with. The two tolerances will be approximately the sum of both services. If the parts are strongly joined, by bolts for example, the two mating parts will be bent over the three high points. This can cause stress to be induced into the parts which may be detrimental. Most designers, including myself, have been lax in looking at these stresses and their effects on the system.

In Summary

a) Contact mounting surfaces should be in one plane, if practical.
b) Contact surface, should be raised like a boss, to define the plain and minimize fabrication costs.
c) The interface bosses may require a lubricant, a gasket, or paint to perform as predicted in severe environments. The load path should be through the bosses in a manner that will not tend to become loose with time. Many materials creep or flow with time and may not function as desired.
d) From the above points, never allow a bolt to become loaded in shear. It will fail at much lower loads than calculated for a well-tensioned bolt assembly.
e) Nonsymmetric assemblies, or bosses, can force correct assembly of a unit. This will be discussed in detail later.
f) When alignment or positioning is critical, use roll-pins, instead of solid dowel pins, in locating holes. Possible inertial welding of axial components like rotating shafts at high speed, etc., can be satisfactorily applied and the alignment preserved.
g) A cone in a cone is an excellent approach to axially align two radial members. Remember the Morris Taper angle discussion? The centering process is more accurate, the smaller the angle of the joint. If the taper angle is smaller than, say, a Morris taper angle, disassembly may be extremely difficult.
h) For instance, alignment for two long shafts can be done by holding them in a lathe-type setup that can result in a near perfect alignment. Then, by using one member to spin the drive head, introduce friction heating until the proper amount of energy is introduced at the joining of the parts to result in inertial welding. The second part is held by the lathe stock. The alignment will be preserved if the two parts are allowed to cool before removing them from the welding setup. The result will be as accurate as the lathe capability, which is usually very good. This method can and has been used in the manufacture of many turbines, engines, and/or super-chargers. See Figure 11 for a description of the concepts.

18. Seal Considerations

Most of the component and system designs require some type of environmental sealing. One either seals something inside or seals something from the outside from getting into the protected volume. Seals fall into two categories, dynamic or static. This discussion is mainly limited to static sealing. Many system designs require static seals to maintain their system quality for a period of years. This requires exacting material property control for both material compatibility and seal function preservation. That is, a seal material must not creep or take a “set” with time. Many seals contain hydrocarbon materials, and these allow moisture to diffuse through them. This diffusion rate may be small, but can be unacceptable for your design requirements. The diffusion rate of flow of water, through material selection, can be controlled to a satisfactory rate of, say, 5X10E-5 cc/s@stp. Remember, one is dealing with partial pressures of the gas, both inside and outside the volume of interest. If this is slightly too large a diffusion rate, then some sort of desiccant can be added to absorb diffused moisture into the control volume for the required period of interest. The amount of desiccant must be sized to the amount of absorption needed, the volume under consideration, and the time of seal requirement.

A fellow Sandian, Bob Grover, stated that the only hermetic seal was a welded one. I believe he was right. His first employment after receiving his B.S.M.E degree was for a refrigeration manufacturer. The manufacturer lead engineer was also the plant owner, and he would not allow any design that did not have welded seals. As you know, these systems now run for years without problems. Moisture in them can cause corrosion, and foreign products and other foreign material in the fluid can ultimately lead to pump/motor failure. Assemblies have moisture in them during assembly from the atmospheric air and the components used in the assembly. This is commonly removed by pulling a vacuum on the volume for a period of time, usually hours. This long period is usually necessary because some materials absorb moisture and/or has material that outgases from some of their manufacturing, or material processes. After this pump down period, the pump can be shut off and the pressure monitored. If the pressure rises, you did not get all the water out, the material out-gassing was not complete, and/or the system has a leak that must be repaired.

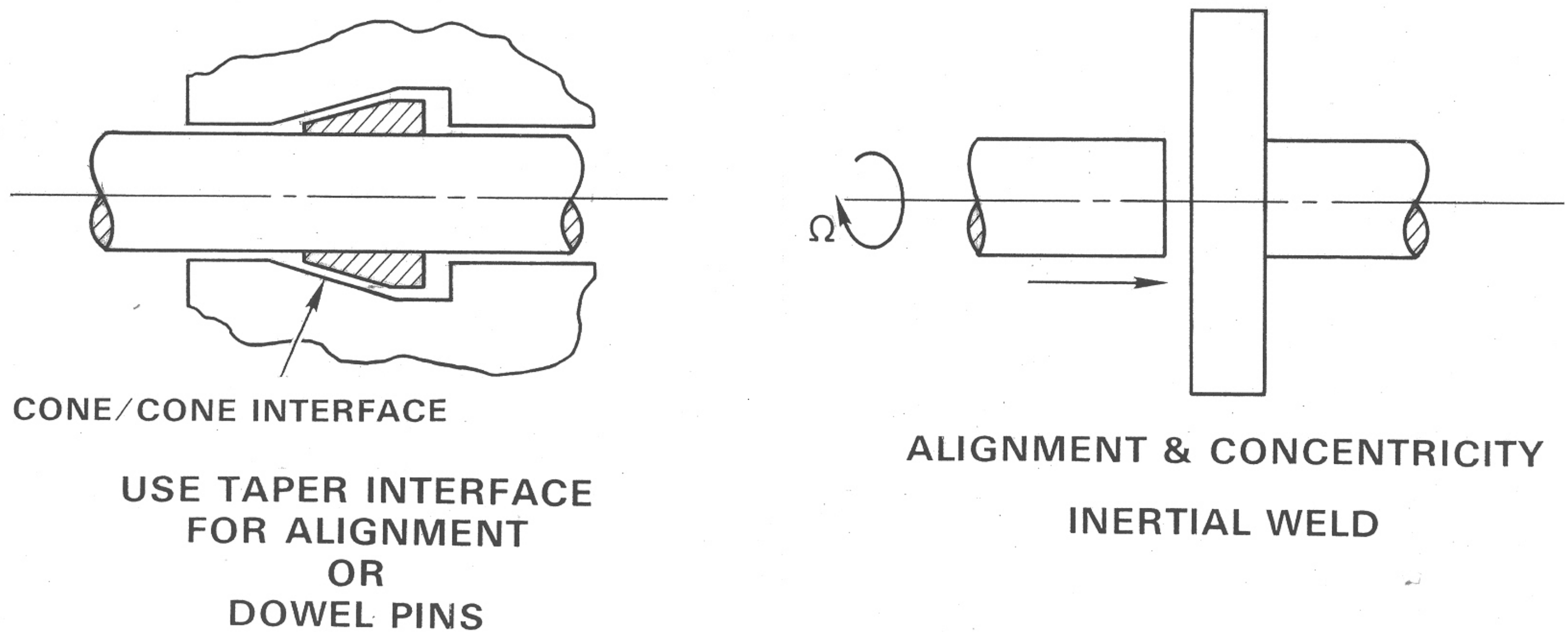

Figure 11. Precision Alignment

Once the leak test and pump down are satisfactorily completed, then you may want to introduce an inert gas, like dry nitrogen or some other inert gas, into the volume. To do this procedure, you need a communication tube going into the sealed volume. This is commonly done by inserting a tube through the volume wall. The design and manufacture is usually done early in the manufacturing and not at assembly time. I suggest looking at the different methods of doing this for a good seal. I prefer the tube with a flange backing plate welded on one end. Make a hole in the part to be used for getting the communication done, insert the tube end through the hole, and weld the backing flange to the inside of the part. Just for insurance, I would also recommend welding the tube to the outside of the feed through part as well, when practical.

The pump can be attached in several ways to this tube, but leave enough tube length to do the following procedure several times, depending upon your requirements. At the desired length from the sealed part, when all requirements have been satisfied with regard to pump down, leak, and gas insertion, squeeze the tube with a proper tool to flatten it near the final extended length and weld it together by the squeezing force. Then cut off the tube on the pump side of the squeezed seal and weld the butt end of the flattened tube. You do not want to use a “Schrader” type valve or other type valves because they have a high risk of leaking over long periods and will probably cost you more than a welded tube to install. This leak is usually the result of the valve seal material used internally.

When a rework of the sealed volume is necessary, or any other physical opening of this volume, repeat the above procedure by cutting off the communication tube, which is above the squeezed area. In reassembly, repeat the above process again. Make sure the desiccant, if used, is replaced with new desiccant material. In general, I designed them for two additional seals after the first assembly. You may require more. If so, the tube may become long compared to its structural properties. In this case, you may be required to add a mounting bracket to this tube to limit vibration, bending, or other undesirable qualities.

19. <u>Some General Seal/Structure Design Considerations</u>

Structure materials are elastic in nature. When the working forces are applied, they will assume a different shape. Most of the time this change is so small it is of little concern. Some of these changes in shape can affect the seal design and performance. When bending stress is added to the working fluid force, this can tend to negate the seal. For instance, this is a reason that hydraulic motion cylinders should always be pinned on the rod and cylinder ends. The pins can move/rotate to prevent this bending load from the cylinder/rod. If play in the mounting is unacceptable in the system, then one should use “tie rod end” type mounting, which will result in a tight system and maintain the required operating strength.

The assembly of the structures, by a series of bolts around the circumference, will result in a scalloped-shaped assembly near the bolts. A seal like an O-ring will be smashed in one area and loose in another. Even though the bolts are tightened to the proper amount, a less than optimum seal will result. This becomes extremely important for a large cylindrical pressure tank, such as those used on large rockets. A design feature to hold the two cylinders concentric and together with a uniform seal compression is necessary to assure the desired joint function. A groove on one member that allows the other member to bite into it, like a tongue and groove, will usually work well.

20. ome Approaches for Good Designs

a) For thermal-cycled systems, use the same structural material in approximately the same thickness so that everything will expand and shrink approximately the same and the design quality is preserved.
b) Seals that use edge sealing are good for thermal cycled due to the springing ability of the seal shape. Be cautious of the “freeze” temperature of “rubber-type O-ring materials”. It must be lower than the operating or storage temperatures.
c) “Swageloks”-type connections on thin walled metal tubing have worked well, but be aware of vibration near the connection.
d) Simple bent continuous tube lines with minimum couples/fittings are preferred to complex ones that may require additional couplings and bends.
e) Long, skinny assemblies can buckle due to vibration and/or resulting torque at assembly.
f) Torsion shafts are usually hollow, as they are light in weight and are strong due to the major stress near the outer diameter shaft material.
g) Design requirements, including design margin, must be clearly defined before conducting the design effort to maximize the total system efficiency and to minimize expenses.
h) The design function must be measurable and predictable. Otherwise an R&D effort will be needed.
i) Be sensitive to fatigue and creep possibilities that may enter into your requirements. Be especially sensitive if you are using titanium or titanium-like materials.
j) Minimize use of friction in the load path. That is, keep the number of joints and members to a minimum.

k) Structural attachments should result in in-plane stresses. That is, refrain from adding torsion stresses to a bending stress member. If the member is in compression, this can aid in the buckling of the member and early failure.

l) Joined materials should be compatible to prevent corrosion. Chlorine in a few parts per million will corrode carbon steel in the presence of moisture. The sources can be fingerprints, forging coolant, electrolytes, etc. Do not use aluminum to carbon steel or even aluminum in the ground, as dirt usually has some moisture and iron in it. Even some stainless steels will corrode. Some corrosive stainless steels can be made noncorrosive at their surface by etching the exposed surface with an acid to remove the corrodable surface iron, usually to a small depth. Especially, do this if the stainless steel is less than 16% nickel content.

m) Allowance for differential expansion should be allowed. Be aware of close fitting cylinders within cylinders of different material or triangle-shaped structures incorporating different materials or the same materials that experience different temperatures.

n) Welded joints should be used with caution. Welding can create both stress concentration and undesired local material annealing. Some welded materials will shrink as a result of welding. The different dimensions may cause problems in the design function.

21. Mechanical Design Considerations of Tolerances

a) Tolerances should be as large as practical to reduce fabrication cost, scrapping, or work overcosts of design hardware.

b) Tolerances should be funneled for multiple assemblies. That is, use datum points or planes to gage. Do not let tolerances build up from multiple tolerance datums or series of datum requirements.

c) Tolerances should be judged on final part process—after plating, lubricating, etc. This is how the assembly is done, and it must work correctly there.

d) Tolerances can dictate the manufacturing process and add unnecessary costs. Use standard manufacturing tolerance when possible. Anything tighter and unnecessary will increase manufacturing costs without system benefit.

22. Mechanical Assembly Considerations

Do not require blind assemblies, as unknown problems can occur. One assembly required mounting a component with bolts through clearance holes and then torqued the bolts to a given value. What could not be seen was that the torque wrench could interfere with another bolt, which locked the wrench and resulted in a false torque reading. This little problem caused an expensive system recall.

When requiring items to be torqued to a certain value, make sure the assemblers understand how to arrive at a proper torque value. As an example, a critical bolt in a system needed to be torqued to a given value, with a given tolerance. To connect to the bolt, a crow's foot wrench was required, with a socket extension tool attached to the torque wrench. What was not understood was that if the crow's foot was attached at a right angle to the torque wrench, one value was obtained, and another was obtained if the wrench was attached in parallel to the torque wrench. The right angle gave the correct value, and the one in parallel gave an erroneous reading, as it added a leverage length to the torque wrench. The system engineer must be on alert for situations like this when approving assembly procedures.

Design your system or subsystem so that it can be assembled or mounted only one way — the correct way. Guide pins, bosses, and nonsymmetrical mounting design will help to accomplish this condition. For precise mounting, use spring roll pins for guides instead of dowel pins. The roll pins expand to fit the location hole and remove the effect of hole diameter tolerance.

Use locking features for assemblies. Lock wire is good, but it is not a locking feature. It is a safety approach to keep loose parts from coming loose or coming off and possibly causing critical damage. Lock washers are good, but will scratch the corrosion resistant material on the mating parts. Chemical locking material, such as Locktite, may have compatibility concerns. One can use interrupted threads or the double nut the bolt approach, and/or the nuts can be constrained by items such as bent flanges around the nut. These can all work well and should be evaluated for each different system use.

Do not allow voids in your assembly where loose items can fall and be extremely difficult to retrieve. When gloves are used to prevent fingerprints and corrosion, the small parts can easily be lost into difficult assemblies. The assembler may not notice that the washer or other small part has fallen into the assembly, and it becomes an unknown part of the assembly. It will be left in the assembly and may cause major problems when the system is in operation. It is preferred that bolts contain captive washers so that this particular problem goes away for lost washers.

For example, a friend had to work on his car's carburetor. The car was almost new but would not start. He did not notice that he had dropped a small washer into the carburetor intake when he was reassembling it. Upon starting the engine, the washer traveled to one of the engine cylinders, broke off a valve, and then knocked a hole in a piston. This initiated a major engine overhaul.

23. Design Margin

One needs to understand the definition of the design margin and safety factor requirements before starting a program or project design. The whole system will be closer to optimum if the design margin and factor of safety are the same. The design margin is 1.00 when the design is engineered to the system requirements. When this is the case, the design to requirement ratio, that is the system or subsystem capability divided by the design requirement is equal to 1.00. A safety factor is when a design part or system is manufactured and tested to its limit and is the result of the failure point divided by the design requirement. High safety factors are costly and do not buy you anything, as the part with the lowest safety factor in a system will control the functional limit for the system. This is akin to a log chain's maximum strength, the weak link is where failure occurs, and all the stronger links are where high costs and weights are derived with no resulting system benefit.

When all subsystem engineers on the project understand these definitions, the system tolerances budget can be much more easily derived and accepted by subsystem design engineers. When the subsystems have their safety factors determined, a cost/benefit study should be done to aid in deciding if a redesign should be done. Even when the safety factor is less than one, a redesign may not be warranted, but the operation envelope definition for the system may need to be modified to limit the operation of the system to a new reduced set of parameters.

Welded seals must be free of inclusions, voids, or cracks. They are crack initiators and these can eventually grow and cause failure. A researched study of the proper weld material and process is usually well worth the effort.

On any threaded joint, use a thread compound or lubricant compatible with the material being sealed. It reduces friction during assembly and will result in less damage as the result of assembly. The assembly torque will be a more true value for satisfactory operation. If the design is in a corrosive environment, this will help to keep the threads of the bolt and nuts from corroding and causing disassembly to be much more difficult.

24. Structural Considerations

Stress concentrations occur in structures anywhere the shape of a structural member is changed. For instance, equal stress lines in a material can roughly be looked upon as equal flow lines in a fluid flow circuit. If a flow exists and a dent is introduced into the wall of the containing tube, the flow lines will be more concentrated around the dent. A few helpful hints are as follows:

a) A hole drilled through a structural member creates a minimum stress concentration of approximately two. This may be significant in a highly stressed structure.
b) A change in size of one structural member to another, like a dog bone, for instance, creates a stress concentration on the smaller part. This effect should be considered.
c) Any radius increase of a structural member reduces the magnitude of the stress concentration. The radius of all sharp corners needs to be defined for the fabrication personnel. If not, your design capability is unknown and could fail in operation. Be as generous as possible for the radii in your design.
d) Very sharp V-shaped notches can result in large stress concentration at the root of the "V" and should not be used. Always specify the radius at the bottom of the notch and make it as large as acceptable to the system. Better yet, do not include a notch like this in your design.
e) Sharp V-shaped notches can lead to early failure in brittle materials by self-induced stress concentrations. This can initiate a crack, especially in brittle materials. Small cracks can be in the part at assembly without being detected, and this gives rise to reliability concerns of the system.
f) Cracks can be repaired, but consideration of cost/benefit should be studied. This is usually done by drilling a hole at the tip of a crack. If it is a weldable material, the hole and crack can be welded and refinished. However, if the hole does not contain the very tip of the crack or the drilled hole has a small diameter, this approach will not work, and the crack will continue to grow. This has been used for many years to stop cracks in sheet metal and glass, as it reduces the stress concentration by spreading the equal stress lines apart. If you are not working on an old car fender, I recommend redesigning the part and replacing the failed one.
g) Analyses should be done on any highly stressed structural member. Good design consideration and design practices can minimize the magnitude of the peak structural stresses, can lead to a better system design, and reduce functional surprises.

25. Additional Items of Interest

Strength of a Material is both Temperature and Time Dependent
Rule of thumb for strength of a material at elevated temperatures.

This rule is for steady state load rate conditions. The rule is to take the absolute temperature of melt for a metal and divide it by two. This will give the temperature value for which one-half of the maximum strength of the material will exist at steady state conditions. For example:

Temperature at ½ strength of Aluminum = ((1100 Degree F. + 460 Degree F)/2) – 460 Degree= 320 Degrees F.

It is empirical and I do not know why it works, but I was informed of this relationship by a respected physicist and fellow Sandian, Al Chabai, and it seems to work. It is good for a least a first try and will let your design approach continue until a better value is found and/or expensive tests are conducted.

High Strain Rate Loading
What is the strength of a material you use in your design when loaded at very high strain rates of short duration, similar to a shock wave passing through it? This is a concern when a tensile stress wave is passing through a bolted assembly and the bolts must transmit the load. The instantaneous stress may be much higher than the maximum steady state strength allowed in the material. Usually, this information is not readily available, if at all, when you are formulating the design. Another rule of thumb, also by Al Chabai, is that it has been found useful to estimate this load by taking the energy under the stress/strain curve up to the point of yielding, as on a Young's modulus graph, with the material at near steady state conditions. Then compare this energy, integral of stress/strain diagram to the point of material strength returns to zero stress, to the high loading profile under the stress/time curve to the near steady state stress/strain curve. If the high strain rate energy is equal to or less than steady state energy values, it is good enough for your preliminary design. Do not forget to evaluate this part of your design more fully by analyses and/or testing before completing the design evaluation. High strain rates can be in microseconds instead of the usual time in seconds or minutes.

26. Cleaning Electrical Components

a) First, always clean the electrical contacts and connectors by the use of lint-free swabs or cloth. This is because lint can leave tracks in potting and/or on connectors that can lead to a current conduction path.

b) Use clean dry air or Freon to clean connectors before final assembly. Dust or other contaminants in the assembly area can present a problem.

c) Do not use metal or other conductive material brushes to clean components or around electrical components. Conductive-type brushes can leave small conductive paths on ceramic or other type of material, which can add a conductive path that is unknown. They may also scratch the plated surface, which could result in corrosion for certain environments that will cause problems later in the system life.

27. Caution in Using Silicone Fluids

This fluid will migrate with time and can possibly get into places that you may not want it to. It has been known to dud PETN and can possibly harm other types of material. It will oxidize with time, collect dust, etc., and its original purpose may be defeated. It may also oxidize and become hard with time in adverse environments. Used properly, it can contribute to an excellent component design. In general, review all materials used in your design for effects of time, temperature, and environment over the design life of your system. This can be done by accelerated aging experiments.

28. When in Doubt, Revert to Basics

One of the first things I was taught in engineering school was to revert to basics to determine if analysis results are reasonable. There are fewer things more embarrassing than doing a lot of analyses, presenting your results, and having them immediately appear wrong to an experienced engineer.

For example, I had a respected engineer looking at a structural response problem resulting from very fast energy deposition on a part of the structure. After some time, he brought his results to me for review and approval for publishing. Now, I do not believe I was as smart as he was, so I applied some basic fundamentals to it. To my surprise, the energy deposition from his calculations indicated that the structural material of interest would heat it above its melting temperature. Therefore, it was nonsense to conduct a structural analysis on a melted material. By stopping the report at the point, it saved both of us embarrassment and system development expenses. The basics to keep in mind during analyses, design, and operation are: conservation of energy, conservation of momentum, material response at use conditions, shock wave physics, etc. Then compare these intuitive results to your analysis results. If things look strange, you may want to consult with an expert in the field of your concern.

29. Structural Response

The group for which I was project leader was involved in a design and testing activity similar to the above example. We brought a specialist into the group to develop a closed form solution to structural responses. The problem was a difficult one, and his estimated time was long compared to the project schedule. We let him continue with his analyses because nothing like this was available in the literature, and the added knowledge for future designs would be valuable.

To keep the project on some sort of acceptable schedule, I reverted to conservation of energy methods. The structure was complex because it consisted of shells with an internal structural support of a rigid material. What was known was the total energy and the maximum amount of energy at any given point on the structure. We knew the relationship of the energy at any other placed on the structure as a function of the maximum energy and the position on the structure circumference. Therefore, we analyzed each shell of the structure for energy per unit of deflection. Then we summed these energies per units of measurement and divided it into the applied energy to get an indication of the deflection at the point of the highest loading.

How did this help the design and testing on the project? Well, the energy balance approach took two or three days, and the project activity moved forward on this evaluation. The closed form solution took approximately three years. Subsequent response testing showed that the two methods were within 3% of each other. This was considered good for all the variables in test that one had to consider. It reduced the project potential time by approximately one-half and saved a lot of expense. The analysis approach is available for future use, and it has been verified. Was the analysis a waste of time and budget? I think not. The next time someone had a problem like this, the closed form solution was available and good for comparison with some of the newer computer models. With the latter solution, one can randomly change material, loads, etc., and get the results quickly and with a high degree of confidence.

30. Nuclear Meltdown Consideration

In another example, there was talk of a nuclear reactor running away and melting itself down to the center of the earth. I believe a movie was even made on this—The China Syndrome. How can one quickly determine the merit of this thinking? I did it by taking a 1-inch-diameter rod of Teflon, as Teflon simulates earth in several ways, drilling a one-quarter-inch diameter hole in one end to an approximate depth of one-half inch. Then I placed an aluminum slug about three-eights of an inch long into the hole. It was then placed into an induction furnace with the rod axis being vertical and the aluminum slug at the top end. The furnace was turned on, and the power was regulated to keep the aluminum in a molten state.

What I observed was the molten aluminum growing into a larger diameter at the top of the molten aluminum, and the upper diameter was growing at a faster rate than the slug was sinking. It dawned on me what was happening. The aluminum metal in a molten state would allow the higher temperature molten material to migrate to the top due to its change in density as a function of temperature. Just thermal expansion at play. We stopped the experiment before top of the molten aluminum broke through the side of the Teflon rod. It was obvious to me that it would form a wider and thinner sheet of aluminum until the energy conducted away was equal to the input or the molten aluminum changed into vapor and went up and out the top of the hole. This is all because the higher temperature liquid would always be at the top of the slug melt. My conclusion, based upon simple thermodynamics, was that a molten material (anything) would not sink to the center of the earth. Reverting to basics, I believe, gave the answer that many may be still working to solve. Reverting to basics should be considered every time one is unsure of the results or no analysis results are available. Again, necessity is the mother of invention, and you may find something totally new by your simplified investigation.

Another example is one that one of my professors, Dr. Fred Mouck, used in one of my undergraduate Strength of Materials courses. We used slide rules in those days for calculating the answer to a problem. He expected the accuracy to be correct to four digits, and this was possible, as you could obtain three from the slide rule and derive the forth digit in your head. Looking back, it was his way of having us use our brain instead of just operating a machine. Today, one needs to revert to basics to check the output of computer, as the analyses are difficult to thoroughly review.

<u>31. Technique for Removing Collars, Bearing Races, etc., from Shafts</u>

Collars, spacers, etc., are used on machines to either grip a shaft, turn a shaft, or maintain a pulley, gear, etc. in a desired location. Sometimes these are used in conjunction with machine keys to maintain precise rotating relationships with other parts of the machine. A tight grip, no play allowed, on a shaft is required for oscillating motion operation.

After a period of use, due to rust, paint, dirt, etc., these pulleys etc. can become “frozen” to the shaft. Machine breakdown, need for design upgrade, or another reason may necessitate the removal of either bearings, pulleys, gears, and/or a shaft. As the designer, you certainly do not want to go into the field to direct good mechanics or machinists without having a well thought out and proven procedure in mind.

Let us think about a procedure. First, assume that the item of interest is not frozen to shaft. This is the easiest of all. Just reverse the assembly for disassembly and then do the procedure forward again with new or remanufactured parts to complete the change.

If the parts are frozen to the shaft, then several items need to be considered. The repair or upgrade will not be as simple as the one discussed above, and the time the machine is not operating is costing the owner valuable operating time and money. If the part has been on the shaft for a long time in a dirty, moist, or other corrosive environment, it will probably be frozen to the shaft. One might first think of using a welding torch to either heat or cut the part loose that needs to be freed. However, the risk of this approach in many locations is too dangerous to risk its use on the parts of interest or to adjacent hardware that may add to the number of parts that must be replaced.

When the welding torch is not a good idea, I have found the following to work satisfactorily. First, clean the shaft and the item to be replaced with emery cloth or wire brush to remove rust, small metal protrusions, paint, etc. Do not remove any more of the shaft metal than necessary. Use a paper towel or cloth to wipe away the loose particles. Second, apply a liberal amount of penetrating oil, such as WD-40, to the shaft and adjacent to the gear, pulley, etc., that is frozen. Let it set for a while to penetrate and loosen the material that may be holding them together, and then wipe the shaft again to remove hard grease and other loosened material. Apply the penetrating fluid again and wait a while for it to penetrate between the shaft and the item to be removed. If this does not free it, then you will need to proceed to the more important operation.

Depending on the size of the shaft, select two fairly heavy hammers. (The larger the diameter of the shaft, the bigger the hammer should be.) Place one of the hammers on one side of the part to be removed from the shaft. Take the other hammer and strike the other side of the part directly across from the held hammer, 180 degrees away from the held hammer, with some good strikes. Be careful not to hit or damage the shaft. One can usually observe when it has loosened from the shaft. If not, take a wrench and lightly clamp the part to be removed and wriggle it see if it is loose. If not, repeat the hammering again in the same place. If the part to be loosened is fairly long compared to the hammer head size, you will want to move the held hammer slightly along the item axis and repeat the hammering process until you have covered a complete line on the item to be removed. You may notice a slight oval shape to the softer collar part to be removed. This should not prevent you from using it in reassembly as a set screw in them is what initially does the holding as it is not a press fit item.

Why does this approach work? First, the energy from the striking hammer is mainly captured by the held hammer, the momentum trap. This prevents the shaft, or other associated parts like a good ball bearing, from taking the load and receiving damage. The stress wave introduced by the striking hammer creates high stress components in the collar and shaft. The shaft is usually solid material and does not compress easily. It can rebound and force the collar to a larger diameter, which is good. The stress wave reflects and causes many compression and tensile stresses at the interface of the shaft and collar to be removed. This interaction is what is needed to break rust and other brittle interface materials that have formed. I would, however, recommend caution when using this approach on hollow shafts, as one might accidentally hit the shaft, for instance, and cause it to bend in an egg shape. Then your problem may have grown larger. For hollow shafts, I usually use smaller hammer and strike the part more times to accomplish the separation so that I will not damage the hollow shaft.

I have personally used this approach on several occasions, and it worked satisfactorily. My most recent time was in the middle of a wheat field during harvest time. The front bearing on the large thrashing cylinder of the combine failed, leaving the combine full of wheat grain and wheat straw and the failed bearing smoking from the friction generated by its failure. The people there wanted to bring a welder to the field and heat the bushing or cut the bushing off so we could remove the bearing off the approximately 2.5 inch diameter shaft. I suggested to them that due to a high wind present and the combine being full of straw, we use a different approach. (One could have cleaned the straw out of the combine, but it would have taken hours to do and enough straw dust would still be in the machine to cause a fire.) I then remembered the above approach and suggested that we try it. Even to my surprise, after about a dozen hammer strikes, the bushing and bearing slid off by hand. Yes, we could brought out a water truck and wet everything down, but the risk of fire was not worth it, and the resulting cleaning required after using the water would have taken another hour or more.

This is a procedure incorporating shock wave interaction and momentum traps that we have learned in the past, which can be used in a practical application.

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