INVESTIGATION OF FLANGES SUBJECTED TO OPERATING CONDITIONS OF PRESSURE, TEMPERATURE AND BENDING MOMENTS

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ABSTRACT

The integrity of flanged joints is of great importance to the safety of operating facilities. This paper presents stress investigations of standard ANSI weld neck flanged joints utilizing spiral wound and composite type gaskets. The joints are analyzed for the effects of pressure, temperature, and bending moments from the attached piping. The finite element investigation included the effect of varying gasket contact stress on the joint.

DEFINITION OF PROBLEM

Over the years leaking at flanged joints has been a continuous problem in operating plants. The gasket in the flanged joint is subjected to varying compressive stress due to the loadings on the flanges. These joints are subjected to initial bolt-up conditions, hydraulic end load forces, thermal induced strain and piping system imposed loadings.
External loading from attached piping systems cause unbalanced forces to be applied across the gasket/flange sealing surface and to the bolts keeping this connection together. This effect is not well understood in the engineering community. Recent works such as those by Ando et al (1997), and Bouzid et al (1997) has provided additional insight into the flange assembly and gasket contact stresses. The varying gasket contact stress appears to be an important aspect of maintaining sufficient sealing capability. The gasket manufactures do not provide sufficient information to facilitate gasket selection based on changing gasket contact stress and how well the gasket material can accommodate this condition.

With recent developments in finite element analysis software and computer capacity, the known anomalies in gasket loadings can be qualified. The finite element analysis software selected for this investigation was COSMOS/M and as described below certain simplifying approaches were necessary to accommodate the investigation. The purpose of this investigation was to quantify the gasket loading conditions and related flange stresses under typical piping system conditions.

INVESTIGATION PARAMETERS

The flange modeled is an ANSI standard 24" 150# raised face weld neck flange with a 1/2" thick pipe attachment. The primary investigation was to determine the interaction effects of bolt stress and gasket contact stress under various loading combinations anticipated while operating. The main physical variable is the gasket type. Two primary types of gaskets were investigated, spiral wound with and without a gauge ring and a composite with elastic binder. This resulted in three gasket configurations to be investigated. The flange set loadings investigated were; initial bolt-up and higher bolt stresses due to maintenance leak tightening, temperature profile for flange and bolting, and piping bending moment similar to typical encountered in normal design practice The bending moment applied to the flange set was established based on developing a reasonable bending stress based on 1997ASME B31.3 allowable thermal induced bending stress.

Finite Element Model

Three dimensional solid elements were used to model the flange and gasket assembly except for the bolts which are simulated by beam elements (FIGURE 1). The gasket investigation nodes were placed at four equal spacings (five node locations) across the gasket to flange contact surface. The total width of the gasket plus gauge rings and the gaskets with out rings was the same to facilitate flange stress comparisons (FIGURE 2). The placement of the five nodes and maintaining of uniform total gasket width provided for consistent evaluation of stresses and displacements. Since the model uses 11,000 nodes and 8,000 elements, it was impractical to impose non-linear contact elements (gap elements) at the interface of the gasket and the flange due to excessive computer run time on a Pentium based machine. Therefore the reported stress/deflection at the interface of the gasket and the flange does not represent the true stress/deflection when the gasket contact stress is indicated to be in tension. However, this indicates that gasket and flange are actually separating where the tensile stress is indicated As no data was available for the variance of the gasket materials Young's modulus during it's compression the modulus was considered to be constant. It should be noted that for the spiral wound gasket with internal and external gauge rings the gasket thickness and the metal center ring thickness are treated the same in the FE model prior to applying the bolt loading. This simplification eliminates the original compression of the spiral gasket area during bolt up and the corresponding original gasket contact compressive stress.

Three types of gaskets are considered in the analysis: spiral wound, with and without gauge rings, and a composite gasket with elastic binder (gasket configurations are indicated in FIGURE 2 and TABLE 11). Linear elastic analysis was performed to investigate the gasket behavior subjected to flange bolt-up load, thermal gradient and bending moment applied to the flange set. Bolt-up load was established to induce bolt stresses of 22,500 psi. The spiral gasket with gauge rings was investigated with increased bolt stresses of 40,000 and 60,000 psi to simulate maintenance leak tightening activities. The bending moment applied to the flange set was established as the moment that would produce a nominal pipe bending stress of 20,000 psi to study the gasket behavior under typical piping system conditions.

The effects of internal pressure and thermal gradient in the flange were also considered for the composite type gasket. Based on field observed temperature profile in a petrochemical plant, the temperature profile varies radially from 500 F at the inside wall to 250 F at the outer rim of flange with bolt temperature of 200 F. The temperature distribution is assumed uniform in the axial direction. Internal pipe pressure of 285 psig was applied. Material properties of the gaskets are shown in TABLE 11. It should be noted that the Young's Modulus for the gaskets was considered to be the same for the gasket before and after original bolt up compression. This is not true as the crushing of the gasket material due to the contact stress results in a significant change in the gaskets' ability to rebound as the gasket contact compressive stress becomes less during various flange loading conditions. There is no published data on the gasket material properties after original compression occurs.

FINITE ELEMENT ANALYSIS RESULTS

Composite Gasket results

All tensile stresses indicated in the gasket contact surface region are not "real" but a result of the model that does not include gap elements and the assumption of a constant Young's Modulus for the gasket material. This approach slightly affects the deflections, compressive stresses and this also slightly skews the deflection plots. These minor effects are considered to not affect the macro results presented here.

Restoration is defined here as the ability of a material to return to its original size and shape after compressive loads are released. Restoration (spring back) in gaskets is not defined but is less than a modulus of elasticity would produce, therefore the results from the 180 degree location where the compressive stresses and deflections become less may actually be indicating a separation of the gasket surface from the flange surface.

Restoration may not be as critical a problem for soft gaskets because the gasket material may accommodate restoration better as entire surface of the gasket is designed to act as a sealing surface and the field observations indicate that some limited restoration occurs for this type of gasket. The inability of a soft gasket to avoid over-compression due to increased contact compressive stresses from imposed piping system moments should be a consideration for selection of gasket materials. The effect of the applied moment on the gasket contact stresses can be observed in the figures contained in the appendix. The bending moment is applied such that the 0 degree nodes are subjected to increased compression loading and the 180 degree nodes have reduced compression loading.

Tables 1 and 2 present the results of the composite gasket investigation. Table 1 presents gasket contact stresses for original bolt up (BU), bolt up plus pressure (BU+P), bolt up plus pressure plus thermal gradient (BU+P+T) and bolt up plus pressure plus thermal gradient plus bending moment (COMB). The tables indicate the 0 degree position and 180 degree position. The BU, BU+P and BU+P+T information is typical of the total flange circumference condition until a bending moment is applied to the flange set. The 180 degree position represents the side of the flange that would be "opened up" due to the applied bending moment. Correspondingly the 0 degree represents the side of the flange that would be "closed up" due to the applied bending moment. The 90 and 270 degree locations are neutral positions and remain relatively unaffected when the moment is applied to the flange set. . Table 2 presents the deflections associated with the above described loading conditions.

The original bolt up of the flange to a bolt stress of 22,500 psi causes the flange to deflect. These are shown in Tables 1 & 2 as Series 1 lines. This deflection is often described as flange rotation. From inspection of Table 1 and 2 it is apparent that the flange rotation is significant. The variance of gasket contact stress varies from 3963 psi compression at the gasket OD to 621 psi tension at the gasket ID (which indicates that the gasket may no longer be in contact with the flange seating surface). The amount of contact surface compressive stress reduction occurring at the side of the flange that is opening up due to the applied moment load is cause for concern because of the unknown amount of restoration available in the gasket. Also when the moment loading is removed as the piping is no longer in full operating condition the ability of the gasket to restore it self is of concern.

Pressure and temperature effects provide minimal impact on deflections or stress results that resulted from bolt up. These are shown in Tables 1 & 2 as Series 2 & 3 lines.

Applied pipe moments affect results much more than pressure and temperature. Table 1 & 2, series 4 & 5 show the affects on the compressive side (Series 4) and the tensile side (Series 5). Although the tensile side deflections (Series 5) show that the gasket should still provide sealing, the restoration amount of the gasket should be around .004" to make this model accurate. It can also be seen that the point at which the deflection is 0.000", the null point, moves outward as the moment load is applied.

Spiral wound gasket results

The results of the investigation of the spiral wound gaskets are shown on Tables 3 through 8. The loading conditions and nomenclature are the same as the composite gasket section above.

All original bolt-up cases show that the main compression occurs on the outside gage ring rather than the gasket material itself. As noted above the original compression of the spiral wound gasket material to the thickness of the gauge ring was not included in the investigation model. Gasket seal material is approx. .030" thicker than gage ring material. Although the outer gauge ring provides suitable resistance for the flange to accommodate imposed bending moments, the flange seating surface does deflect such that gasket restoration is a consideration. Field observations on spiral wound type gaskets indicate that very little restoration occurs with this type of gasket.

Pressure and temperature effects produce negligible changes in the gasket contact stress and deflections. Therefore this information is not included on the accompanying graphs and tables for clarity.

Deflection plots (Tables 4,6, & 8) show that gasket will be compressed over the width of the sealing area upon initial bolt up, although the stress plots show very little compression in this area. Moment loading on the flange set causes a greater positive deflection at all locations. From inspection of the deflection tables it is apparent that the flange gasket contact surface is lifting up from the spiral wound gasket material approximately 10 to 33 % of the original gasket compression. This is again due to the flexibility of the flange itself and causes the "null" point to be on the gage ring as well. Higher bolt loading causes the overall general angle of deflection, or rotation, to increase, but does not cause the "null" point to move outward as much as the soft gasket does. As the gasket manufactures do not publish data on the restoration of the gasket sealing material, it is not possible to determine the true gasket contact stress as the flange seating surface deflects away from the gasket. The gasket restoration ability may not be enough to continue to seal as the flange sealing surface lifts off the spiral wound area. This results in a concern for leakage as the only sealing mechanism at this location is a metal-metal surface on the outer gage ring itself, for which the gage ring is not designed.

The spiral wound gasket without gauge rings was investigated to simulate the flange effect with a high seating stress gasket. The results are presented in Tables 9 and 10. Inspection of this data and comparison to the soft gasket results discussed above results in the same conclusions as above. The ability of a spiral wound gasket to restore itself to accommodate the flange deflections under moment loadings is of concern for this type of gasket or for any composite gasket with a 10,000 psi seating stress. It should also be noted that the loss of compressive contact stress on the spiral gasket ID, with out a gauge ring, may cause the gasket to unwind at the ID resulting in gasket failure.

FLANGE STRESSES

The flange stresses are indicated in Table 11. The authors have presented the flange hub stress values to indicate that moments applied to flanges and excessive bolt stress can increase the flange hub stress significantly which will result in strain displacement, commonly described as flange rotation, in the flange to gasket contact surface. These stresses are to be considered qualitative as no effort was made to converge the model. These values are suitable for comparison of one flange condition to another.

The increase in the flange stress to accommodate the piping system imposed moment is consistent with the deflections noted above. The increased bolt stress was investigated and was found to have a significant impact on the flange hub stress. The indicated flange hub stresses are in excess of 1998 ASME Section VIII allowables for bolt stresses above the 22,500 psi level and for most of the conditions where the piping system moment is applied to the flange set. In actual applications these stress levels are common and have not been found to be damaging. It is obvious that several of the FE indicated stresses are above the material yield stress but this may not be a problem until the flange is distorted such that sealing surfaces abecome ineffective.

Inspection of the FE stress results presented in Figures 3,4,5 and 6, clearly indicate that the flange hub stress is greater for the soft gasket application versus the spiral wound gasket with gauge rings. This is due to the actual bending fulcrum point of the flange. The flange bends around a null deflection point on the gasket. For the spiral wound gasket the null point is at the outer gauge ring which results in a fulcrum point nearer the bolting and this results in much less flange hub bending to accommodate the bolt forces.

CONCLUSIONS

The investigation concluded that the flange loadings of original bolt up, pressure, thermal gradient and applied moment produced considerable changes in the gasket contact compressive stresses. References such as Crocker's Piping Handbook (5th edition) suggest that the residual gasket contact compressive stress should be 5 to 10 times the system pressure that the gasket is sealing against. It is apparent that the gaskets' ability to maintain suitable sealing conditions will depend on how well the gasket can accommodate the flange gasket seating surface deflections and the change in deflections as the flanges are subjected to varying load conditions during operations.

The flange bends to accommodate the imposed forces on the flange. Piping system moments change as the system is placed in operation or the operating conditions change and this results in the seating surface to displace relative to the gasket original boltup position.
The composite gasket compresses on one side and attempts restoration on the opposing side as the flange set accommodates the piping system imposed moment. This deflection of the gasket subjects the material to varying contact stresses each time the system cycles such as during start-up or shut-down. As indicated in the results of the investigation the effect of the piping system bending moment is the largest component in the changing gasket stress.

The use of a spiral wound gasket with gage rings in the 24" 150# flange may not provide a leak free connection due to the flexibility of the flange. The flange flexibility causes the gasket sealing surface to bend at the outer gage ring of the gasket. This causes the sealing surface to "rock" on the gage ring and reduce the compressive seating stress on the gasket seal material. Little information is available on the spiral wound type gasket's ability to restore to the original thickness as the flange bends and this gives concerns for leakage. This concern is consistent with field observations of leaking 24" 150# flange sets with spiral wound gaskets incorporating gauge rings. The flange bending can apparently lift the flange seating surface from the spiral wound gasket surface and as the surface does not display restoration with this movement it's sealing effect may be lost. Little information is available for the rebounding capability of the spiral wound gasket and field observations are that little or no rebound ability is available in this style gasket. If the sealing surface does not rebound the outer gauge ring becomes the sealing surface.

The flange hub stress is reduced by use of an outer gauge ring. This also reduces the total flange displacement at the gasket contact surfaces. This reduced rotation indicates that a gasket which has the ability to support the flange near the bolt circle will require less restoration ability to maintain a seal under normal flange loadings.

RECOMMENDATIONS

The industry needs to establish information relating to the ability of a gasket to accommodate the deflections that are produced as the flange strains due to imposed loadings. The development of design procedures that include consideration for the bending of the flange and a gaskets' ability to accommodate this bending is necessary. The current proposed design procedures do not appear to address this consideration.

With advancements in Finite Element Analysis software it may be possible to qualify deflections in the seating surface of flanges under imposed loadings. Design procedures that would utilize information about a gaskets' ability to accommodate this deflection should be developed. This aspect of flange set leak control design may well be as critical a consideration for gasket selection as operating pressure and temperature.

From the information developed in this paper there is an obivious conclusion that the best approach to maintaining a gasket seal is the use of a gasket material that will accommodate the deflection loadings. This means that the gasket materials' ability to achieve satisfactory restoration is a property that should be available to the engineer to aid his material selection and design.

Further investigation of the use of an outer gauge ring and a gasket material with good restoration ability may confirm a better gasket sealing application with resulting flange increased flange loading ability.

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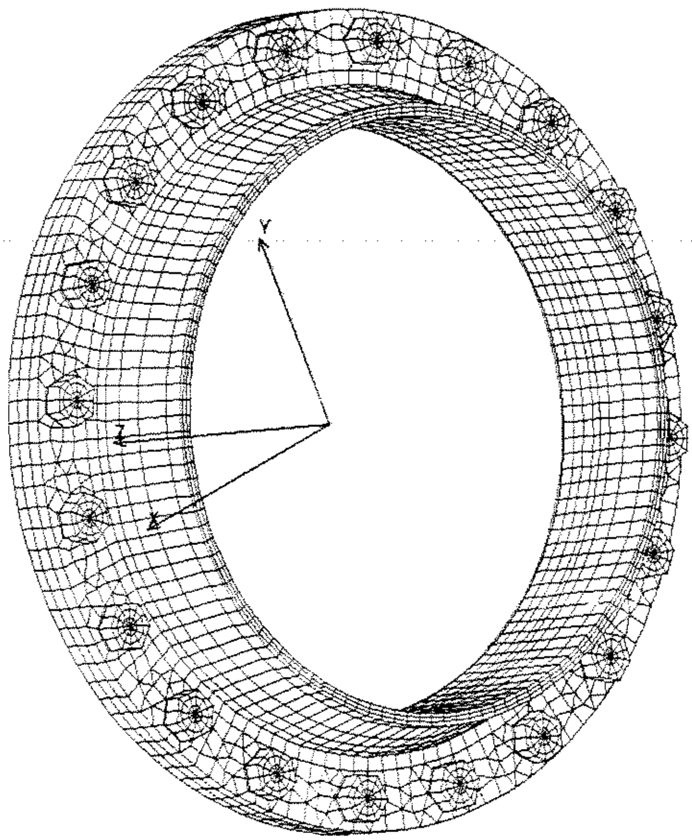
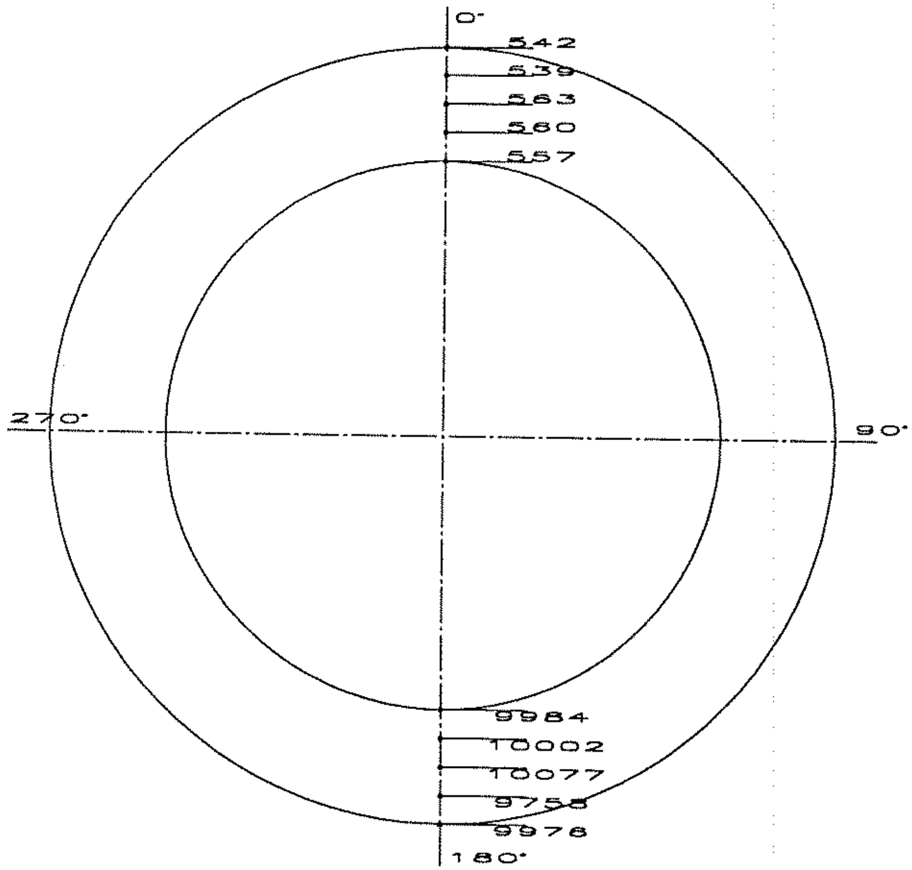
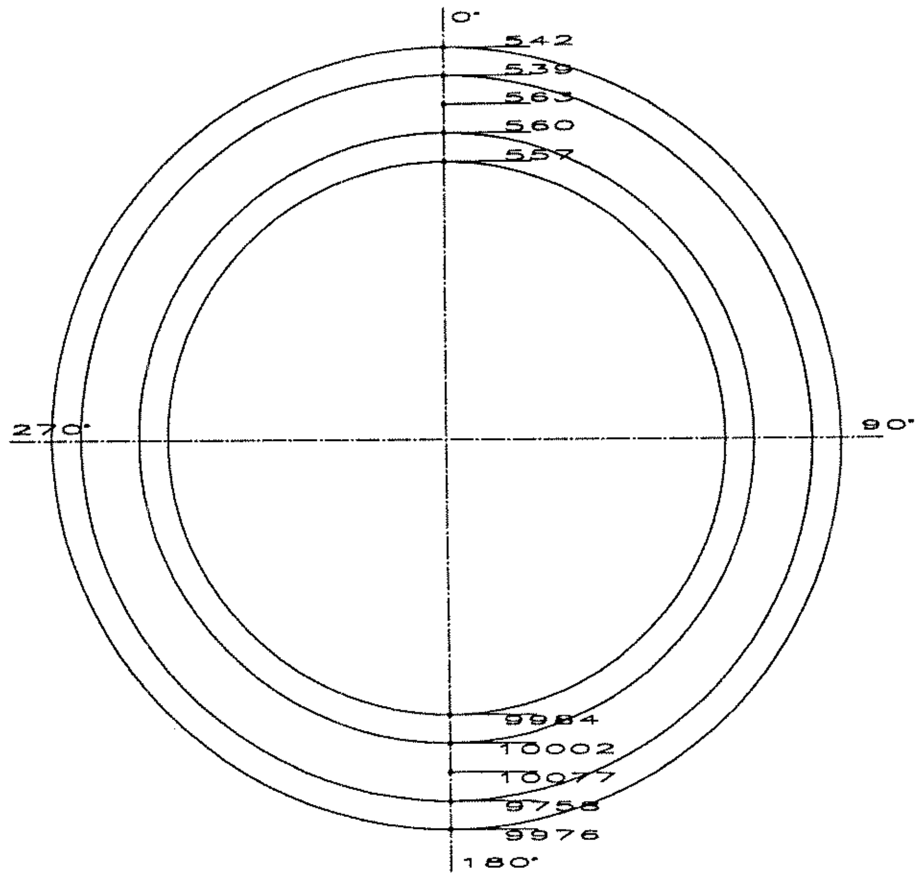


Flange Finite Element Model

Figure 1



NODAL POSITION FOR GASKET w/o METAL RINGS



NODAL POSITION FOR GASKET w/ METAL RINGS

Figure 2

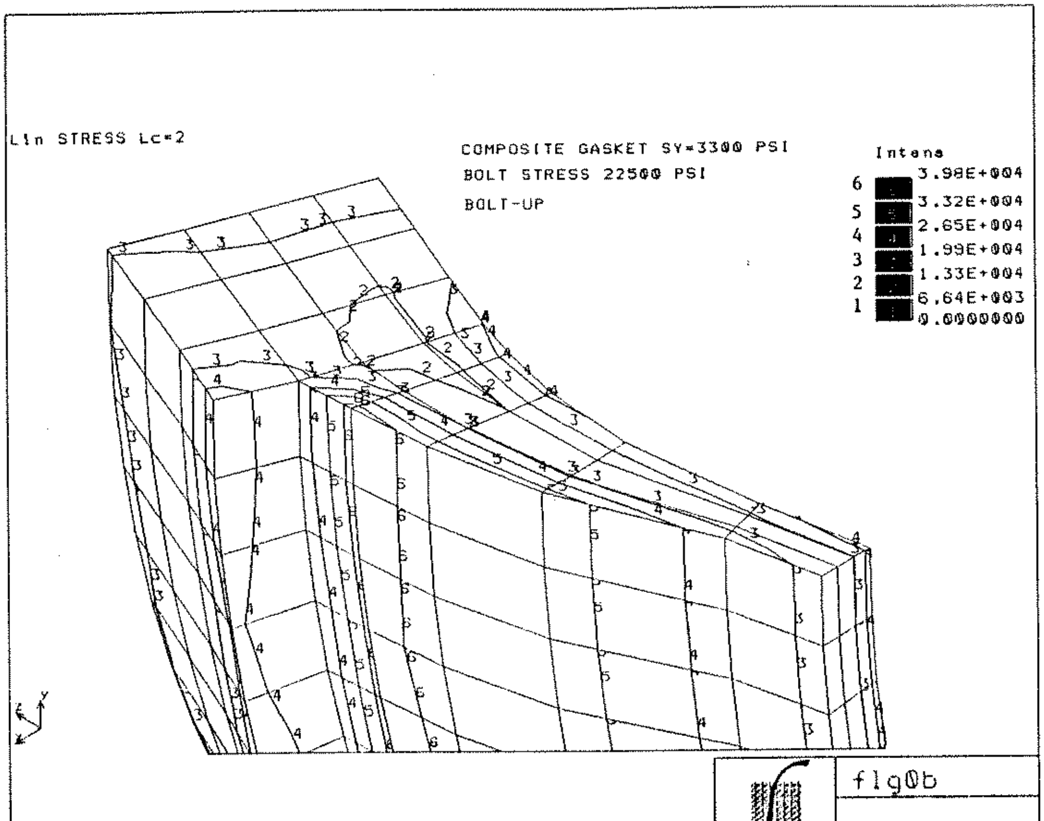


Figure 3

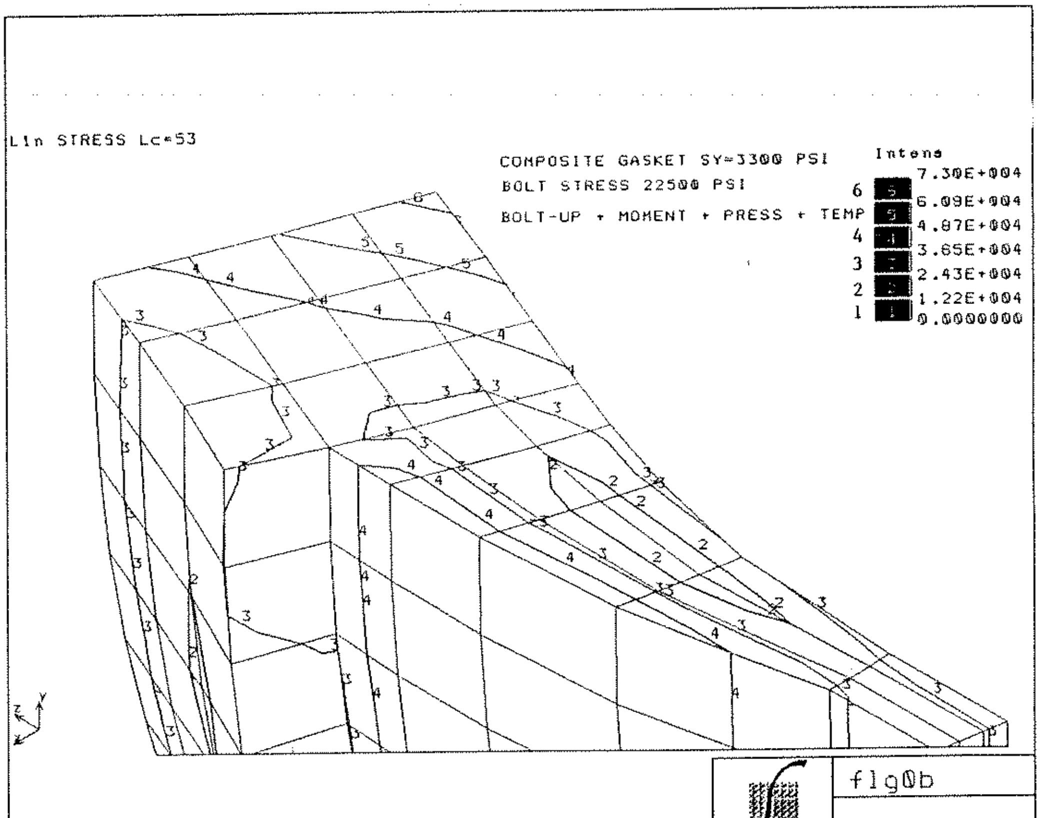
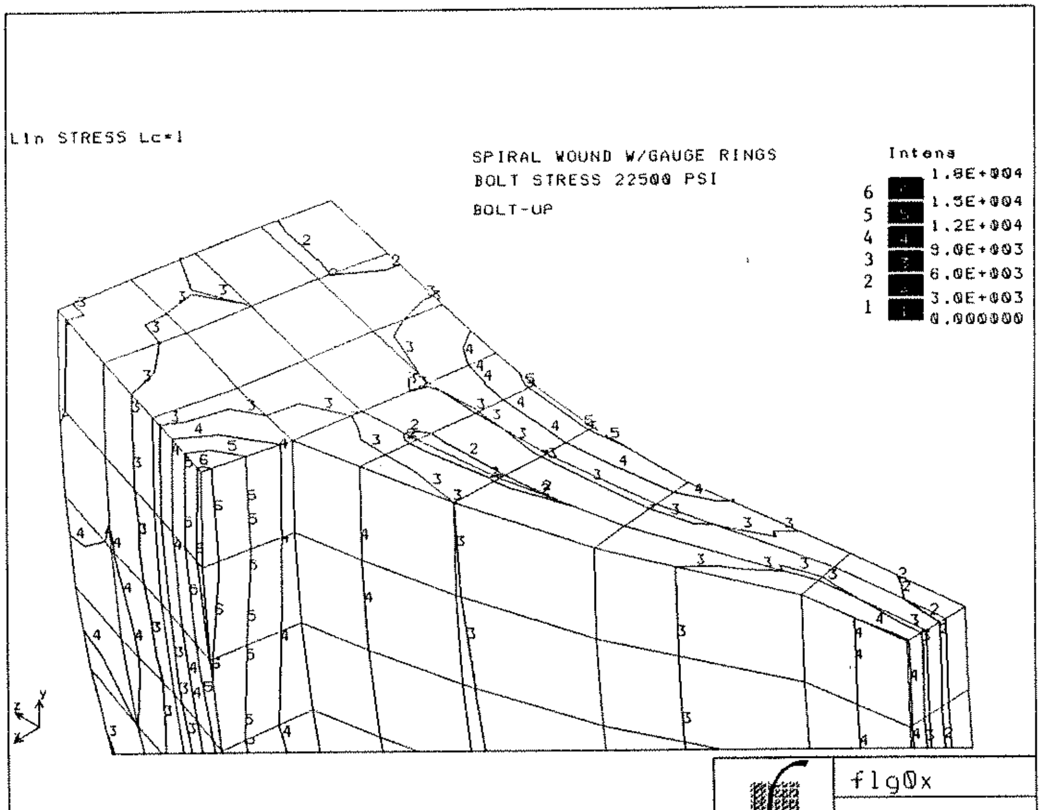


Figure 4



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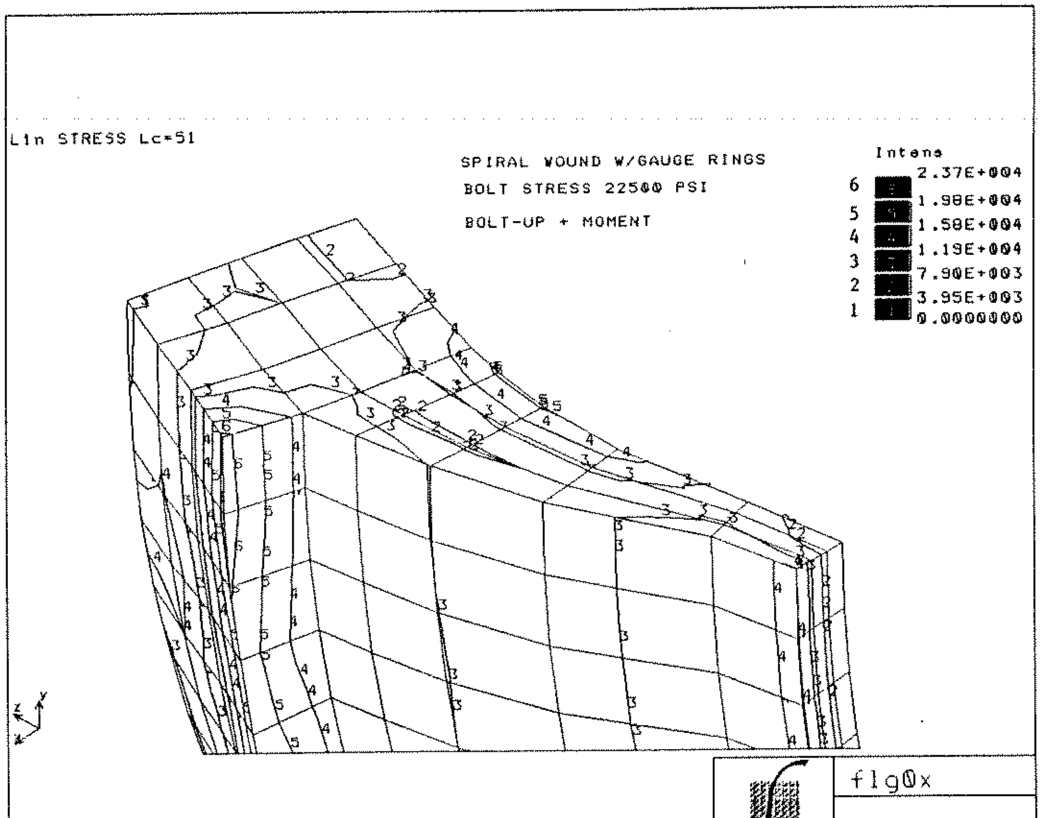


Figure 6

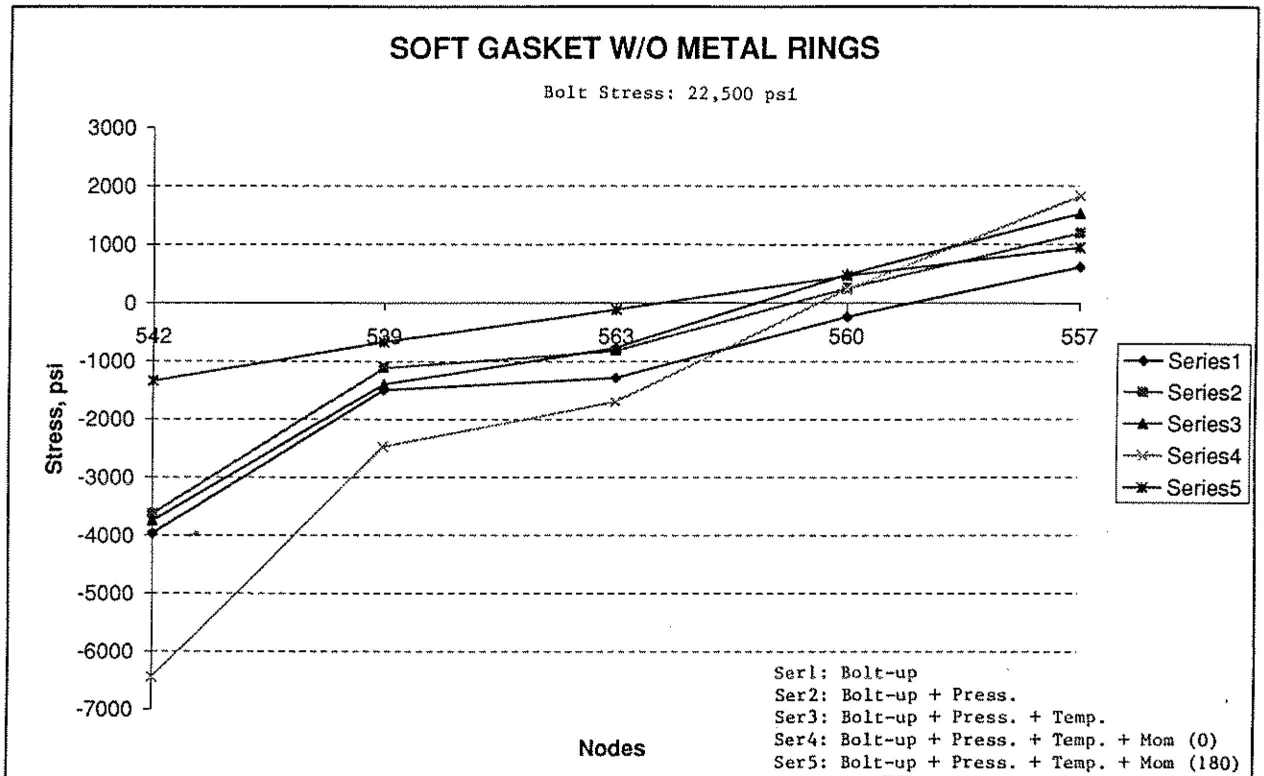
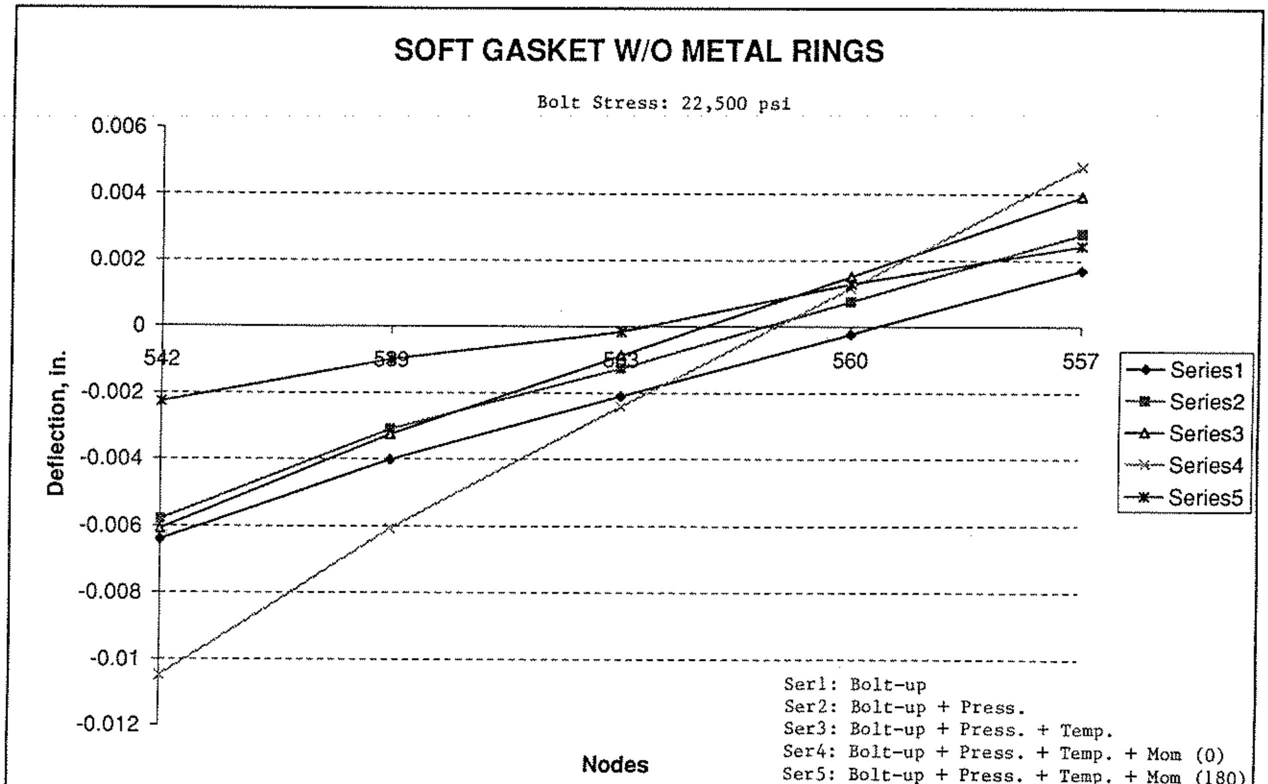


Table 1



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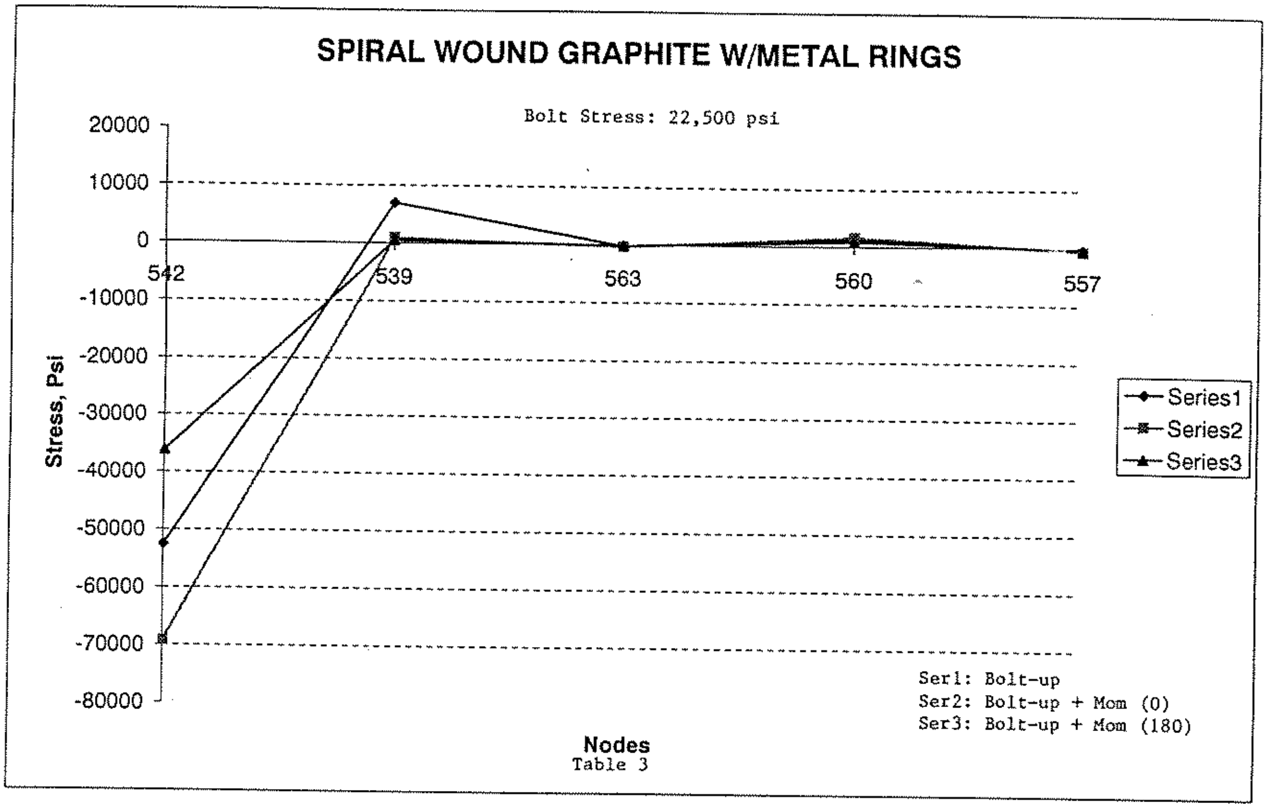
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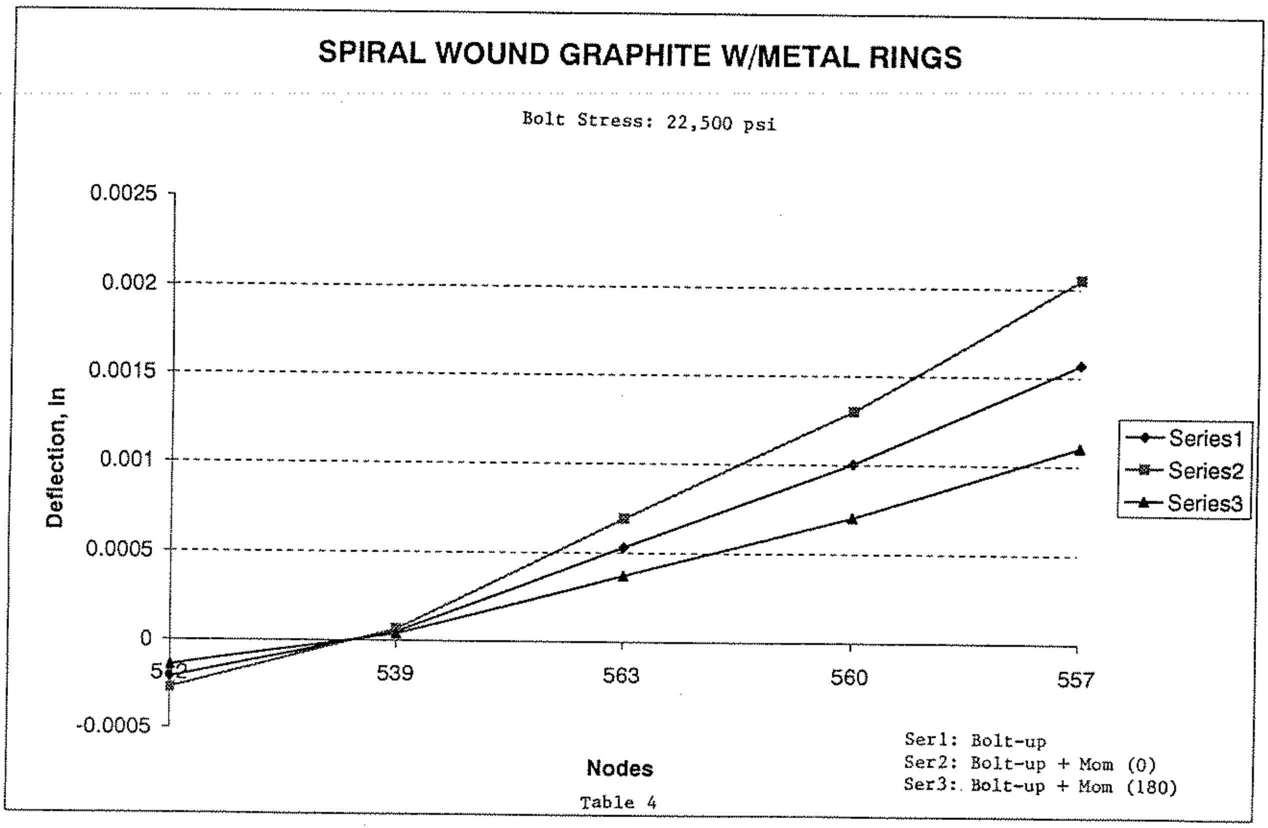
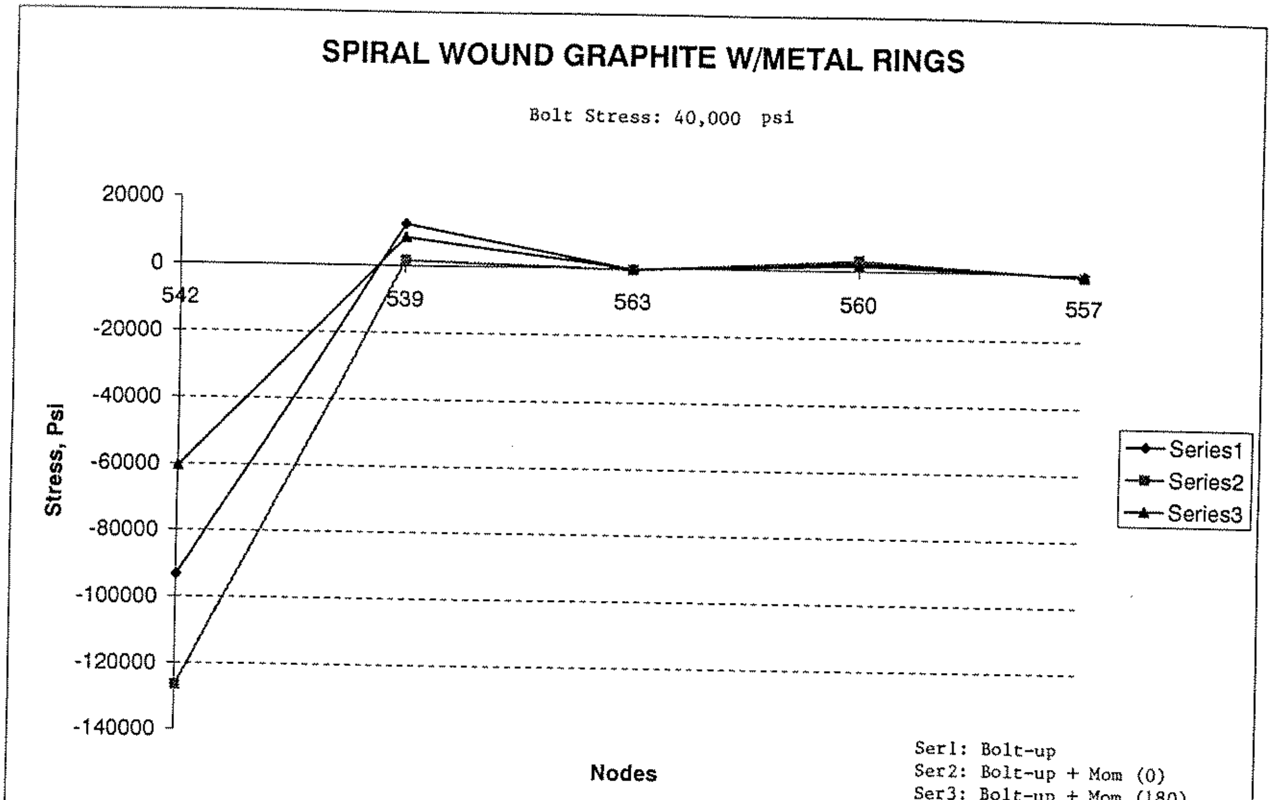
Bolt Stress: 22,500 psi
Stress, Psi
20000
10000
0
-10000
-20000
-30000
-40000
-50000
-60000
-70000
-80000
542
539
563
560
557
Series1
Series2
Series3
Ser1: Bolt-up
Ser2: Bolt-up + Mom (0)
Ser3: Bolt-up + Mom (180)
Nodes
Table 3


SPIRAL WOUND GRAPHITE W/METAL RINGS
Bolt Stress: 22,500 psi
Deflection, In
0.0025
0.002
0.0015
0.001
0.0005
0
-0.0005
542
539
563
560
557
Series1
Series2
Series3
Nodes
Ser1: Bolt-up
Ser2: Bolt-up + Mom (0)
Ser3: Bolt-up + Mom (180)
Table 4



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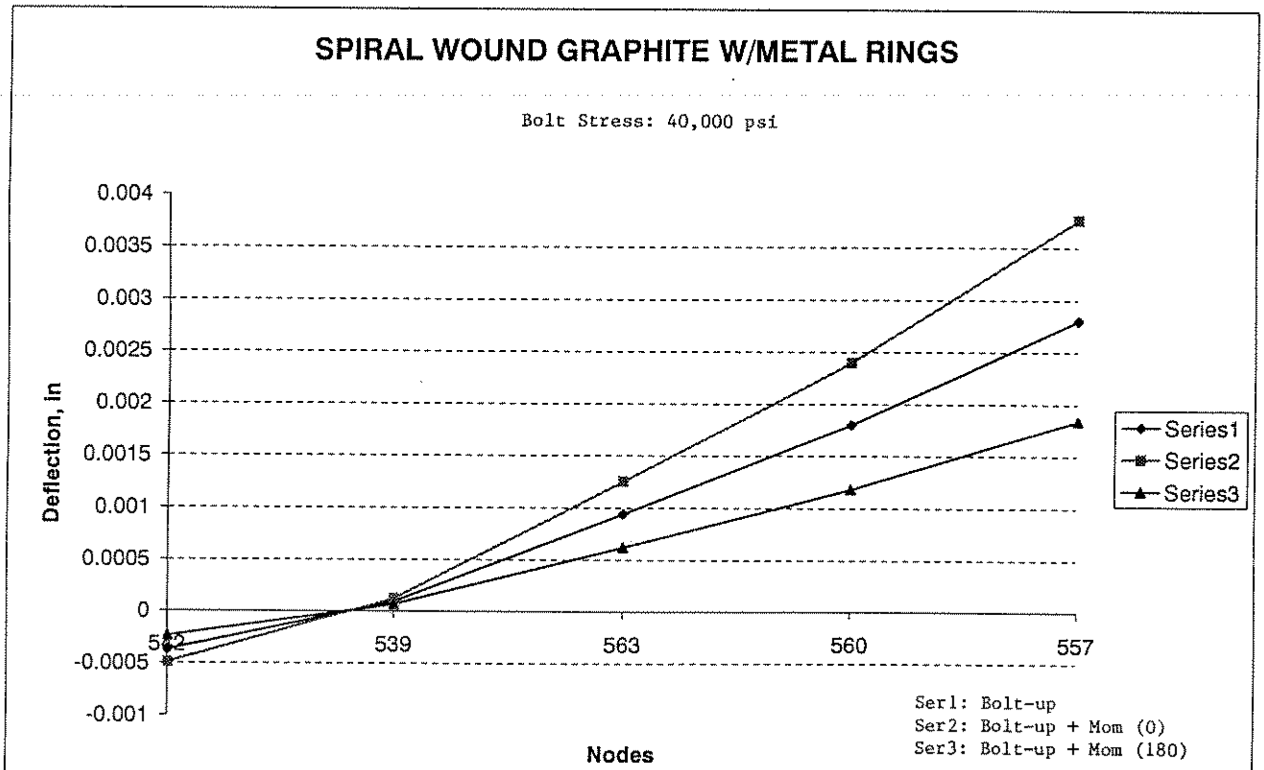

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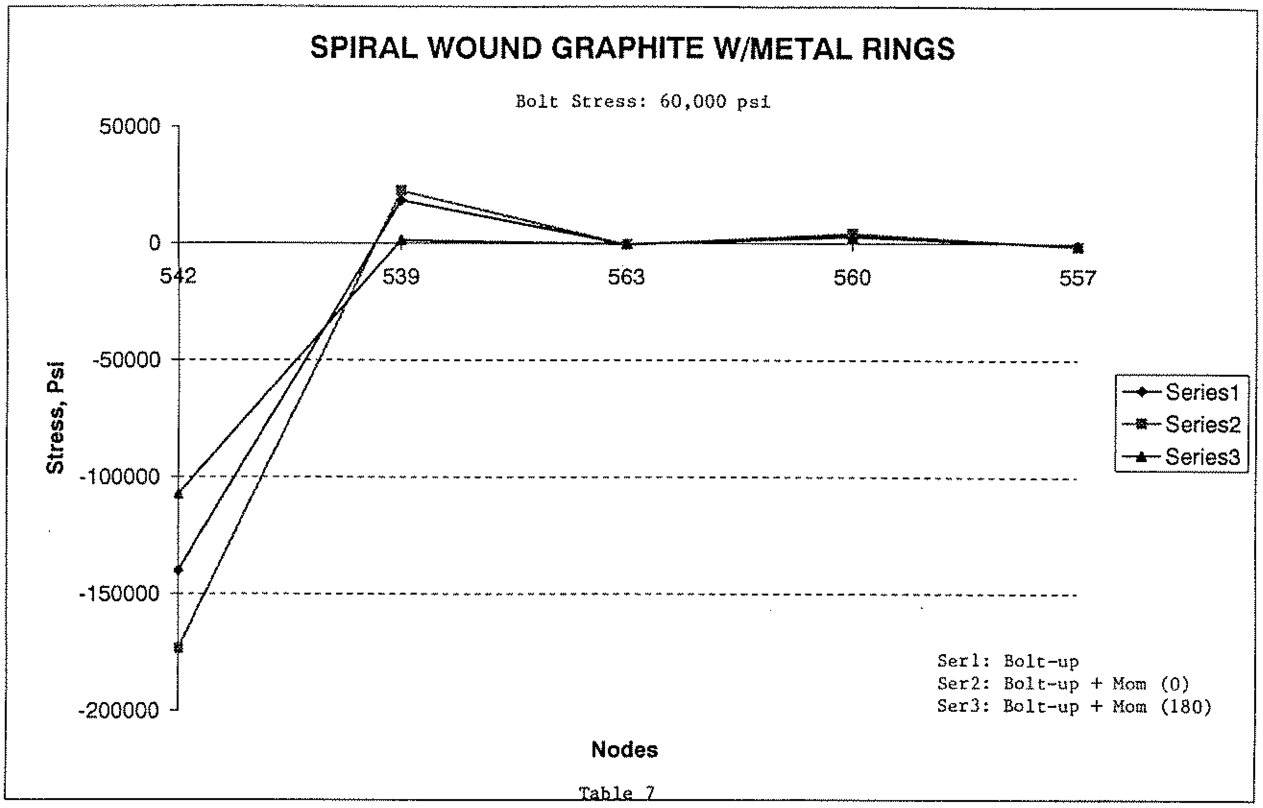

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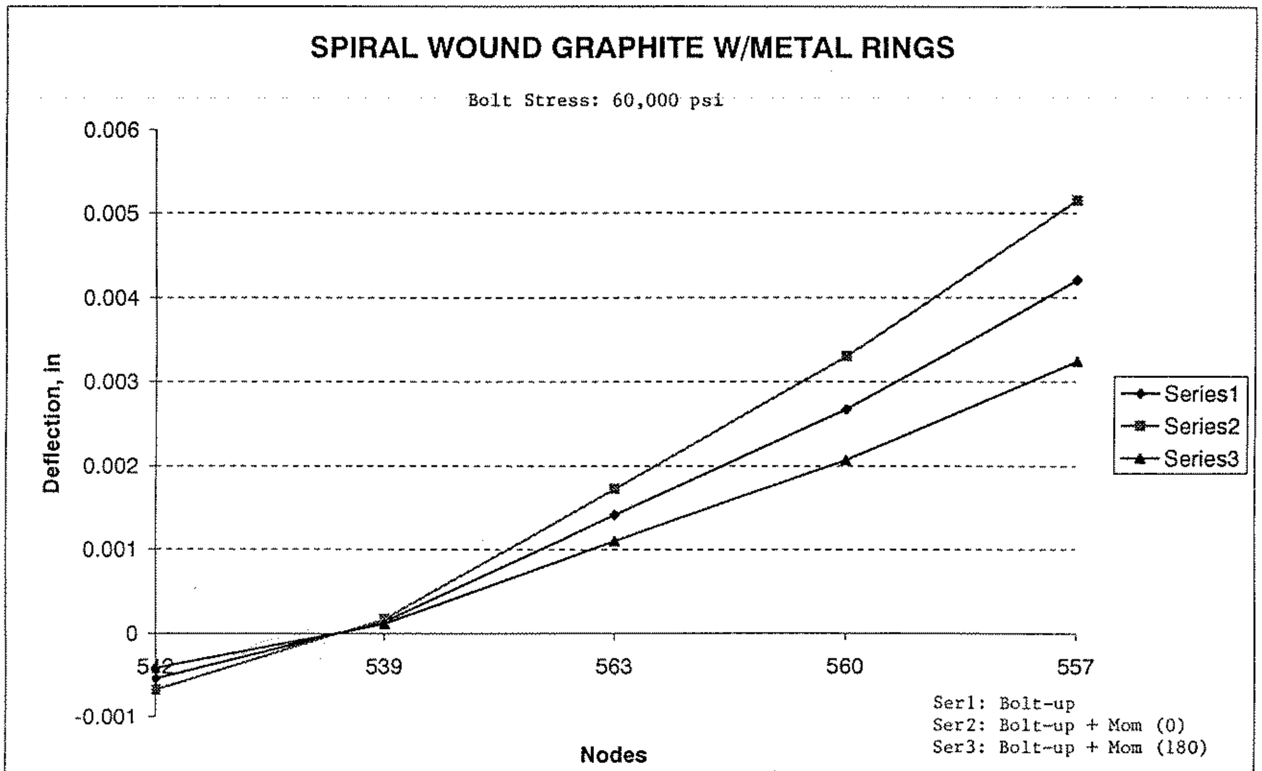

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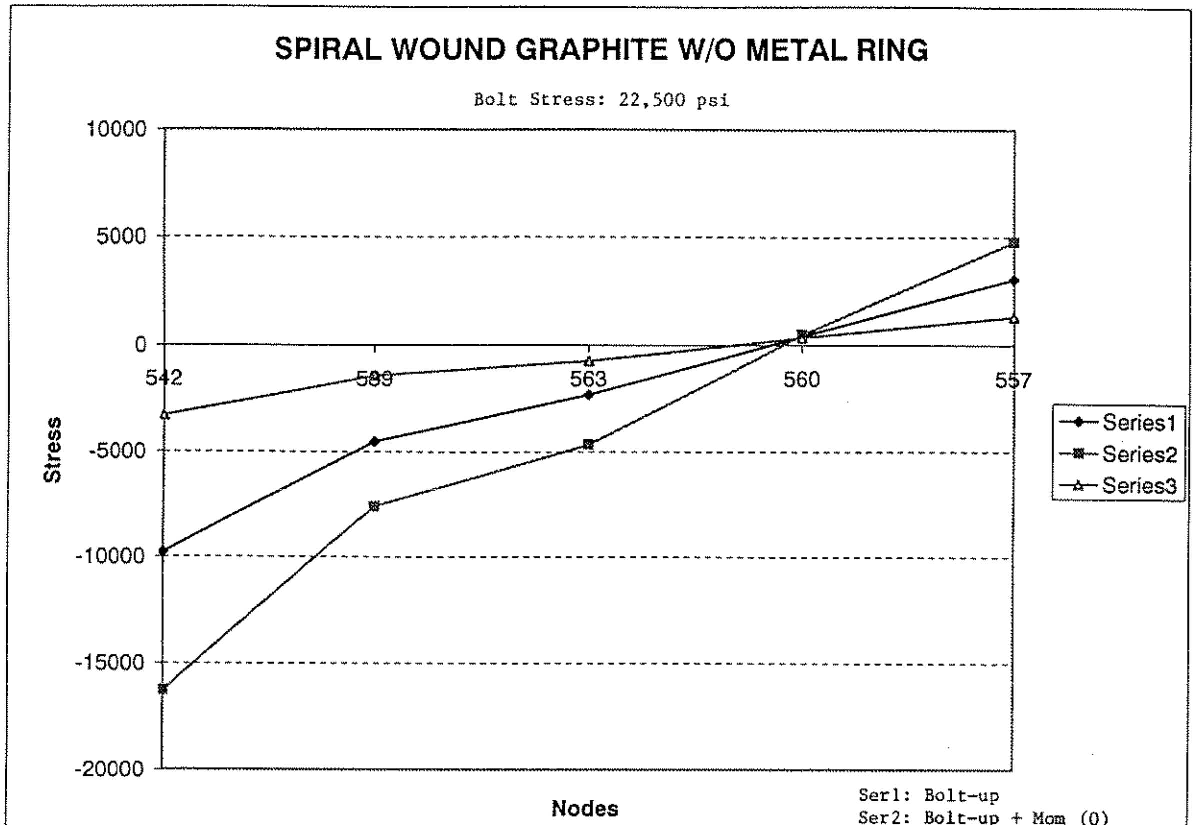

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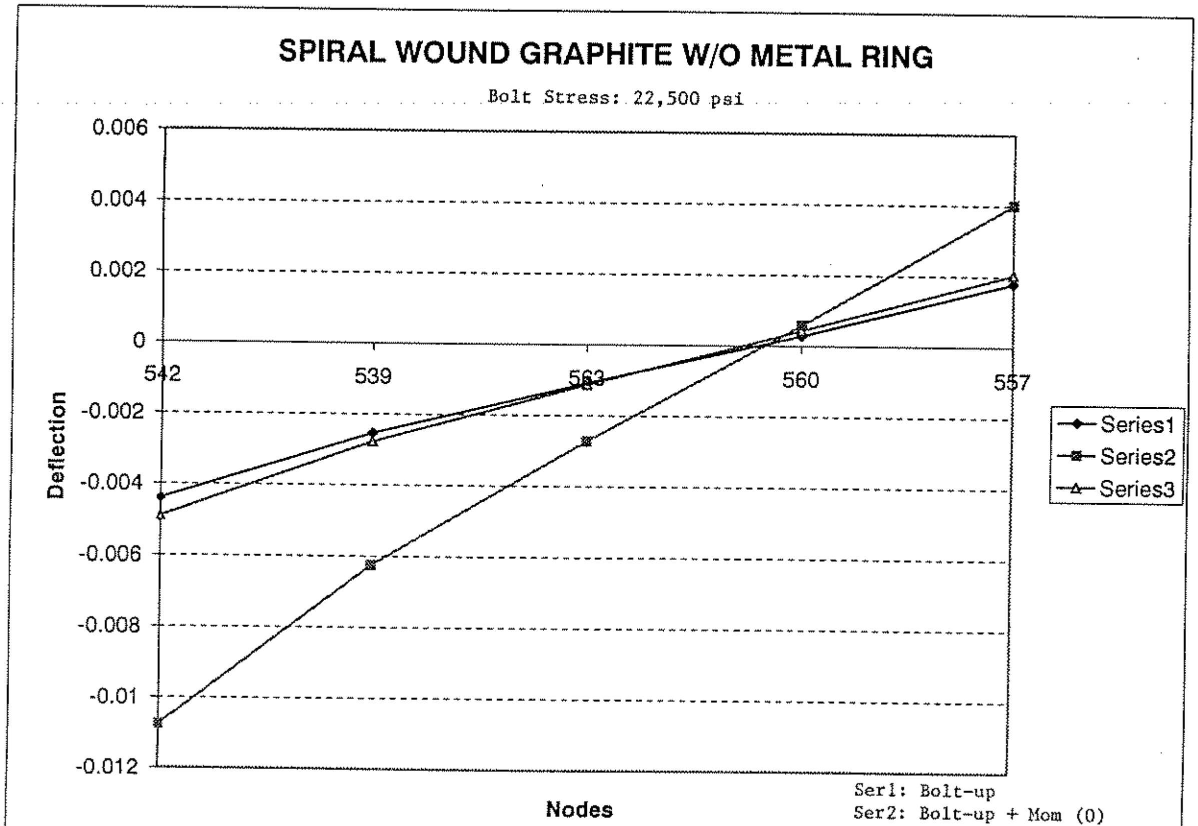

Table 10

MODEL	GASKET	DESIGN CONTACT STRESS (PSI)	YOUNG'S MODULUS (PSI)	METAL RING	BOLT STRESS (PSI)	FLANGE HUB STRESS INTENSITY (ID)		MAX. COMP. STRESS @ GASKET & FLANGE CONTACT SURFACE		
						BOLT-UP	BOLT-UP+ MOMENT	BOLT-UP	BOLT-UP+ MOMENT (0)	BOLT-UP+ MOMENT (180)
FLG0X	Spiral Wound	10,000	200,000	YES	22,500	14,000	19,000	190	250	110
FLG0X1	W/Composite	10,000	200,000	YES	40,000	25,000	34,000	340	450	200
FLG0X2	Filler	10,000	200,000	YES	60,000	37,500	51,000	500	620	350
FLG0A	Spiral Wound	10,000	200,000	NO	22,500	24,600	39,200	9,800	16,000	3,300
FLG0A1	W/Composite	10,000	200,000	NO	40,000	44,000	58,300	17,400	24,000	11,000
FLG0A2	Filler	10,000	200,000	NO	60,000	65,600	80,000	26,000	33,000	20,000
FLG0B	Composite	3,300	50,000	NO	22,500	27,500	41,000 *	4,000	6,500	1,300
FLG0B1	W/Elastic	3,300	50,000	NO	40,000	48,600	65,000	7,000	9,700	4,400
FLG0B2	Binder	3,300	50,000	NO	60,000	73,000	89,000	11,000	13,000	7,800

* Include Pressure and Temperature

Table 11