Advanced Sealing
13452 Alondra Blvd.
Cerritos, CA 90703
(562) 802-7782

Tech Notes
FROM ADVANCED SEALING

Advanced Sealing
3803 Old Mobile Hwy
Pascagoula, MS 39581
(228) 938-8000

Topic: Belleville Washers on Heat Exchangers

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One of the “solutions” that is sometimes applied in an attempt to solve the challenge of leaking heat exchangers is Belleville washers.

Belleville washers look like heavy-duty flat washers – except they have been slightly deformed, or coned, so that there is a small taper from the ID to the OD. This taper is very gradual. The drawing below depicts a 3X-scale cross-section of a Belleville washer designed for a 1-1/8” stud bolt.

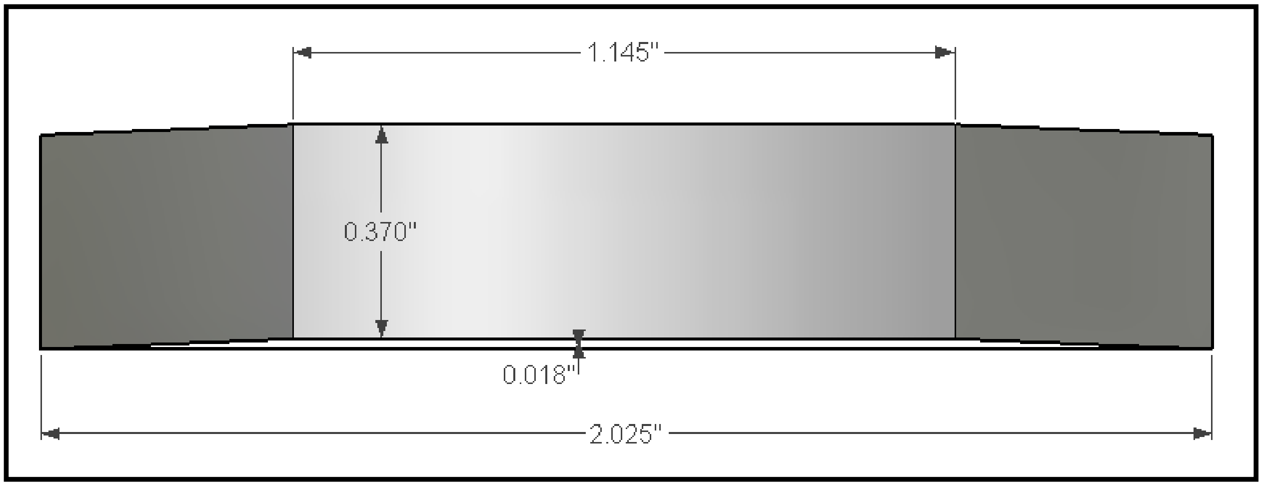


Figure 1

This very slight taper turns the washer into a spring – a spring that has been designed to flatten under a specified load. In the case of the part shown above, it is designed to flatten under an applied load of 47,400 pounds, which occurs when the stud bolt is stressed to 60,000-psi.[1] Like most springs, Belleville washers are linear devices[2] – that is, the compression of the spring is directly proportional to the load applied. Dividing the force to deflect by the total deflection gives…

47,400 / 0.018” = 2,633,000 lbs/inch

… which is the spring constant (or K value) of the washer. This means that for every 2,633 pounds of force applied, the spring will compress 0.001”.

[1] The force that the bolt delivers is equal to the stress of the bolt (in psi) times the Tensile Stress Area of the bolt. The Tensile Stress Area of a 1-1/8” stud bolt is 0.790 square inches. At 60,000-psi stress it delivers (60,000 x 0.790) 47,400 pounds of force.
[2] When the ratio of the taper of the washer to its thickness is less than 40% - as in this case - the force/deflection “curve” is linear. For the purposes of this paper we will consider Belleville washers as linear springs, ignoring any frictional and flattening effects.

The use of Belleville washers on heat exchanger flanges is based on this spring deflection; as it is reasoned that the spring in the washer will keep the flanges tight if the gasket should relax or lose thickness.[3]

So are Belleville washers the answer to offsetting the relaxation inherent in heat exchanger gaskets? Should they be routinely used to improve reliability and prevent leakage in heat exchanger joints? The short answer is "no". The limited amount of good they do is more than offset by added cost, increased complexity, and added failure modes. Here's why.

1. Mismatch of loads needed and delivered

The real secret to sealing heat exchanger gaskets is GASKET STRESS. As of this writing, Chevron is the most successful operator of heat exchangers in North America – and arguably, the world. They have thousands of heat exchangers in operation; with zero reported leakage from turnaround to turnaround. Their experience teaches that exchanger gaskets must have a full-width seating stress between 12,000-psi and 40,000-psi in order to run leak-free, with the exact amount dependent on the number and size of studs, the system pressure, the size, type and configuration of the gasket and other such factors.

To attain these gasket stresses, Chevron often finds it necessary to take the stud stress well beyond 60,000-psi – routinely going over 90,000-psi on studs under 1". In many cases, studies show that stud stresses lower than 50,000-psi under-load the gasket, and increase leakage risk.

Here is the problem. If the dynamic range of the spring washer correlates to a stud load of 0 – 60,000 psi, but the required gasket loads correlate to a stud load of 50,000 – 90,000-psi, then much of the dynamic range of the washer will never help seal the gasket. It is only the narrow overlap between these ranges – the region between 50,000-psi and 60,000-psi that the washer can contribute to the sealing of the gasket. Because the washer is a linear spring, only 1/6th of the 0.018" cup in the washer – or 0.003" – could effectively contribute to the sealing of the gasket. The rest of the relaxation in the washer occurs at levels too low to prevent leakage.

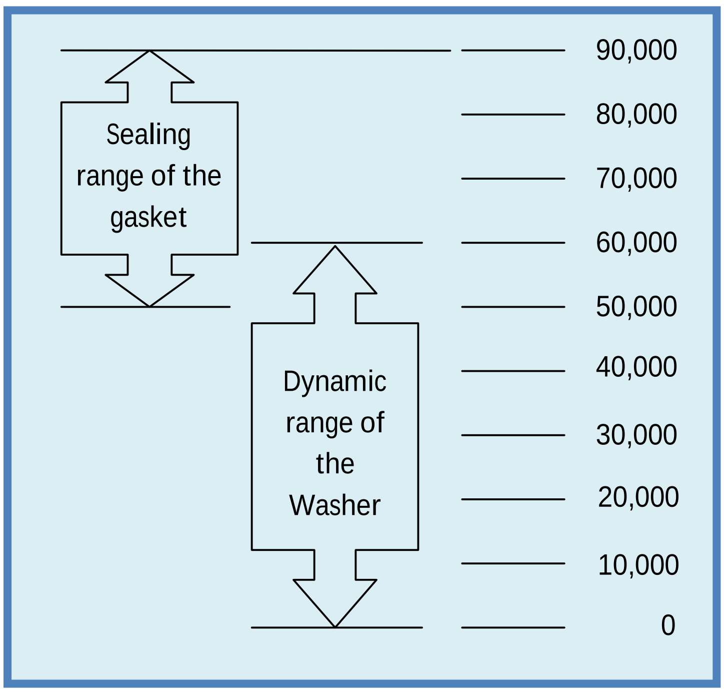
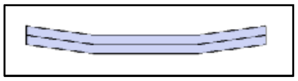


Figure 2

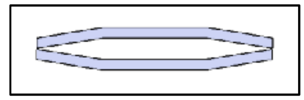
[3] "Relaxation" occurs due to a thinning of the gasket because of consolidation, deterioration, distortion, displacement, migration or compression of the gasket material. As the gasket thins, the elongation (or stretch) in the studs is reduced, resulting in a drop of stud stress and gasket stress. Spring washers can reduce this stud load loss by adding additional spring travel to the stud so it is less impacted by the amount of gasket relaxation.

2. Increased Complexity

The person well versed in Belleville washers will point out that the above explanation is far too simple, and that by combining a short stack of washers with either "up" or "down" orientation it is possible to achieve any spring rate (or K value) desired. This is true.



Ignoring frictional effects, stacking two washers on top of each other facing in the same direction (in parallel) doubles the force needed to deflect the same distance, thereby doubling the K value; whereas stacking them in opposite directions (in series) cuts the K value in half, creating a spring that moves twice the distance with the same force.



Most often, Belleville washers are used in even stacks – that is, the same number of washers will be facing up or down in every part of the set; which results in a linear spring rate over the full range of compression. Even with that restriction, multiple set arrangements are possible – as can be seen in these drawings showing a simple 4-washer set. In both cases, two of the washers face up, and two face down. Both sets are also "even" sets, with the same number of washers in each alternate-facing segment. But the spring rate for the arrangement shown in Figure 3 is only 25% of the spring rate for that shown in Figure 4. The set in Figure 3 will compress 0.072" with just 47,400 pounds of force, whereas the set in Figure 4 will compress just 0.036" with 94,800 pounds.

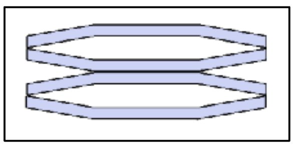


Figure 3

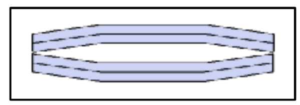


Figure 4

No matter how many washers a set may have, or how they may be arranged, the resultant spring constant of a stack of washers (K_T) can be determined by the following equation:

$$K_T = K / ((1/N_1)+(1/N_2)\ldots)$$

Where:
K = the spring rate of one washer, and
N = the number of washers in each successive set in opposite orientation.

So the stack of washers shown in Figure 5 would be evaluated by the following equation:

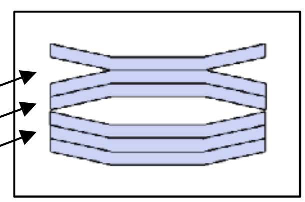


Figure 5

$$K_T = K / ((1/1)+(1/2)+ (1/3)) = 0.546\ K$$

This K_T would prevail only until the single spring flattened out, essentially removing it from the stack. The remaining washers would then be evaluated as:

$$K_T = K / ((1/2)+ (1/3)) = 1.200\ K$$

…until the two washers were compressed. At that point the remaining three washers would act as if they were alone, with a spring rate of :

$$K_T = K / (1/3) = 3.000\ K$$

As you can see, using different numbers of washers in alternating directions results in the set compressing at different rates under different load ranges. It is this added level of complexity – resulting in a non-linearity in the spring response of the total set – that drives most users to design sets with the same number of washers in opposing directions.

The ease with which these values can be computed means that custom Belleville washer sets can be designed to overlap gasket load requirements. For example, let's take another look at the example discussed in Figure 2, this time using a 4-washer set as shown in Figure 4 instead of a single washer. The spring rate of this set is given by:

$$K_T = K \,/\, ((1/2) + (1/2)) = 1.00\ K$$

… or exactly 2,630,000 lbs/inch, just as a single washer, but with twice the travel. As stated earlier, the set compresses evenly, and would compress 0.036" with 94,800 pounds of force – a load that would be equivalent to 120,000-psi stud stress[4].

Figure 5 shows the changes that would result. With this "optimized" set, just 33% of the compression on the set of Belleville washers – or 0.012" – would be available to offset relaxation in the gasket before the load on the gasket surface dipped to levels which risked leakage[5].

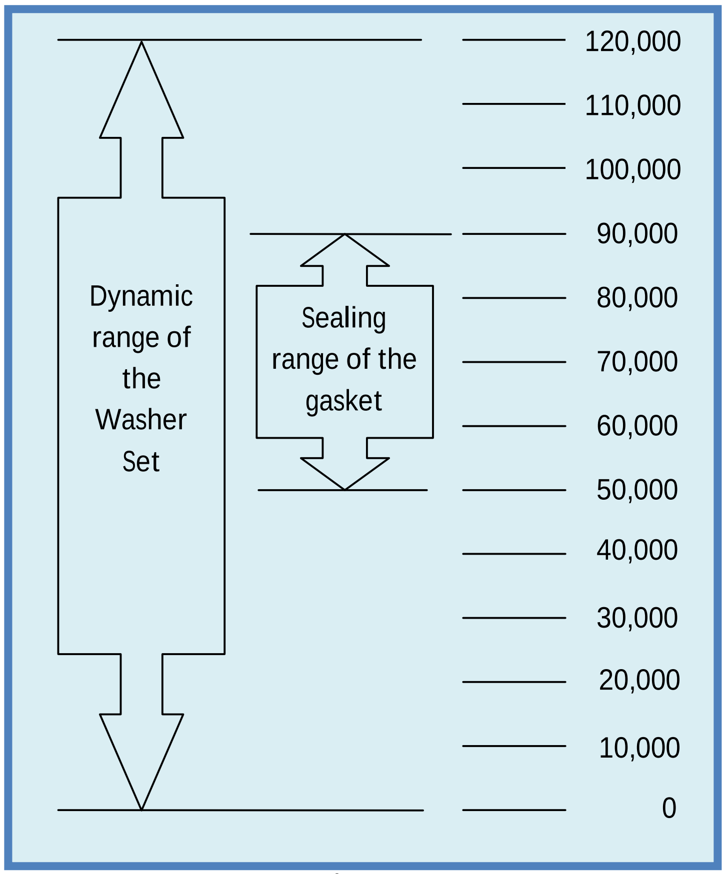


Figure 5

While this exercise shows how Belleville washer sets can be used in a balanced approach that takes into account the factors that control gasket seating stress, it also demonstrates the increased complexity that argues against using them routinely.

Routine use of Belleville washers as described above would require that custom sets be designed for <u>every flange connection</u> on <u>every heat exchanger</u>. In order to contribute effectively to the seating load on the gasket, those sets would need to be designed with K values that generate effective spring motion in the range of stud stresses that would be applied in a properly tensioned joint. The number of washers – and their exact orientation – would need to be carefully communicated to the work crew; simply getting one washer upside down would make the set far too soft (or hard) to contribute meaningful compression.

[4] Since the yield on a B7 stud is 105,000-psi, this 120,000-psi value is merely a mathematical extrapolation, and is included here to discuss the spring characteristics of the washers.

[5] For a more rigorous discussion of this example, see Appendix A

What is the chance that an error can be made in installation? Significant. The number of unique ways that a washer set can be configured (and the number of ways it can be done wrong) increases with the number of washers. A 4-washer set can be configured 5 different ways. An 8-washer set has 22 possible combinations.

The ease with which the sets can be installed incorrectly is an argument for using them only on rare occasions – occasions when their use is tightly managed, and when better processes and procedures are not available. Another reason to limit the use of Belleville washers is….

3. Cost

At a price of about $12.50 per washer (for the 1-1/8" size), the washers for the tube sheet joint of a heat exchanger with 60 bolts at the tube sheet – each requiring 4 washers – would cost $3,000. If washers were also used for the channel cover and shell cover, the costs could easily be anywhere from $6,000 to $10,000 per exchanger, depending on the complexity of the stack and the size of the washers. Additional cost increases will be incurred to purchase the longer stud bolts to accommodate the washer stacks.

In itself, the "cost" argument is not a deal-killer. Yes, $10,000 in additional expenses is something that has to be looked at seriously. But if it could be shown that the washers were the deciding factor as to whether or not the exchanger leaks, then it's not unreasonable. If, however, the same end can be achieved without these added costs, then save your money!

4. Greater Risk of Failure

Whatever benefits may come through the use of Belleville washers, one negative is the introduction of an additional part that can fail. Users have found that under the wrong conditions Belleville washers can develop hydrogen embrittlement and crack, whereupon they immediately flatten. If the load on the gasket is dependent upon the function of the washers, such failure will result in a leak. This possibility of failure must be considered when deciding whether or not to use Belleville washers.

5. Better Methods are Available

The greatest perceived benefit of using Belleville washers is that they can offset the relaxation that occurs in gaskets, keeping the joint tight and leak-free. However, by studying the relaxation of gaskets in working heat exchangers, Chevron has come to understand the dynamics of gasket relaxation, allowing them to develop procedures to offset this relaxation without the use of Belleville washers.

All gaskets do in fact relax. Data shows that the relaxation occurs on an asymptotic curve, with the most rapid relaxation happening within the first hours and days after installation, and with the first heating cycle. What has become clear from Chevron's research is that neither the stud bolt nor a single Belleville washer has enough spring to offset the initial relaxation that will occur in the gasket. This relaxation must be manually removed by doing a hot re-torque[6]. Once the re-torque has been done, the remaining relaxation in the gasket is sufficiently small so as to be accommodated by the stud bolt alone.

Simply stated, the Belleville washer is not needed.

6. Philosophy

Strangely, perhaps the best reason not to use Belleville washers routinely comes down to a question of philosophy.

As everyone in the gasket industry knows, there are countless products and/or procedures that have been proposed as the "magic pill" to cure the problem of leaking heat exchangers. These include special gaskets, fancy bolting hardware, the use of nubbins, the practice of insulating flanges, bolt tensioning, etc. Often, customers are driven to try one or more of these "solutions" out of shear desperation, hoping to find the right combination of factors that will resolve persistent leaks.

Most of these proposed solutions do little good, and some do actual harm, as they fail to address the two root causes of heat exchanger leaks. By selecting a gasket that resists damage due to radial shear, and by using procedures that offset gasket relaxation – two fundamentally simple concepts – heat exchanger leaks can be eliminated.

Adding another element just serves to obscure this simple, effective approach, and confuse people as to how to best address the root causes of leakage.

Conclusion: Belleville washers do augment the spring travel of studs, and can be useful in the rare cases where a hot retorque is difficult or impractical. In most cases however, proper tightening procedures will result in sufficient stud elongation to offset the relaxation in the joint. Therefore, Advanced Sealing recommends against the routine use of Belleville Washers on heat exchangers.

[6] The hot re-torque procedure developed by Chevron is discussed more fully in a "Tech Note" dedicated to that topic.

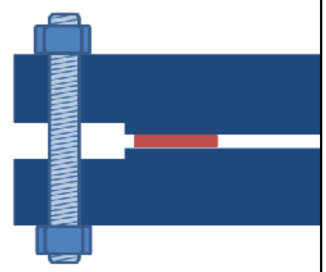
Appendix A

Example of shared load distribution

Figure 6 shows a 1-1/8" B7 stud with an effective length of 10" that has just been tightened to 71,141 pounds of bolt load (or 90,000-psi stud stress). Using Hooke's Law we can determine the amount of "spring" in the stud at this load.

$$dl = FL/EA$$

Figure 6



Where:

- dl = the change in length of the stud
- F = the applied tensile load
- L = the effective length of the stud
- E = Young's Modulus of Elasticity
- A = the Tensile Stress Area of the Bolt

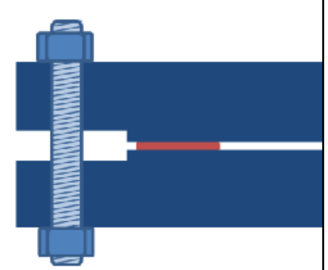
This evaluates as:

$$dl = ((71{,}141 * 10) / (29{,}700{,}000 * 0.790)) = 0.0303''$$

This stud elongation is essential to maintaining a tight joint. As relaxation occurs in the joint – and for the sake of simplifying this discussion, we will assign all of the relaxation in the joint to the gasket – the stud will shorten, supplying the travel needed to offset the thinning gasket.

In Figure 7 we can see that the gasket has undergone relaxation, as the gasket is noticeably thinner. The joint is still tight, but only because the stud has given up some of the earlier elongation. The stud load now stands at 39,523 pounds (or 50,000-psi stud stress), and a reevaluation of Hooke's Law tells us that there is now...

Figure 7



$$dl = ((39{,}523 * 10) / (29{,}700{,}000 * 0.790)) = 0.0168''$$

... of stretch. The stud has given back 0.0135" of its initial stretch to offset the relaxation in the joint. This allows us to calculate the spring rate of the stud as ((71,141 – 39,523)/0.0135), or K_S = 2,342,000 lbs/inch.

Figure 8

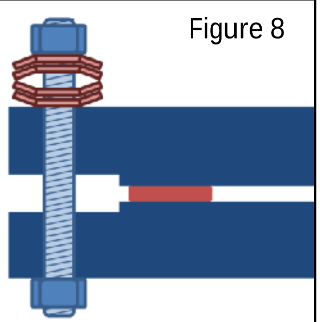
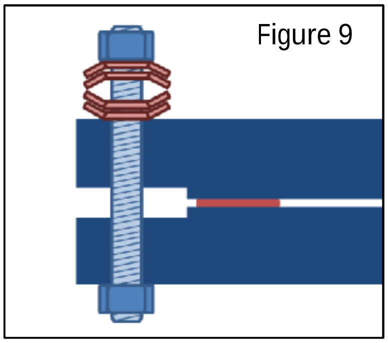


Figure 8 shows a 1-1/8" long B7 stud with a 10" effective length that has been tightened to 71,141 pounds of bolt load (or 90,000-psi stud stress). While similar to Figure 6, this joint includes a 4-piece set of Belleville washers – two facing up, and two facing down, as seen in Figure 4 (page 3). From our earlier discussion we know that it takes 120,000-psi stud stress to flatten this set of washers – so at this point they are only 75% compressed – a compression of 0.027". The stud itself has the same stretch as the stud in Figure 6 – 0.0303". Notice that the load on the washers has to be in equilibrium with the load delivered by the stud to the gasket. It all has to balance.



In Figure 9 we have allowed the gasket to relax the same amount – 0.0135" – as the earlier example. Notice that the gasket is thinner, and that the washers have relaxed. But what is now the load delivered by the stud to the gasket? What is the load on the washers? How much has the stud shortened? How much have the washers decompressed? Fortunately, we can calculate all of these factors.

The key is in understanding that the load on the washers and the stud must still remain in balance, and that the total change in length of the stud, combined with the expansion of the washers, must equal the relaxation of the gasket. Mathematically, all we have to do is set up two simple equations, and solve for X.

1) $dL_S + dL_W = 0.0135$

and

2) $dL_S \times K_S = dL_W \times K_W$

Where:

dL_S = the change in the length of the stud
dL_W = the change in the length of the washers
K_S = the spring rate of the stud = 2.342 (10^6)
K_W = the spring rate of the washers = 2.633 (10^6)

Simultaneously solving these equations enables us to determine that the change of stud length is 0.0071", and the change in the washer set is 0.0064". We also see that the load in the stud and washer set are in equilibrium, both having given up 16,700 pounds of load.

The bottom line? In this example the load delivered to the gasket by the bolt alone dropped from 71,141 to 39,523. When Belleville washers were added, the same amount of relaxation in the joint dropped the load to 54,441 pounds. The difference is due to the fact that the washers provided 47% of the travel, allowing the stud to preserve additional load.

Is this an argument for using Belleville washers on exchangers? No. While sets of Belleville washers can be designed in a way that can be shown to augment the stud load, of what use is the extra cost if the bolt alone can be deliver the needed spring-back to offset the gasket relaxation? For this reason Belleville washers should be seen as a helpful item that should be reserved for the rare occasion when proper torquing and hot-retorquing are not practical.