LARGE UHV JOINTS (I.D. 1100 mm, $< 10^{-10}$ TORR)

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ABSTRACT

The Antiproton Accumulator (AA) at CERN comprises a 160 m long UHV system with apertures up to 1100 mm. The design parameters of this machine called for an average pressure $< 10^{-10}$ Torr employing bakeout temperatures up to 350°C. Prior to its construction several sealing techniques were examined with a view to their space requirements, ease of mounting, reliability and cost. These studies included different types of demountable, as well as in-situ welded joints. Particular constraints were the limited space available for the joints and the lack of freedom with respect to axial rotation of the components to be joined. The solution adopted consists essentially of demountable joints of the WHEELER type (VARIAN trademark), but with some special improvements. During 6 years about 100 such joints have been successfully in use at CERN on various machines operating at pressures down to $2 \times 10^{-12}$ Torr.

Geneva, December 1986

Paper presented at the 10th International Vacuum Congress in Baltimore, 27-31 October 1986
I. **DEMOUNTABLE OR WELDED JOINTS?**

In the design phase of the AA machine at CERN in 1978 it became apparent that some fifty joints with I.D. from 720 mm (28") up to 1100 mm (43") would be required. Unlike most other modern particle accelerators and storage rings working under UHV this machine required these large apertures without any restrictions over distances up to 65 metres. The outer shell of the so-called beam pipe, therefore, would become more like a vacuum tunnel, but, since the inner beam path would be conductance limited by kicker magnets, screens, electrodes etc., it needed all the features of a bakeable UHV system.

One of the first questions raised by these requirements was whether the joints should be, at least in part, of a welded or entirely of a demountable type. The first solution seemed attractive since elsewhere the limited space available in the inter-magnet gaps of the machine imposed in situ welding of several joints of about 500 mm (20") by 150 mm (6") between adjacent vacuum chambers. By taking advantage of the welding technique required for this operation, it would have been profitable to weld all the large joints, including those for the special tanks containing the complex equipment mentioned above. The generally accepted technical argument that welded joints, once leak tight, are more reliable than all commonly known demountable types, became attractive. However, at this stage, it was decided to test to the greatest possible extent all the vacuum chambers, including the special tanks, individually with respect to their end vacuum prior to installation. Accordingly, this would require some additional, and preferably demountable, blank-off system during the initial test phase. Furthermore, it was now admitted that any of some 15 special tanks might have to be opened several times, in particular during the first year of the running-in of the machine as well as in later operation. In view of the requirements and forecasts outlined above, a first design study included several compromise solutions, as shown in Fig. 1. These designs are clearly inspired by the Fischer-Souchet\(^1\) seal design with a view to the possibility of using clamps as in the WHEELER\(^2\) flange design.

II. **TYPE OF DEMOUNTABLE JOINT**

Essentially three types of UHV demountable joints were considered, namely the:

- ISO Standard 3669 (extrapolated)
- Fischer-Souchet design
- WHEELER design
A modified WHEELER flange design and the so-called compliant gasket flange designs as published in 1977 by W.R. Wheeler\textsuperscript{3} were not pursued because no experimental data seemed available at that time.

A. ISO standard 3669 (extrapolated)

This standard (updated in 1986) gives general guidelines for the dimensions of bakeable vacuum flanges of the bolted type up to I.D. 1000 mm. However, manufacturers are free to select both their preferred design of sealing surface within the specified seal area and type of gasket, provided that the required tightening force be kept within certain specified values. This type of UHV flange, (and similar designs, which probably led to the standardisation), were commercially available well before the construction of the AA machine at CERN. Nevertheless, the small number of manufacturers at that time, at least in Europe, who offered this type of joint, limited their range to a maximum nominal size of I.D. 630 mm (25\textquotedbl). Furthermore, the gasket commonly offered for these joints was of the gold wire type which was compressed between flat sealing surfaces. Unfortunately, the field experience gained with smaller sizes of this type of joint at CERN around 1960-65, and probably elsewhere as well, did not inspire too much confidence. Some reluctance concerning the use of gold as a gasket material, as will be mentioned later, could not favour this solution either. Other types of gaskets like HELICOFLEX\textsuperscript{4} or similar were not excluded as such for use together with the ISO Standard flanges. However, for reasons of lack of experience with the above joint configuration and cost considerations related to the required dimensions, this type of joint was abandoned in the course of the design study.

B. Fischer-Souchet design

This type of joint had been extensively used at CERN for UHV tanks with an I.D. up to 680 mm (27\textquotedbl), using either gold or pure copper wire gaskets. However, by scaling this type of joint to larger dimensions it had been experienced that the radial width of the centering rings had indeed to be increased at least linearly with the overall diameter in order to resist the sealing force transmitted by the gasket\textsuperscript{5}. For joints with I.D. 1100 mm this would mean inconveniently heavy centering rings weighing from 20 to 30 kg, depending on the mechanical properties of the material, the dimensional tolerances of the sealing surface, the cross-section of the wire gasket etc.
C. WHEELER design

The answer to the apparent complications with the enlarged Fischer-Souchet joints seemed to be the classical WHEELER flange design, or similar, where the capturing of the gasket as well as the centering of the mating flanges are incorporated without any additional centering ring. Admittedly, this design has the constraint of having asymmetrically mating flanges, but this should be no problem in a system practically built up of only unique pieces.

For the AA machine it seemed especially attractive to use joints equipped with clamps, thus avoiding heavy rotatable flange configurations otherwise needed for the angular alignment of the large aperture bellows to be fitted between the adjacent chambers and tanks. Furthermore, because of the packing factor aimed at in most particle machines, space is generally scarce for vacuum joints, in particular, in the longitudinal direction. Accordingly, clamps which could be brought in radially to the mating flanges would in this case offer an additional advantage over standard bolts. This argument would become even more valid once the vacuum vessels were equipped with their voluminous bakeout equipment. Finally, clamped joints, as compared to those equipped with standard bolts, offer the possibility of increasing the overall tightening force by simply adding clamps as long as there is space available around the periphery of the mating flanges. In principle, this would permit the use of gasket types requiring higher sealing pressures. Of more practical interest would be the possibility of adding clamps locally to a leaky joint whenever needed.

III. TYPE OF FASTENERS

Although in the foregoing part of the design study a certain preference for the WHEELER type of flange with clamps had become obvious, certain questions related to clamps versus standard high tensile bolts had to be verified. Firstly, it seemed to be confirmed that for any suitable thread size several makes of commercially available clamps could offer tightening forces equal to that of standard high tensile bolts. This theoretical comparative study applied to austenitic stainless steel for both types of fasteners. More important, however, was the finding that clamps were claimed to have more elastic tensile strain than the equivalent sizes and classes of standard bolts. This effect could, therefore, possibly compensate for the higher induced elastic strain which one might expect from the slight warping of the bolted flanges due to the inevitable distance between their bolt circle and the seal area. Last but not least, the expected higher capital cost of the relatively large number of
clamps had to be compared with that of the design using standard high tensile bolts. A rough estimate showed that the price difference between the more expensive clamps and the standard bolts would be compensated by the possible saving of extra material and machining costs as required for the bolted flanges.

Finally, it was decided to equip a prototype joint with the well proven standard type of the WHEELER clamp. The alternative solution would have been to use the DIN Standard clamp or some similar type, as shown in Figure 2. This type of clamp is different from the WHEELER design in so far that one of the clamp segments has a 'back-leg' and, thus, this part must always bear on the back of the other clamp segment. In this way the possible bending of the clamp stud is reduced. In addition, the design of the DIN Standard clamp is such that the tightening force is transmitted to the flanges from the nose of the segment hooks to the base of the grooves in the flanges. With this design the grooves can be made shallower, which will ease the machining, whilst the clamp segments including their hooks would be forged.

IV. TYPE OF GASKET

Extremely quick and easy mounting or removal of the gaskets because of, for instance, induced radiation, was not considered to be a requirement in the AA machine. For the choice of the gasket material the question was, essentially, whether to use gold or copper wire. Tests carried out at CERN with the Fischer-Souchet type of joint had shown that the difference between the characteristic stresses produced in the two types of wire gaskets was marginal, i.e. about ten per cent lower for gold\(^8\). A more important advantage of pure gold, as compared with copper for the gasket material, would be its immunity to the effects of oxidation when baked to 300°C or above. Hard flakes of copper oxide tend to stick to the sealing surfaces, and may destroy the surface during the re-assembly of a joint. Heavy oxidation due to extensive baking may also directly produce leaks when using copper gaskets\(^9\). However, with the fluctuations of the gold prices, seen so far, the material cost for one single gasket of the larger dimension would have been up to 7800.- US$. It is clear that the book-keeping of large amounts of gold in an extensive laboratory easily becomes, at the best, an important effort in time and money. Therefore, in the first instance, annealed oxygen free copper wire was chosen as the gasket material for the prototype joint.
V. PROTOTYPE JOINTS

One prototype of a large joint, manufactured according to the proprietary WHEELER design, was procured for evaluation tests at CERN. For practical reasons, the nominal size of this prototype was limited to 1020 mm (40""). The overall dimensions of the cross-sections of the prototype flanges, as agreed between the manufacturer and CERN, are shown in Fig. 3. The corresponding dimensions of other commercially available flanges similar to the WHEELER type, as well as those of bakeable flanges according to the ISO Standard 3669, are shown for comparison. As can be seen, the cross-sections of the prototype flanges were relatively small, i.e. practically identical to those normally used for similar clamped flanges up to a nominal I.D. 600 mm (24""). As a result, the ovality of the finished and supposedly mating flanges was several times more than the average radial clearance. However, due to this slender design, the flexibility of the flanges allowed easy assembly and correct tightening by means of the standard clamps. Although not needed for the mounting, a single point load $P$ (N) at the periphery of one of the flanges would give an elastic deformation of about $\Delta D = P/1500$ (mm), as calculated and later checked by measurements. (It may be of interest to note that the dimensions of the prototype flanges, as later adopted, are close to those specified, for instance, in the DIN Standard 28 036 for stainless steel pressure vessels with clamped flanges.)

The geometry of the sealing surfaces, which 'capture' the wire gasket between the mating flanges, was kept as in the original WHEELER flange design. Finite element calculations of this geometry, including the wire gasket after tightening, were made with various angles of the conical sealing edges from 15" to 45". The variation of this parameter did not result in any significant changes in the calculated stresses, i.e. sealing pressures, in the gasket.

The prototype joint was subjected to seventeen bakeout cycles up to a nominal 300°C, (minimum 240°C/maximum 350°C), without any leaks showing-up. During these tests, the standard copper gasket was replaced after three and again after another eleven bakeout cycles. However, these baked gaskets were relatively difficult to remove because of 'sticking', probably due to some slight diffusion welding between the copper and the stainless steel. As expected, deposits of copper oxide on the flange sealing surfaces had to be cleaned off with great care prior to the remounting of a new gasket. In order to eliminate the problem of oxidation of the copper gaskets, it was decided to procure the wire material plated with a 10 µm layer of silver. This technique has been used successfully at CERN for other types of copper gaskets for many
years\textsuperscript{10}). With such gaskets the 'sticking' problem was also eliminated, since silver has no affinity for bonding to stainless steel\textsuperscript{11}).

In view of the encouraging results of the preliminary tests with the first prototype joint, it was decided to equip three prototype tanks with similar joints. These tanks, with apertures from 720 mm to 1100 mm, were needed for the UHV testing of ferrite magnets, moveable shutters and other special equipment being developed for the AA machine. In order to save time, some of the flanges were roll-formed from rectangular stainless steel bar stock material into rings which were joined by welding. Again, as for the first prototype, provisional plain copper wire gaskets and standard WHEELER clamps were used for these joints. The more complex test programme which now followed was carried out in different laboratories at CERN and true field testing of the prototype joints was achieved.

Minute leaks which tended to show up systematically on one of the large flanges during bakeouts were not a complete surprise. Such leaks were easily traced to the position where one of the provisional roll-formed flanges had been welded prior to machining. However, these leaks could always be eliminated by adding a few clamps to the leaking section of the joint assembly. Examinations of the leaky gaskets performed with a scanning electron microscope confirmed that these leaks developed repeatedly at the interface between the gaskets and the flange due to the slightly poorer surface finish provoked by the inhomogeneous grain structure in the weld.

Some specific problems related to the available standard clamps were encountered during the field testing of the prototype joints, and these clamps had therefore to be modified. The recommended tightening torque was 60 ft-lbs (about 80 Nm) provided that an appropriate high-temperature lubricant be applied. The corresponding effective tightening force produced by such a standard clamp was measured to be 20'000-30'000 N. The lower value of this tightening force is not always sufficient for the copper wire seal in question when the joint is mounted with a reasonable number of clamps, i.e. with an equi-distance of typically three times their width. The limited performance of the standard clamps was attributed to two phenomena. Firstly, the moveable segments tended to 'bite' into the shafts of the studs, thus producing high friction losses. Secondly, not only was the machined thread on the studs of a rather poor finish, but also the yield strength of the studs was variable with minimum values of about 540 N mm\textsuperscript{-1}. These flaws were remedied by chamfering the holes in the segments and replacing the standard studs with special, but commercially
available high quality cold rolled studs having a yield strength of about 770 N mm$^{-1}$. Finally, for the modified clamps used on the prototype joints an optimum tightening torque of 60 Nm (about 45 ft.-lbs) was specified corresponding to a measured tightening force of 30'000-37'500 N per clamp, see Figure 4. According to current practice at CERN for fasteners on UHV joints, the nuts had been pre-treated with a high-temperature dry lubricant. This torque would guarantee leak tightness without destroying either the clamps or the lips at the periphery of the grooved flanges.

IV. CONSTRUCTION AND OPERATING EXPERIENCE

Based on the prototype design, and similar to the original WHEELER joint, about one hundred large joints with an I.D. up to 1'100 mm have been manufactured and successfully put in service on various machines at CERN, see Figure 5. The flange material specified by CERN has normally been forged, high purity stainless steel of grade AISI 316 L alloyed with 0.14-0.18 per cent nitrogen. The machining of the flanges, which form an integral part of the chambers, the tanks and the flexible metal bellows, etc. has been performed by different companies according to CERN drawings. The fasteners used for the joining of these flanges have been, so far, the modified WHEELER clamps. However, the trend at CERN seems to be in favour of the DIN Standard type of clamp. Such clamps, which have been successfully tested, would save the deep grooving of the flanges and avoid a possible deformation at the periphery of the present lip. Gaskets for all sizes of the joints were easily prepared in the laboratory by cold pressure welding of a spliced joint in the silver-plated O.F. copper wire.

The operating experience with these large UHV joints has confirmed that the right option was taken when it was decided to provide demountable joints for the A4 machine. Since 1980 most of these joints have been opened and remounted routinely several times and all of them baked at least six times. These interventions have not been necessary because of inadequate performance of the vacuum system or leaks in the joints, but rather these interventions, for reasons related to machine operation, have been possible due to the reliability of the joints. During a period of six years, two leaks at the detection limit of 1 * 10$^{-10}$ Torr lsec$^{-1}$ have been recorded; one was caused by a fibre and another due to poor welding of the gasket. Both could, in the first instance, be eliminated by adding a few clamps.
VII. CONCLUSIONS

Three conclusions can be drawn from the present experience. Firstly, the following opinions seem to be generally accepted concerning demountable UHV joints, namely that 'certain dimensional factors cause serious problems as the size increases' and that 'fixed radial clearances (including tolerances) become proportionally tighter as the size increases whilst roundness and flatness become more difficult to maintain'. However, the additional but controversial statement is made here that 'designers often scale up the flange cross-sections proportionally to the first or even higher power of its diameter, but wrongly so'. Therefore, large joints tend to become too rigid, thus preventing elastic deformations which could otherwise compensate for flange ovality and waviness which are inevitable imperfections under all circumstances. Instead, correct scaling in the design of large UHV joints should be a compromise between the utility of having relatively flexible flanges and the possibility of proper jiggging permitting near to perfect machining. Secondly, high quality fasteners providing the required sealing force in a reproducible manner are indispensable. Both product quality control and discipline with the tightening procedure are important features in this respect. Thirdly, for large demountable UHV joints with stainless steel flanges, copper wire gaskets provide reliable leak tight joints, but silver-plating of such gaskets is highly recommended.

REFERENCES

4. Trade name of CEILAC, 42029 St. Etienne Cedex, France.
8. CERN Internal Report, ISR-GE/CM/Emg of 78.10.10.
Figure 1

Fischer-Souchet joint design;

a) bolted;
b) welded and fixed with brackets;
c) clamped, including option for welding.
Figure 3

Prototype flanges (overall dimensions: 30 mm * 40 mm) compared with commercial designs and ISO Standard 3669
CLAMP TIGHTENING FORCE
= f (torque)

Figure 4
Figure 5

Joint I.D. 1100 mm, with transition to joint I.D. 720 mm, as installed in the AA machine (bakeout jackets not mounted).