HYDRAULIC EXPANSION OF TUBES

M. PODHORSKY

Abstract:

The hydraulic expansion process HYTEX is, in the meantime, 20 years old and is now established as a recognized process in the heat transfer equipment construction sector worldwide. It was above all the technical advantages, the wide range of possible applications for the process and the superior quality achieved compared to other tube fastening process wich have led to the HYTEX process being widely used.

Hydraulic Expansion of Tubes

1. The origin of the HYTEX process

The hydraulic expansion process HYTEX is, in the meantime, 20 years old and is now established as a recognized process in the heat transfer equipment construction sector worldwide. It was above all the technical advantages, the wide range of possible applications for the process and the superior quality achieved compared to other tube fastening processes which have led to the HYTEX process being widely used.

In the early 1970s Germany was going through an innovative phase, particularly in the plant construction sector, heat transfer equipment construction sector for the chemical industry and last but not least the power engineering sector. The first commercial nuclear power plants had been commissioned and further ones were being steadily planned.

The high degree of availability to be fulfilled by the individual plant components and the more stringent operating safety requirements justifiably led to the question of possible improvement of the tube/tubesheet joint in a heat exchanger being raised.

At the time the tube expansion processes by rolling, which had been used for 150 years and were based on practical experience, were regarded as state of the art.

The frequency with which tube damage occurred in the tube/tubesheet joint section increased at an alarming rate in this period. Spectacular tube damage occurred above all in the heat recovery boilers in ammonia plants [2]. These heat exchangers which at the time were mainly fabricated as U-tube constructions, cooled the hot process gas in the tubes and generated saturated steam on the shell side. They fulfilled practically the same function as a steam generator in a nuclear power station with pressurized water reactor.

Dr.-Ing. M. Podhorsky, D-4030 Ratingen, Balcke-Dürr AG

...

The tube/tubesheet joint understandably became a very topical subject and in Germany a working group was set up in which the experts from the heavy machinery and heat transfer equipment sector joined forces with material specialists and tube expander manufacturers to determine ways and means of improving this tube fastening method. It was intuitively known that the high residual tube stresses in the area around the expansion points and the presence of gaps between the tube and the tubesheet were the cause of the damage.

Extensive testing for corrosion due to stress cracking was therefore carried out at the tube/tubesheet joints during which different expansion moments, tube materials, geometries of the rotated hard steel expansion cylinders as well as different types of expansion equipment were investigated. The results were disillusioning. It was not possible to determine a clear trend and any assumed order was completely disrupted when the tests were repeated.

Parallel to these expansion tests we contemplated with interest the initial results of tests in which the tubes were exploded into the tubesheets. We were not, however, convinced by this new, at first sight seemingly simple method of tube fastening because it was found that the increase in material hardness and the presence of a gap had a great similarity with the expanded tube joint.

During a discussion about the advantages and disadvantages of the explosive tube fastening it become apparent that the cause for the unacceptable properties of the joints made in this way lies in the very high deformation speed.

The knowledge of this fact and its analysis then led to the idea of a "gentle", i.e. slow tube fastening process using a fluid. That was how the idea of the HYTEX process was born [7]. It was tried out straightaway using simple means without a great deal of theorizing and con-

...

stantly improved after encouraging initial results. The improvements related mainly to the equipment. The first, self-made expansion unit expanded the tubes using hydraulic fluid. This however, led not only to the inner surface of the tube being fouled with oil but also to the workplace becoming unacceptably dirty. This disadvantage was soon eliminated by integrating the medium separator in the HYTEX unit (Fig. 1). This medium separator separates the pressure generating hydraulic fluid from the expansion fluid and ensures that the expansion section is filled with this fluid.

After several further development stages the HYTEX unit reached its present set-up and form (Fig. 2). Great significance was attached to the reliability of the plant and to ease of operation and at the same time to achieving and maintaining a high standard of quality. The unit was equipped with a piezoelectronic high pressure sensor and an electronic monitoring system to measure the expansion pressure directly. The obvious physical and mechanical conditions which prevail during the tube fastening process based on hydraulic expansion soon led to the inception of a suitable calculation method which could reliably determine the quality of a tube/tubesheet joint in advance [1]. This fact made it possible to develop an understanding of the mutual influence mechanism of the two partners, i.e. the tubesheet and the tube as it is known today [12]. The fact that it is possible to calculate the joint was one of the main reasons for the HYTEX process being applied worldwide within a very short period of time [3, 4, 8]. The research work carried out at the end of the 1970s and the beginning of the 1980s at AECL contributed significantly to this [9, 10, 11].

2. The principle of hydraulic expansion

The principle of hydraulic expansion is amazingly simple. In the expansion sector, the tube at first becomes elastic then plastically deformed due to the pressure of the hydraulic fluid, and is then pressed against the borehole wall. By increasing the pressure further,

...

the tubesheet or the header also becomes elastic and in some cases subsequently also plastically deformed. A greater elastic reverse deformation of the tubesheet compared to the tube after the pressure is relieved is decisive to ensure the residual adhesive pressure between the tube and the tubesheet.

The extent of the reverse deformation depends on the geometries and the yield points of the tubes and the tubesheets and can be determined in a calculation. The extraction force can be controlled by the expansion pressure level and the expansion distance.

The principle of hydraulic expansion is illustrated in Fig. 3. First of all the tube is subjected to elastic stress until it starts to yield and until the clearance between the tube and the tubesheet becomes smaller and smaller. When the tube is supported by the bore-hole wall, the tubesheet is also subjected to elastic and in some cases partially plastic stresses. Once the expansion pressure is relieved, reverse deformation occurs. The extent of this differs because in most cases the tube and the tubesheet are made of different materials and have different geometries. This is why the slope of the elastic reverse deformation curves differ. For reasons of equilibrium, a radial adhesive pressure p_H then remains between the tube and the borehole. In this way the tube is embraced and also fastened. This adhesive pressure only occurs when the free reverse deformation of the tube is less than the free reverse deformation of the tubesheet.

The fact that the tube can only be fastened as a result of the deformation and expansion of the structure by the hydrostatic pressure renders it possible to calculate the necessary expansion pressure. Furthermore it is possible to determine the stresses in the tubesheet during and after the expansion process. These are indispensable to assess the efficiency and reliability of a tube/tubesheet joint.

...

Assessment by calculation facilitates the selection of the materials and geometries of the tubes and tubesheets right from the planning stage. The theoretical derivation of the hydraulic expansion was published in [7].

3. Structural aspect of the tube/tubesheet joint

The tube/tubesheet joint can have various different structures. Some of these are illustrated in Fig. 4. The most frequent construction is expansion into the plain borehole. Variant b is applied if high extraction forces are required. The smooth groove is very easy and economical to make and therefore no significant additional costs are incurred.

In certain specific cases a joint incorporating an inserted contact sleeve made of plastic or metal may be beneficial.

As shown in [13] it is extremely easy to determine the adhesive pressure. The decision as to how high the minimum adhesive pressure must be depends on the surface quality of the borehole and the tube as well as on the expansion distance and the fluid pressure. A differentiation must be made between just expansion and fastening. An adhesive pressure of approx. 200 bar is adequate for mere expansion whereas adhesive pressures of 300 to 500 bar and more are required for fastening.

The calculation method derived for the design of hydraulically expanded tube/tubesheet joints assumes that the tube is rendered to a completely plastic state but that the tubesheet is not stressed to beyond is elastic limit. This would be desirable but in practice, however, for a wide range of reasons, both material combinations and tube/tubesheet geometries are often selected which require the tubesheet to be in a partially plastic state during the fastening process in order to achieve the required degree of fastening. In these cases it is not possible to build up permanent adhesion without this partial plastic deformation.

...

This fact makes the question of the maximum admissible expansion pressure, which does not negatively affect the adjacent joints, seem very relevant. In such cases it is nowadays also economically viable to carry out an elasto-plastic finite element calculation in order to determine the stress, the course and the extent of the plastic area during the expansion process.

Fig. 5 gives an example of such an elasto-plastic FEM calculation. In this case it is assumed that there is a radial gap of 0.3 mm between the tube and the borehole. A constant contact force cannot be built up until this gap no longer exists as a result of the plastic deformation of the tube. In order to fulfill this condition a total of seven gap elements were used to join the tube to the borehole.

Fig. 5a shows the curves of the same equivalent stresses during the expansion process with pi = 2500 bar. The shaded areas are the plastically deformed areas of the tubesheet and the tube during the expansion process.

Similarly Fig. 5b shows the curves of the same equivalent stresses during an expansion process with pi = 3500 bar. The plastic area in the tubesheet ligament has extended considerably.

The comparison of the FEM calculation with the analytical calculation of the residual adhesive pressure between the tube and the borehole wall once the pressure has been relieved shows that the results tally very well, as the deviation amounts to less than 8 %.

The problems of possible inadmissible interference during the expansion process are extremely important from the point of view of safety and designing an economic construction. An elasto-plastic parameter study was carried out for a whole series of common tubesheet geometries in order to establish appropriate decisive criteria. According to material law the ideal was assumed to be elasto-plastic without any hardness increase.

...

Calculations were carried out for the following geometries t/D1 = 1.1; 1.2; 1.3; 1.4 using the FE-program ANSYS (Fig. 7). Here the start of the plastification process and the progress of the plastic area were observed. Relatively low internal pressure increments of p = 50, each with approximately 100 iterations, were required for this.

The results were published in [13]; here Fig. 6 shows the spread of the plastic area relating to the plate geometry t/Di = 1.2. The individual illustrations show the spread of the plastic area in graphic form.

It is not easy to answer the question regarding the exhaustion of the ligament bearing capacity because the support effect of the rest of the tubesheet and the curvature of the borehole have a great influence on the bearing and deformation capacity of the ligament. It is, however, important to know whether or not the expansion or adhesive pressure places inadmissible stress on the adjacent tube/tubesheet joint. Fig. 7 sets out the appropriate information for different tubesheet geometries.

In Fig. 7 the radial displacement of point 1, i.e. the pressure on the adjacent borehole, is plotted as a parameter for the four different tubesheet geometries as a function of the internal pressure related to the yield point. The penetration of the plastic area and the related joint takes place at the end of the continuous curves. The broken curves denote the further pressure beyond this point up to twice the initial internal plasticizing pressure. No acceleration of the radial displacement can be detected which means that the bearing capacity of the structures has not yet been reached at twice the initial internal plasticizing pressure.

4. <u>Advantages of the hydraulic expansion process</u>

The hydraulic expansion process is an alternative method of tube fastening, which has numerous advantages over the conventional expan-

...

sion method used for tube/tubesheet joints. The expansion of a tube only takes seconds, irrespective of the fastening length. No tool wear is involved and therefore it is also possible to save costs. Only one person is required to operate the plant during the expansion process. It is not necessary to clean the tubes.

The advantages of the hydraulic expansion process are listed below:

- time and cost saving
- calculability
- uniformity of all joints
- minimal residual stresses in the tube
- closure of gap between tube and tubesheet
- reliable monitoring
- possibility to regulate the tube force
- low deformation speed

The advantages of the process predestine the HYTEX process for heat exchangers in which there is a risk of crevice corrosion. It is the only process which enables easy quality control during manufacture.

5. New construction possibilities in the heat transfer equipment sector using hydraulic expansion

The process of hydraulically fastening tubes into tubesheets opens the way for new constructions in the heat exchanger construction sector. In this sense the HYTEX process not only has an innovative influence on the tube/tubesheet joint but also on the entire heat exchanger design.

For example tube/tubesheet joints with difficult access can be reached using flexible probes (Fig. 8). This means that the headers, in which the heat exchange tubes end, can be kept correspondingly small. The heat exchanger can be constructed more compactly and the volume of the tube-side medium can be minimized. Another example for new possible

...

constructions in the heat exchanger sector is the expansion of tubes at a great depth. Tubes were successfully expanded and fastened to the tubesheet at a depth of 14 m (Fig. 9).

Previously at least one tube-side waterbox was required for each shell-side pressure stage. This new technology means that it is possible to divide the shell section into several pressure sections without having to resort to a costly waterbox.

This fact means that vessels connected in series can be combined to form a multi-stage unit (Fig. 10). A good example for a heat exchanger constructed in this way is the duplex preheater. Space-saving construction, short and simple pipe routing and compactness are the features of this system which are highly valued in power stations (Fig. 11.).

An interesting technical solution which can only be achieved with HYTEX is the straight tube heat exchanger which requires intensive cooling from the shell section due to the tubesheet being subjected to high temperature. In most cases this involves heat recovery boilers which cool the process gas from various chemical processes and bring the feedwater up to boiling temperature in the shell section. The steam generated in this way is mostly fed into the process. Fig. 12 is a diagram showing the construction of such a heat recovery boiler.

As the thin tubesheets are intensively cooled by the cooling medium in the shell section, two thin tubesheets supported by the heat exchanger tubes are required. The different temperatures of the tubes and the shell generate tube forces which together with the internal pressure produce considerable stresses in the tubes and also in the tube/tubesheet joints. In many cases these stresses cannot be controlled in conventional constructions.

One remedy is the Strain Blocking System (SBS), a process based on the pre-stressing of the tubes. Using this process the tube stress can be

...

minimized during operation. The sequence of the individual work steps is as follows: at first the tubes are hydraulically expanded into a tubesheet and welded to the tubesheet (Fig. 13). If necessary, the entire heat exchanger is heat treated. No annealing damage can occur as the tubes can expand freely. In the next step the individual tubes are preheated with a heating probe.

Once they have extended by a fixed, calculated amount they are hydraulically expanded into the second tubesheet. The expansion process takes only seconds and the sequence in which the individual tubes are fastened is of no significance as far as the resultant pre-stressing of the tubesheet it concerned. The tubes are permanently anchored in the thin tubesheets as a result of the deformation of the tubes in the smooth grooves. The tube/tubesheet weld joints only fulfill a sealing function, they are not involved in the transfer of tube forces. In practice the process can be very easily monitored [14]. No additional expensive equipment is required and it is user-friendly [13].

Fig. 14 shows an example of the tubesheet deformation of a loaded tubesheet. In this case, it is determined that the tubes extend by 2.3 mm so that the tubesheet deformation remains as small as possible under operating conditions [5, 6].

A time-tested application of the hydraulic expansion process to refurbish damaged tubes in service is HYTEX sleeving.

A thin-walled tube of a suitable material is inserted in the weakened tubes and pressed against the original weakened tube using a hydraulic fluid (Fig. 15). During this process the entire plastic deformation of the composite tube must be determined and restricted. If necessary, hydraulic expansion can be carried out at a higher pressure in the tubesheet section. When selecting the material for the sleeve, it is important to consider the stress caused by internal or external pressure and temperature as well as the stress due to surpressed thermal expansion in an axial direction.

...

A carefully considered construction, testing in the development workshop and practical experience guarantee a favourably priced and rapid refurbishment of damaged heat exchangers during a short inspection outage.

6. Summary

Since it was introduced approximately twenty years ago, the process for the hydraulic expansion of tubes has been developed further and new possible applications established in connection with the construction of vessels. The advantages of the process were recognized. In addition to the closing of the gap and the uniformity of all the joints, it is, above all, the low deformation speed of the tubes which is increasingly being acknowledged.

The low inherent stresses and the slow tube deformation ensure crack-free tube/tubesheet joints which are not sceptible to corrosion. Areas with difficult access and also at different depths can be reliably reached by using the flexible probe. Multi-stage heat exchangers can be constructed without expensive headers. These are characterized by low costs and greater availability.

The SBS permits specific pre-stressing of tubes and thus the appropriate construction of the tube/tubesheet joints for each specific application. HYTEX sleeving is a time-tested process for refurbishing damaged tubes in operation. It offers a rapid and low-priced solution to unexpected problems and is recognized by plant operators as a practical remedy in an emergency.

...

Bibliography

[1] Podhorsky, M., und Krips, H.:
Hydraulisches Aufweiten von Rohren
VGB KRAFTWERKSTECHNIK 59 (1979), H. 1

[2] Prescott, G.R., Podhorsky, M., and Blommaert, P.:
Improvements in Boiler and Tubejoint Design
AICHE Symposium, Minneapolis/USA (1987)

[3] Riha, Z., and Lichy, I.:
Qualitative Evaluation of the Technology of Joining the Pipes with Plate in Heat Exchangers
6/CPVT, Beijing/VR China (1988)

[4] Podhorsky, M., Riha, Z., and Lichy, I.:
Lebensdauererfahrungen mit Rohr-Rohrplattenverbindungen
VGB KRAFTWERKSTECHNIK 67 (1987), H. 11

[5] Prescott, G.R., Blommaert, P., Grisolia, L., and Podhorsky, M.:
Experience with a new design of reformer waste heat boiler, synthesis steam generator and steam superheater
AICHE Ammonia Safety Symposium, Denver/USA (1988)

[6] Krips, H., Podhorsky, M., und Blommaert, P.:
Der Geradrohr-Dampferzeuger im Energiekreis von Steam-Reformer-Anlagen
Chemie-Anlagen-Verfahren (1987), H. 9, September

[7] Krips, H., und Podhorsky, M.:
Hydraulisches Aufweiten - ein neues Verfahren zur Befestigung von Rohren
VGB KRAFTWERKSTECHNIK 56 (1976), H. 7

...

[8] Fino, A.F., and Dumas, W.A.:
Hydraulic expansion system produces leak-free tube-to-tubesheet joints
Power, October, 1979

[9] Bertin, L.:
On-site retubing of Candu units
Nuclear Engineering International, June 1982

[10] Gaffoglio, C.J., and Thiele, E.W.:
Tube-to-tubesheet joint strengths
ASME-Paper 81 -JPGC-Pwr-7

[11] Scott, D.A., Wohlgemuth, and Aikin, J.A.:
Hydraulically Expanded Tube-to-Tubesheet Joint;
Journal of Pressure Vessel Technology
Vol. 106, February, 1984

[12] K.P. Singh, and A.I. Soler:
Mechanical Design of Heat Exchangers,
Arcturus Publishers Inc. 1984

[13] Podhorsky, M., and Krips, H.:
Wärmetauscher, Vulkan-Verlag Essen, 1990

[14] Patentschrift DE 361 1108 C1

...

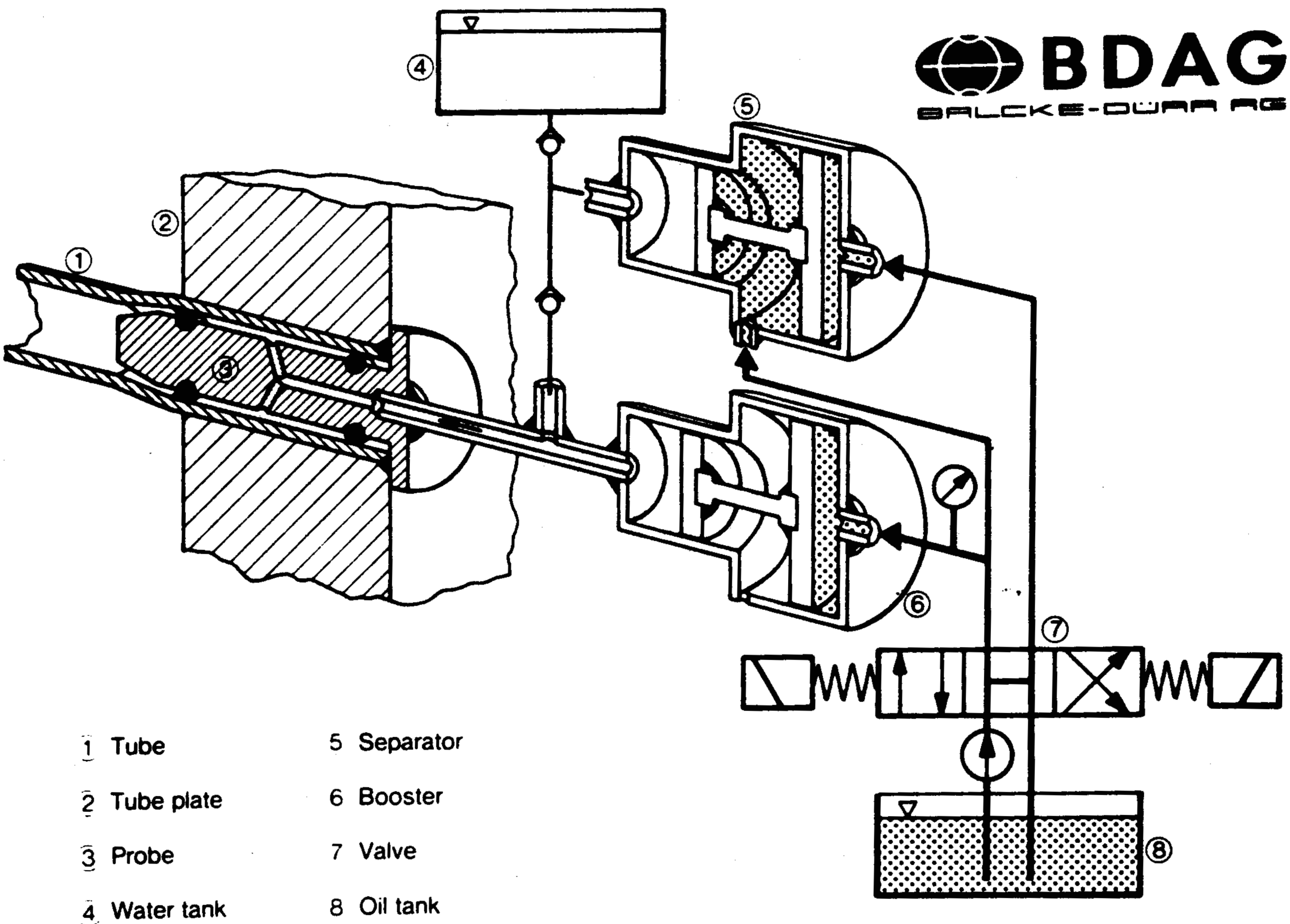


Fig. 1 Diagram of HYTEX expansion equipment

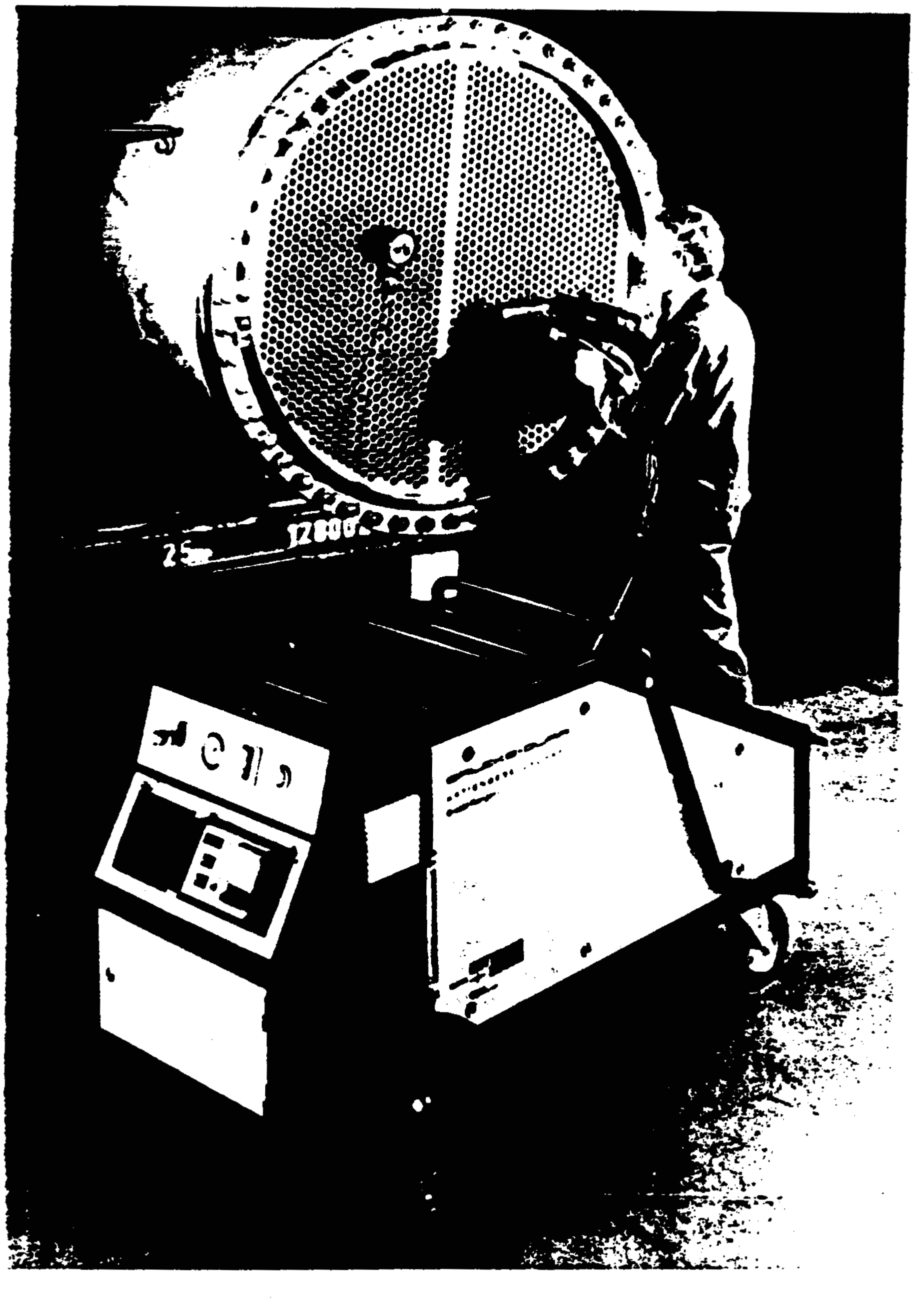


Fig. 2 HYTEX expansion equipment

BDAG
BALCKE-DÜRR AG

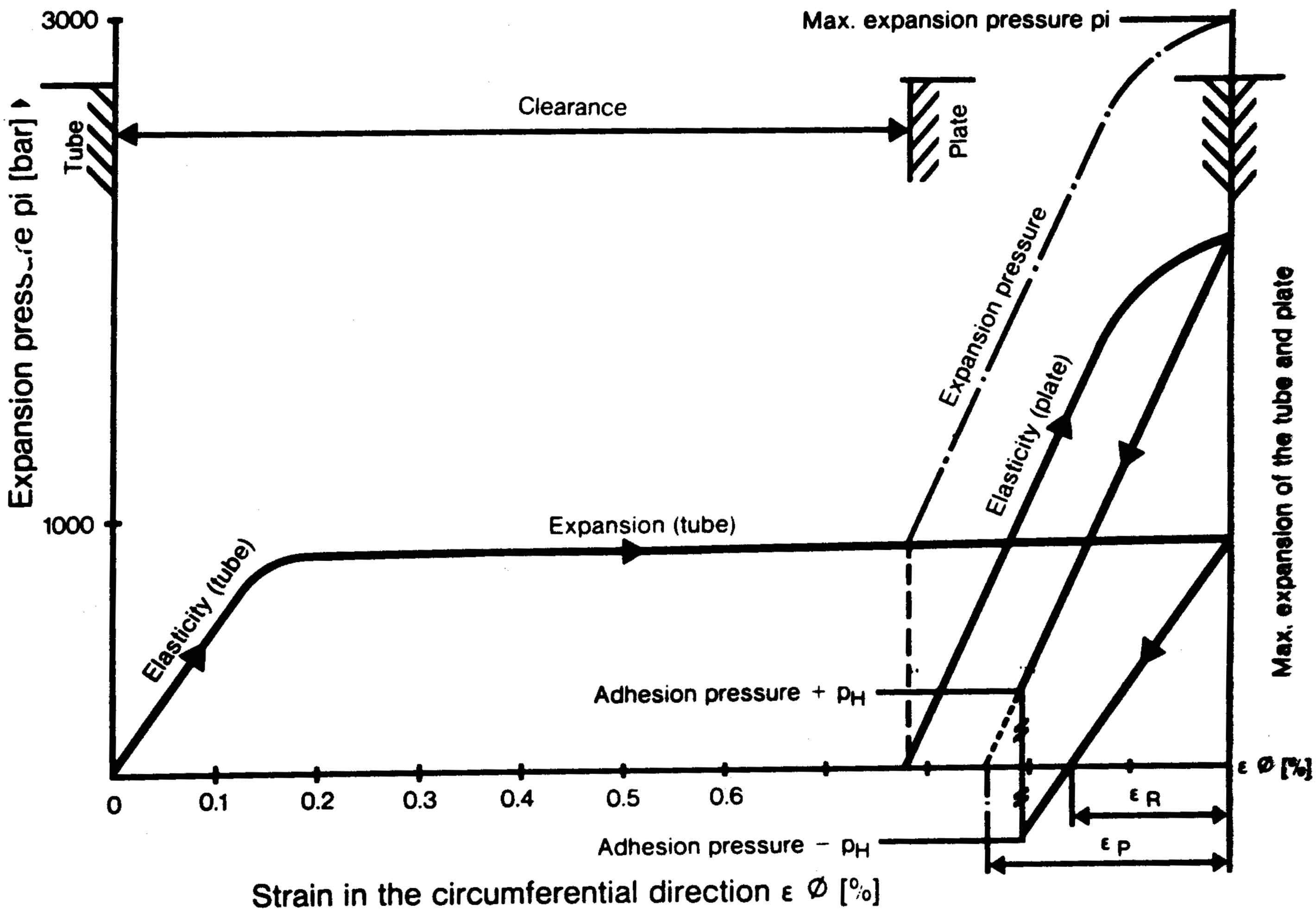


Fig. 3 The principle of hydraulic expansion

BDAG
BALCKE-DÜRR AG

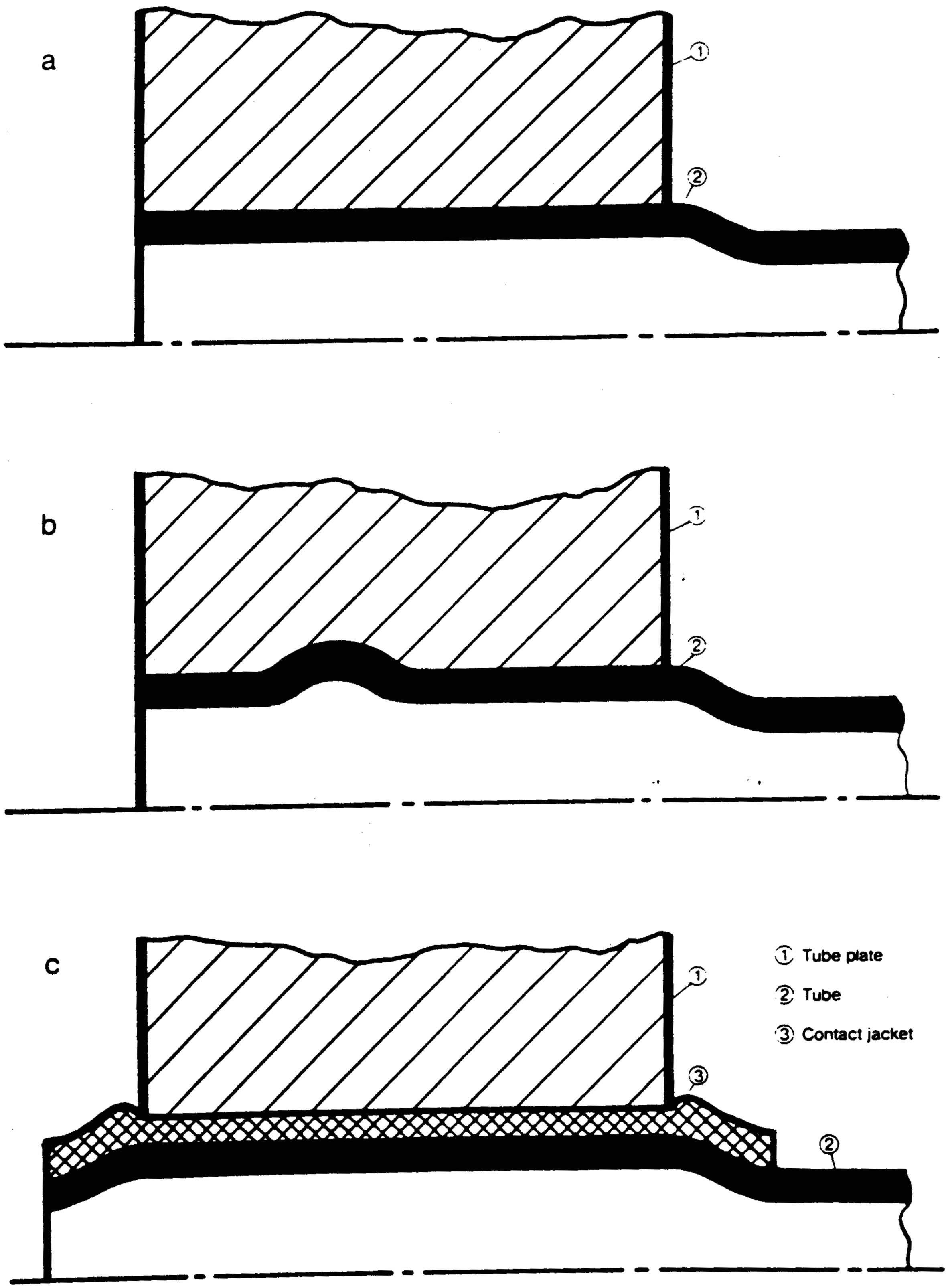
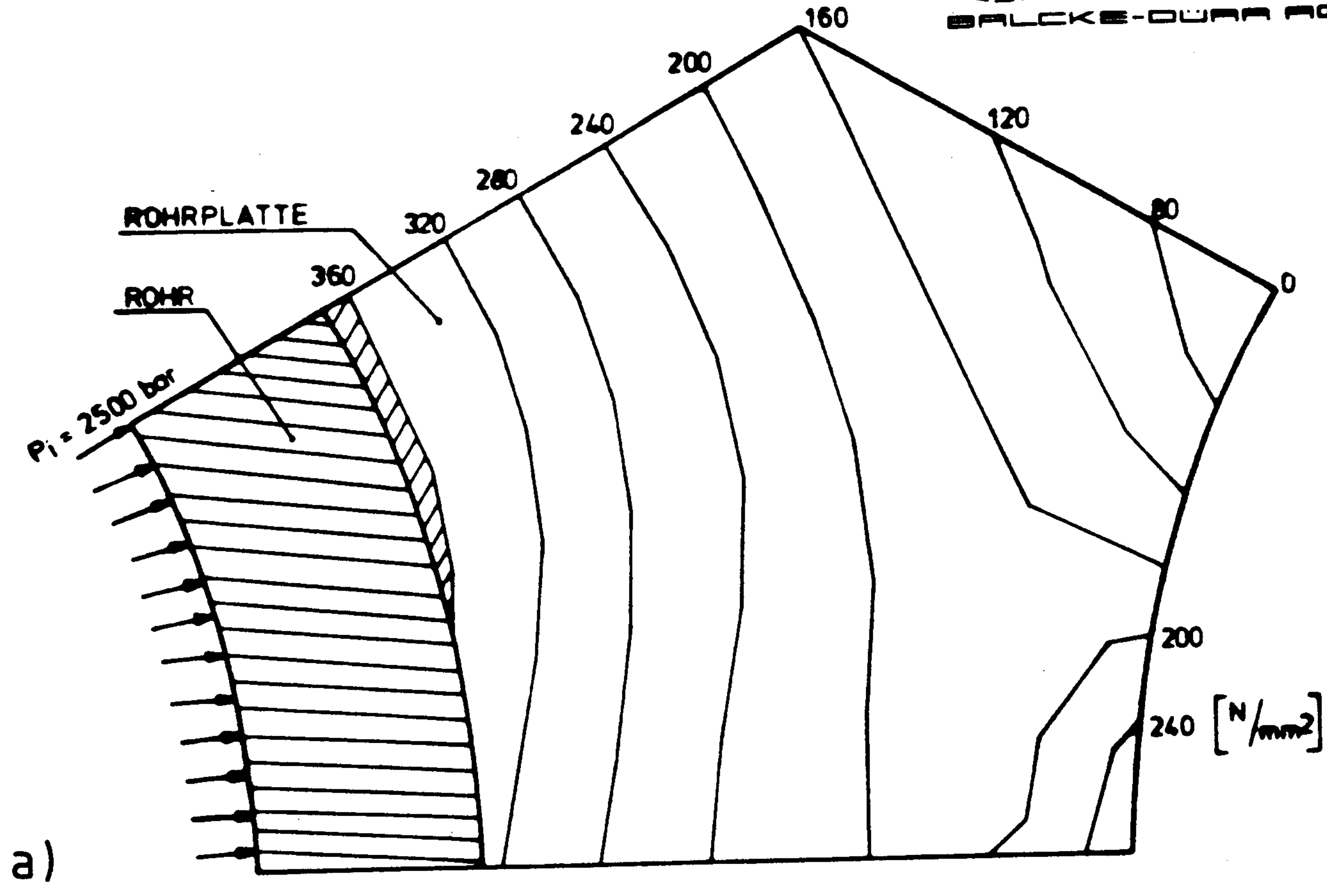


Fig. 4 Various types of tube/tubesheet joint

BDAG
BALCKE-DÜRR AG



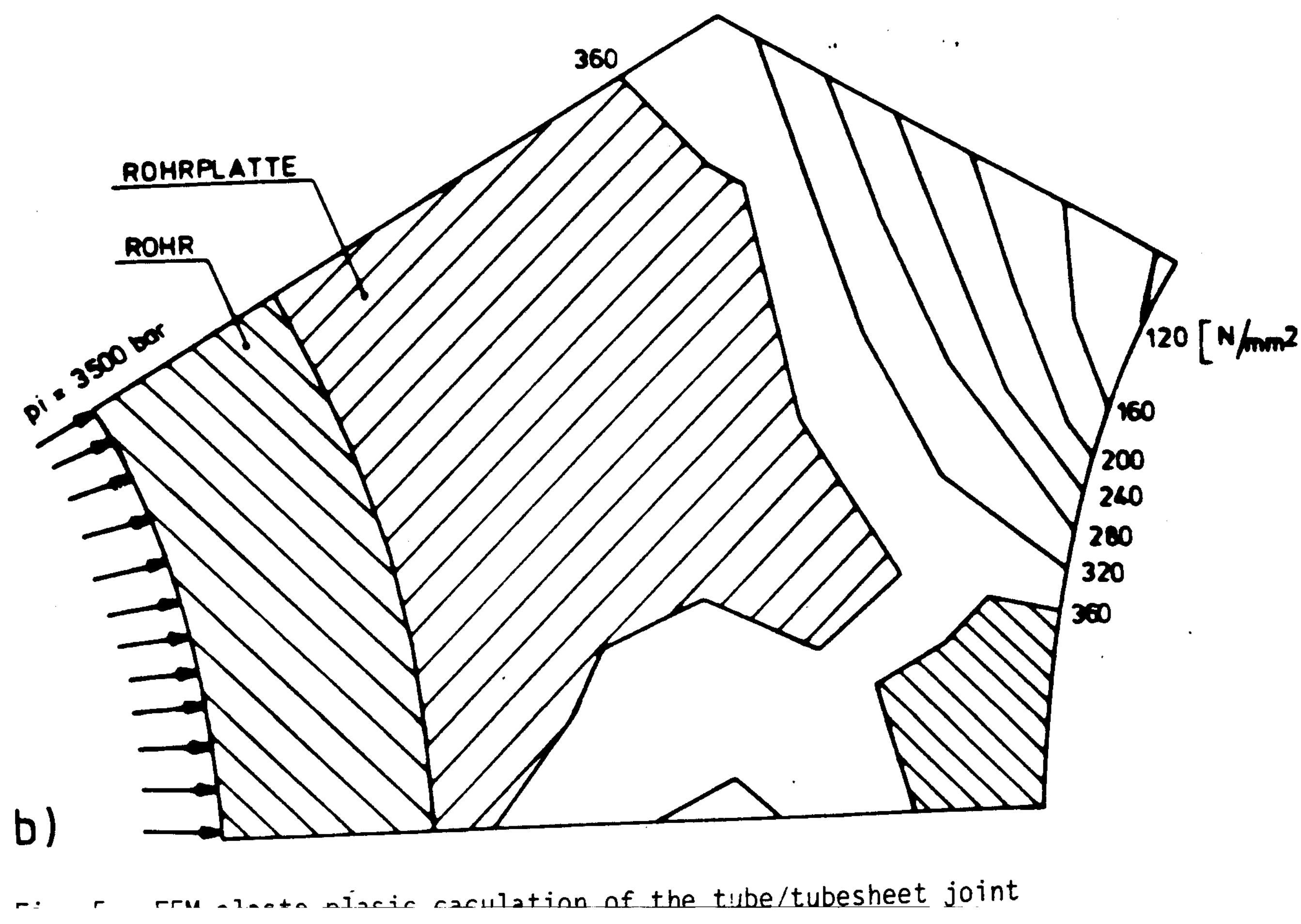


Fig. 5 FEM elasto plasic caculation of the tube/tubesheet joint

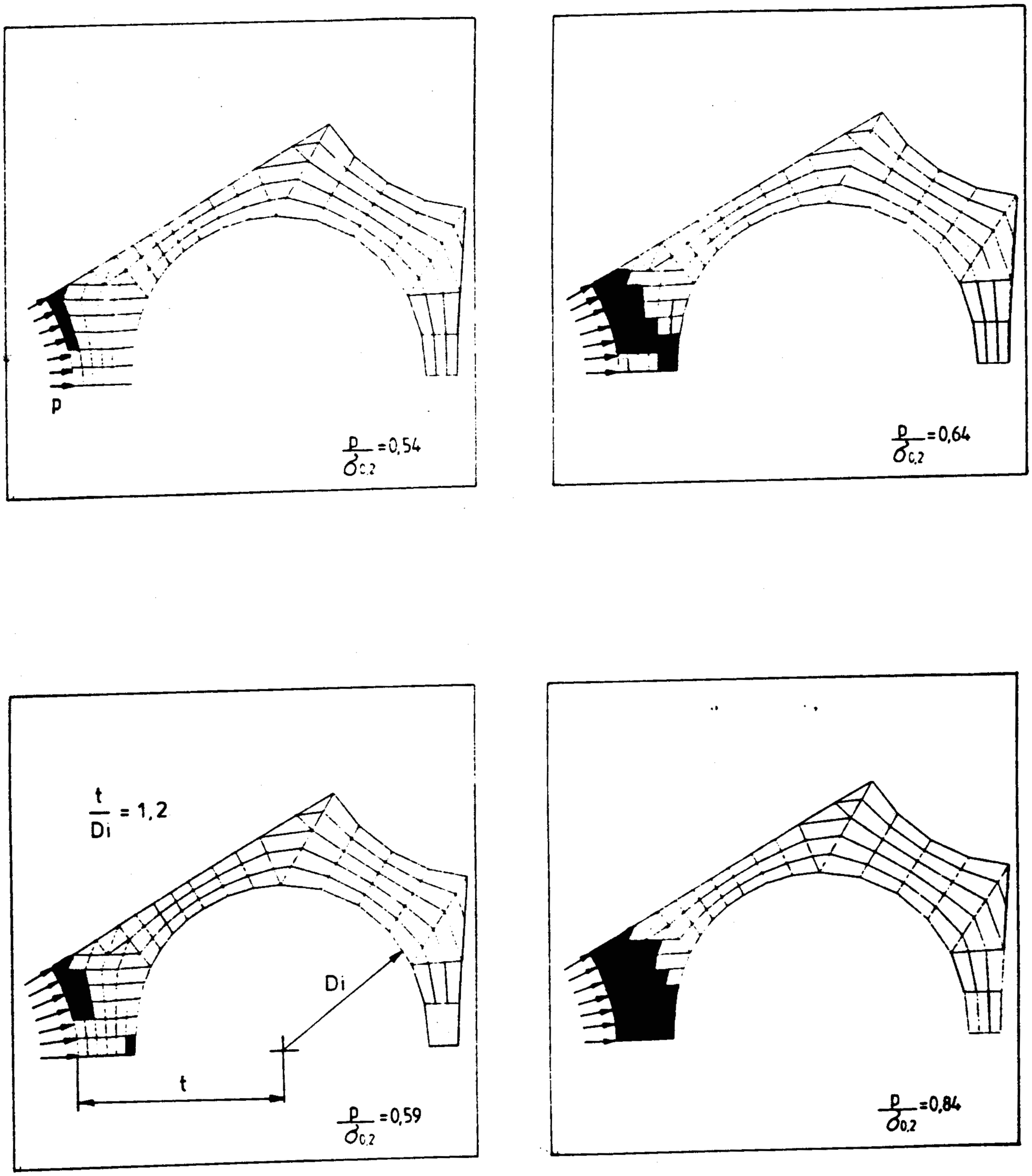


Fig. 6 Results of an elasto-plastic FEM calculation for t/Di = 1.2

BDAG
BALCKE-DÜRR AG

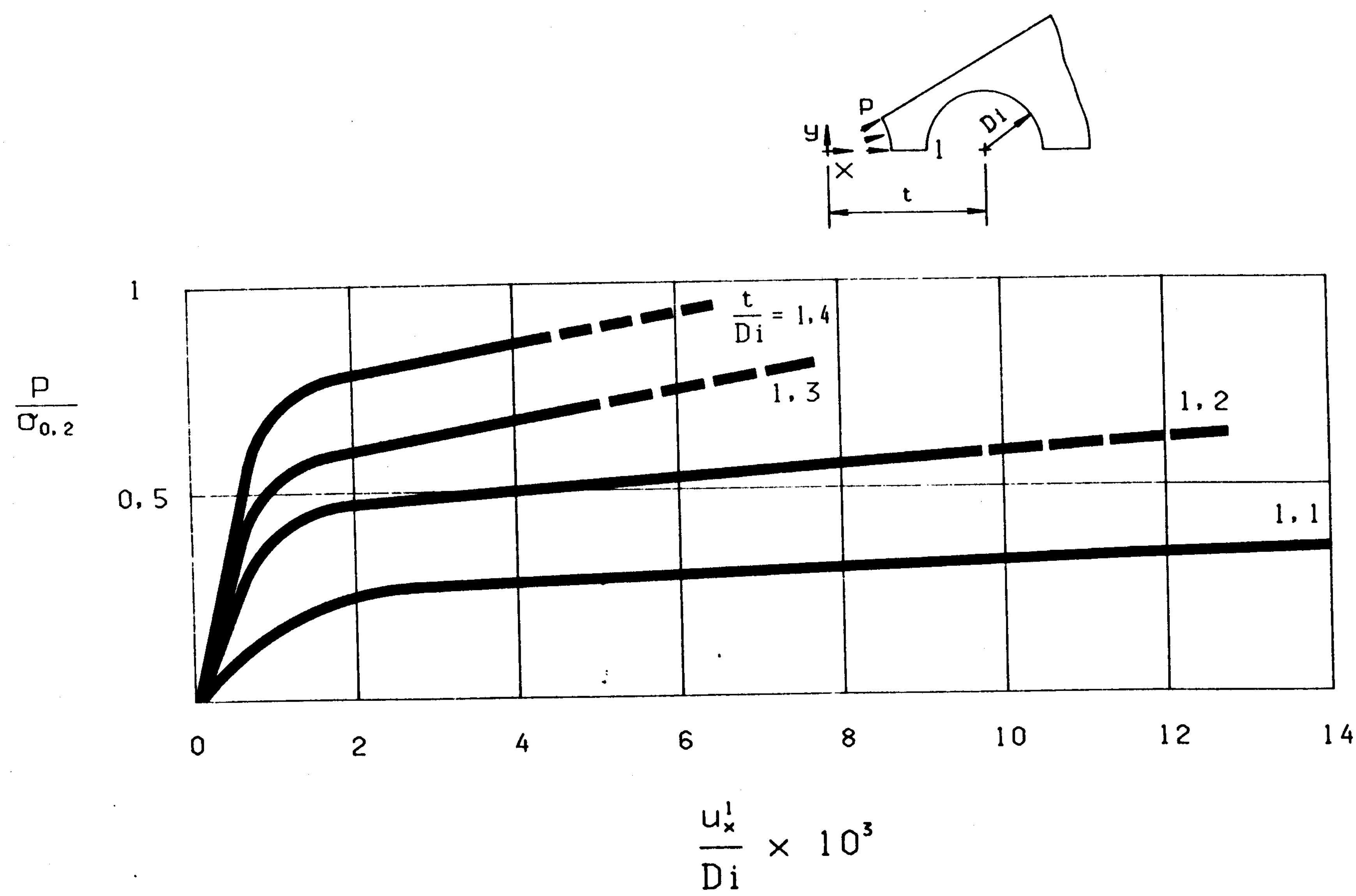


Fig. 7 Radial deformation of the adjacent borehole wall

BDAG
BALCKE-DÜRR AG

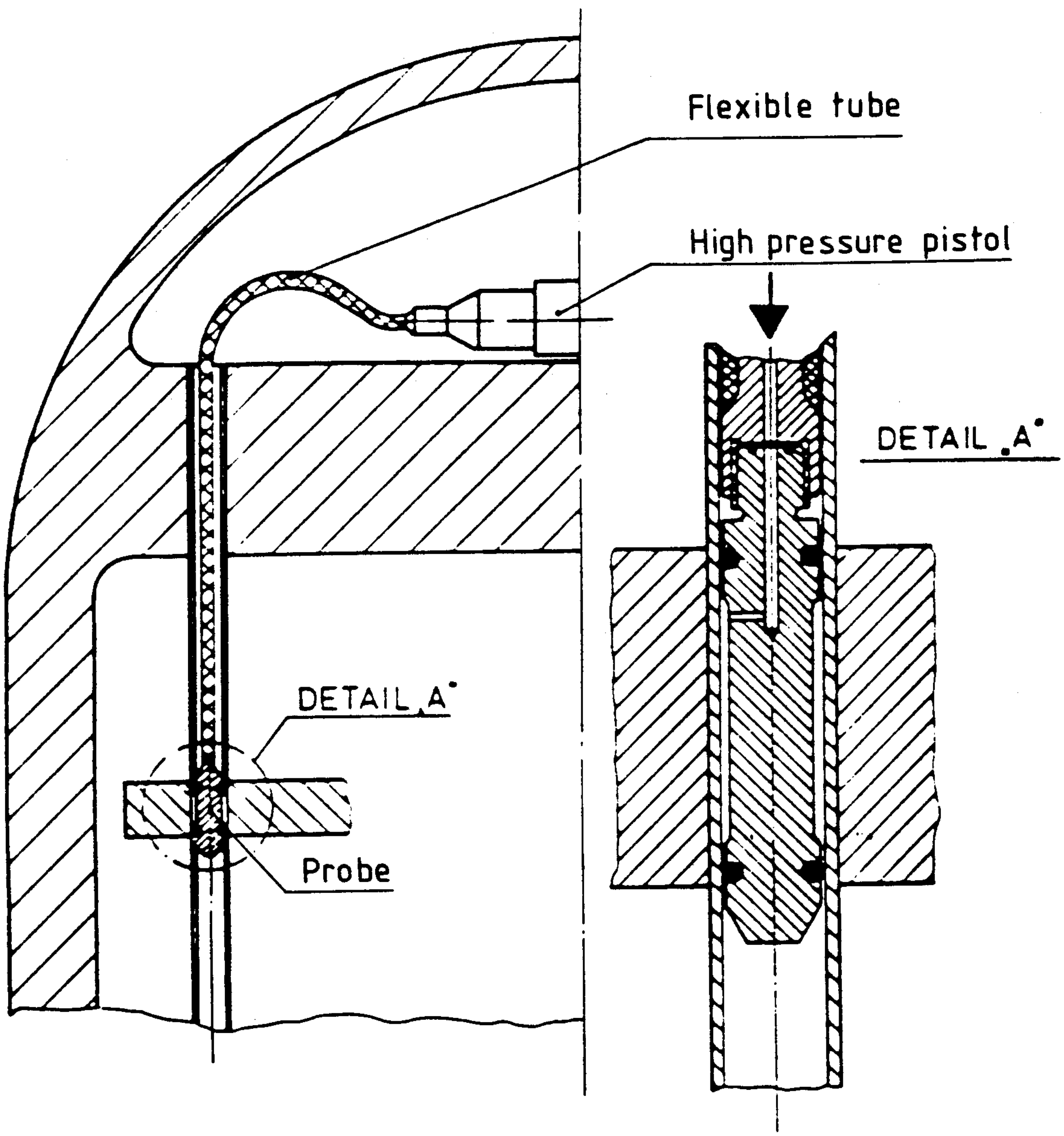
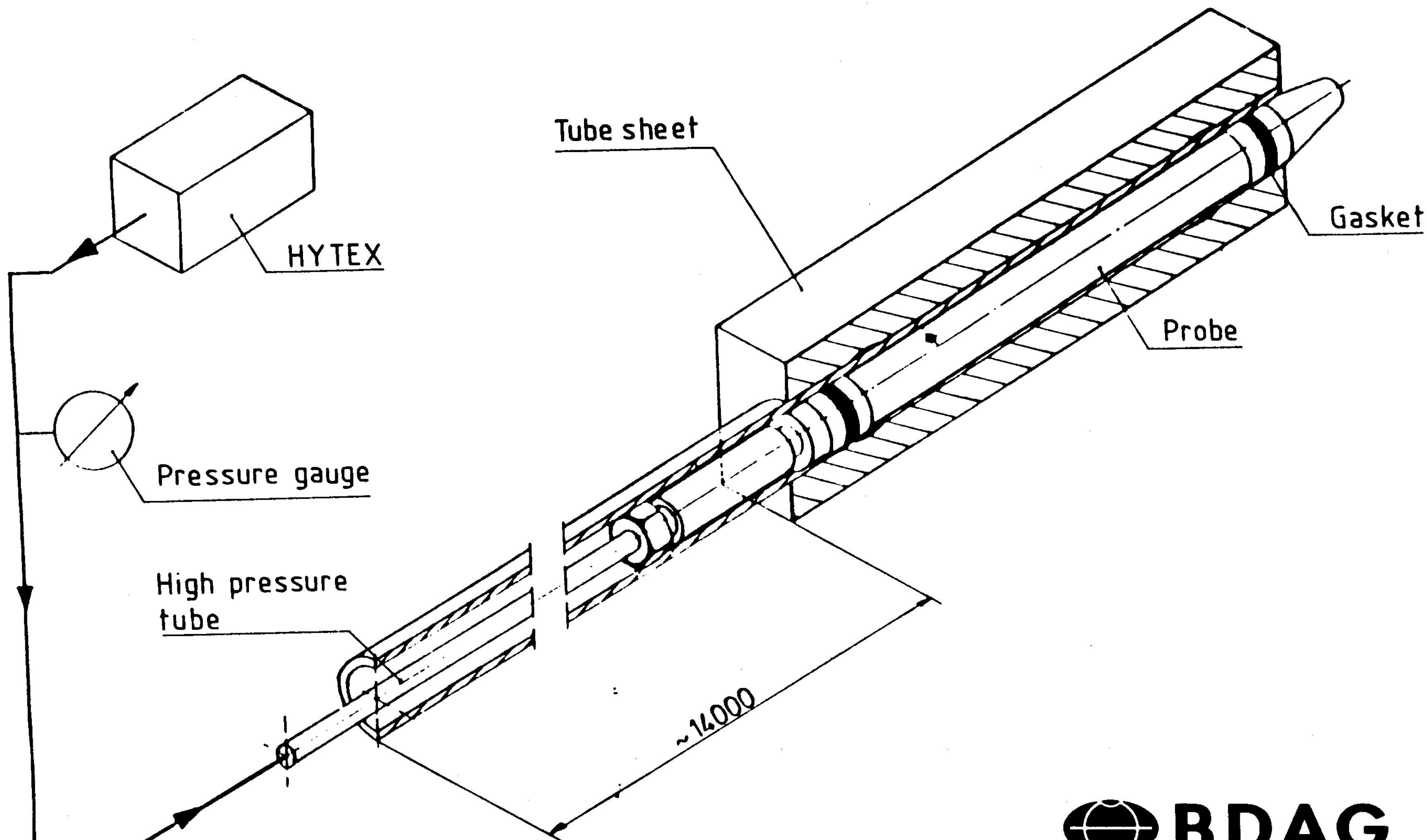


Fig. 8 Use of the flexible probe



BDAG
BALCKE-DÜRR AG

Fig. 9 Expansion at great tube depht

BDAG
BALCKE-DÜRR AG

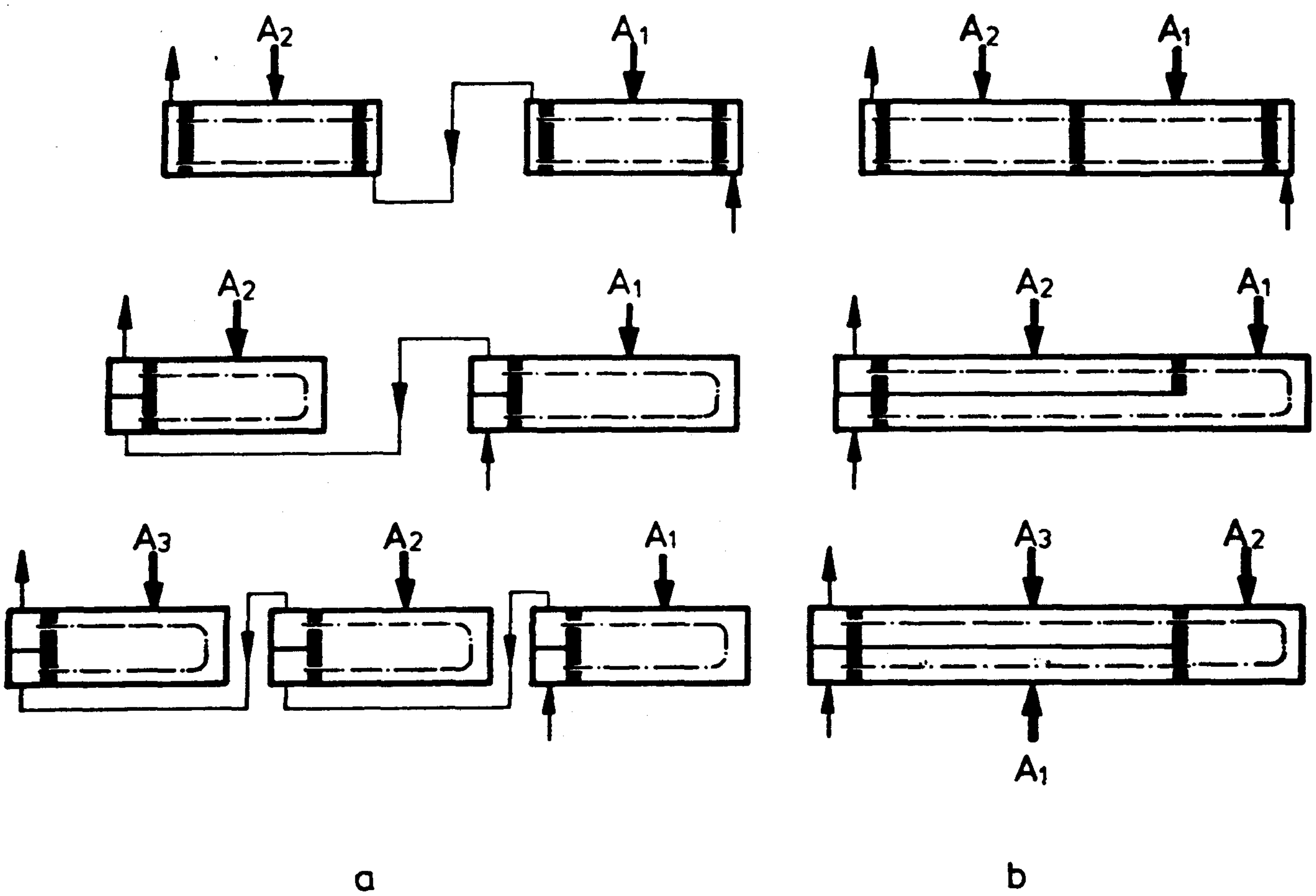


Fig. 10 Comparison of single and multi-stage constructions

a) single stage construction
b) multi-stage construction

BDAG
BALCKE-DÜRR AG

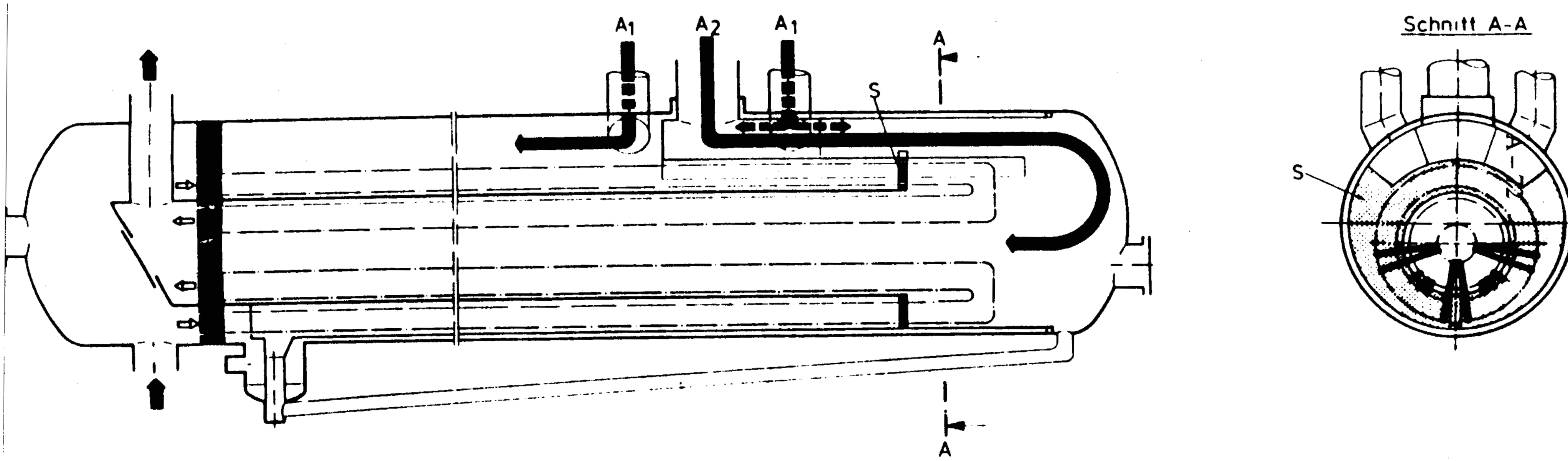


Fig. 11   Duplex preheater of a multi-stage type

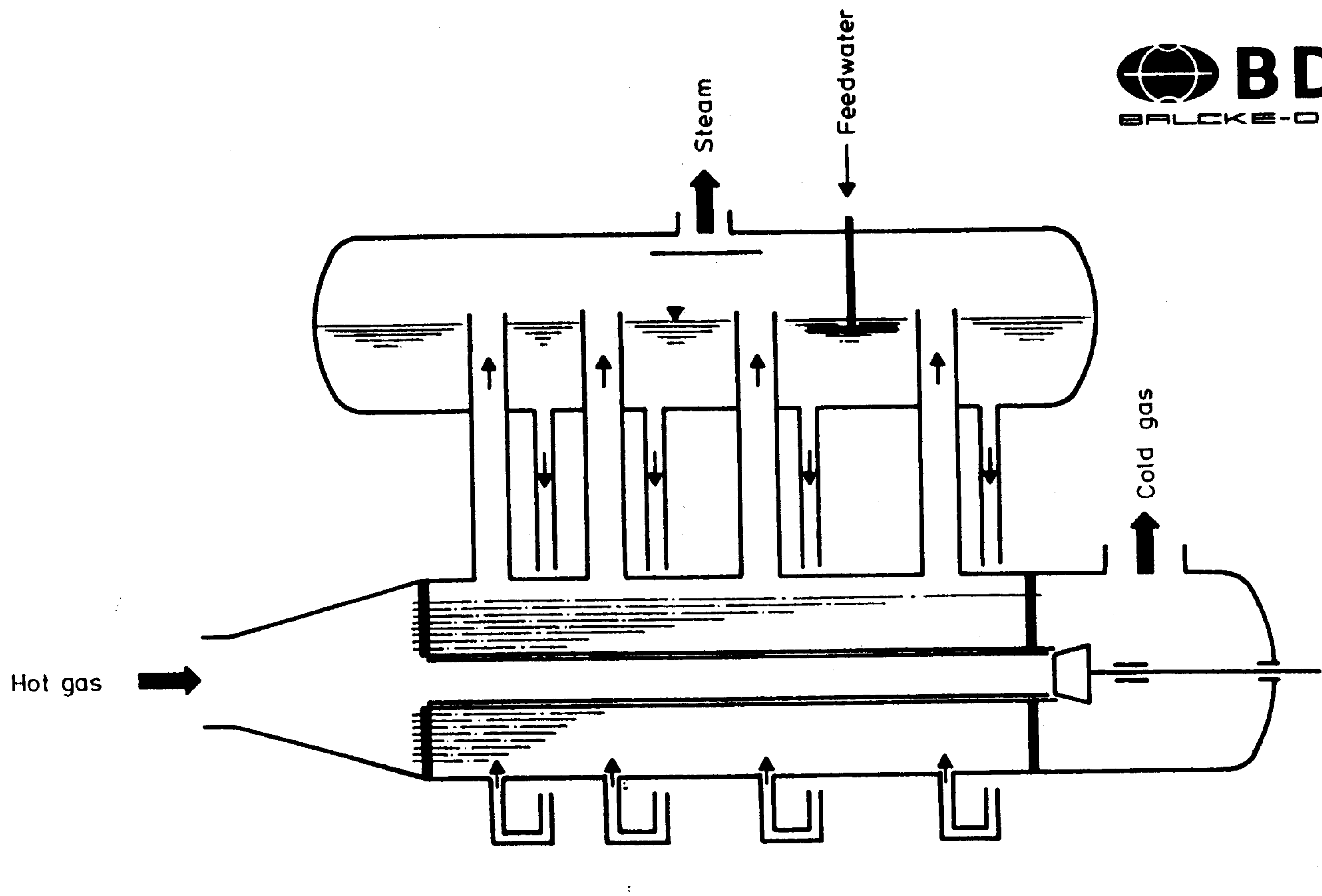
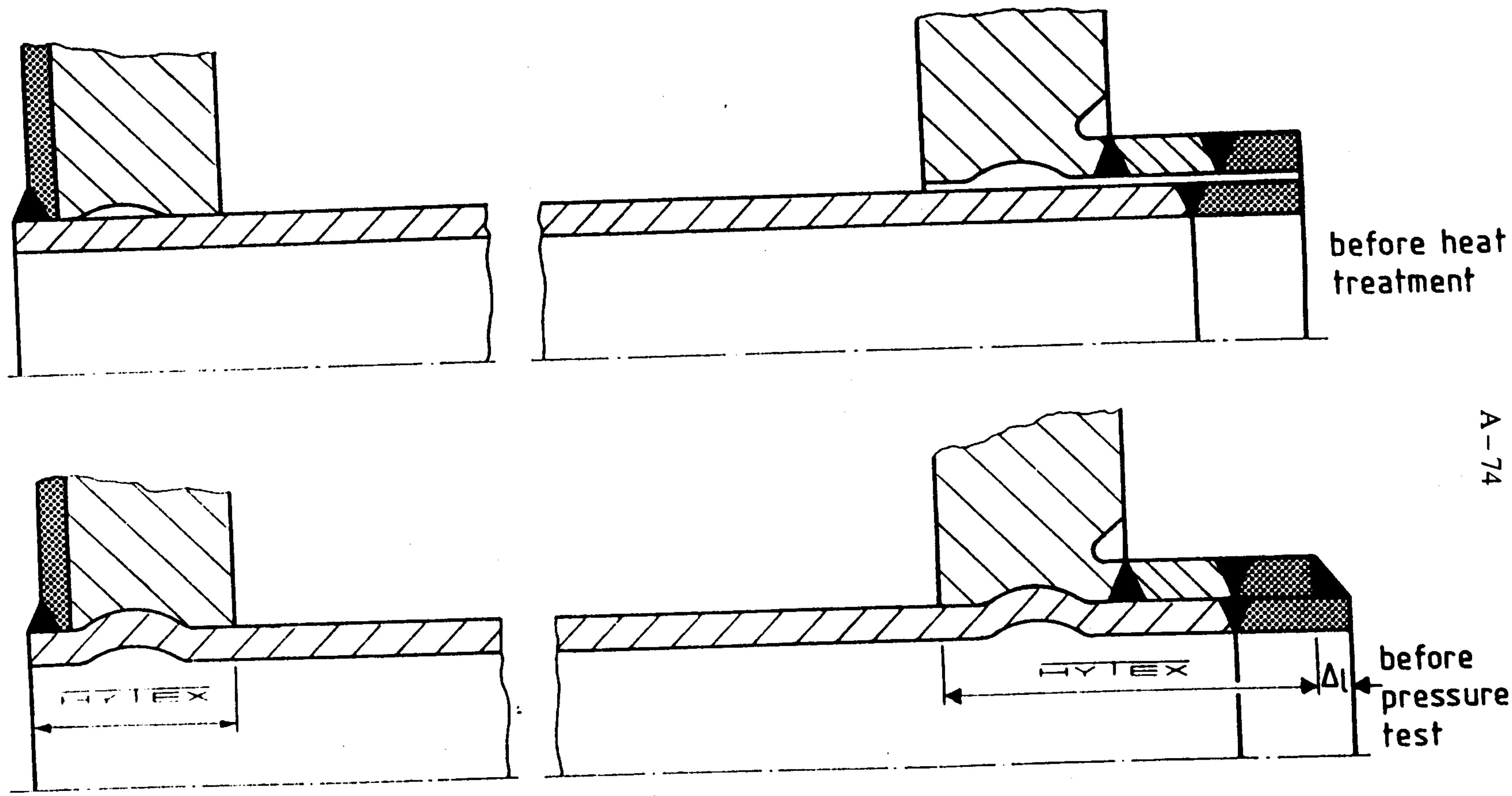


Fig. 12 Diagram of heat recovery boiler



BDAG
BALCKE-DÜRR AG

Fig. 13 Principle of the SBS process

BDAG
BALCKE-DÜRR AG

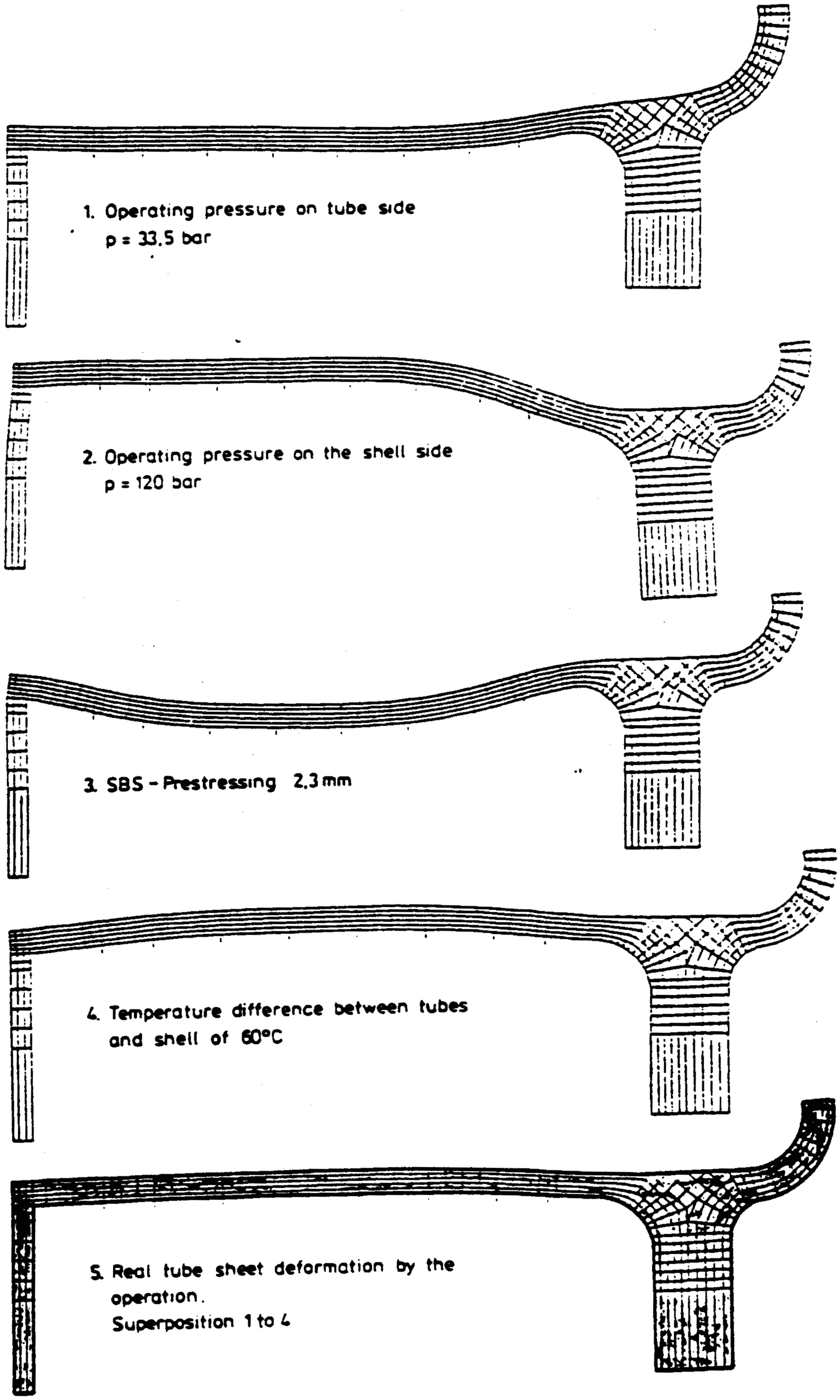


Fig. 44 Deformation of the tubesheet.

BDAG
BALCKE-DÜRR AG

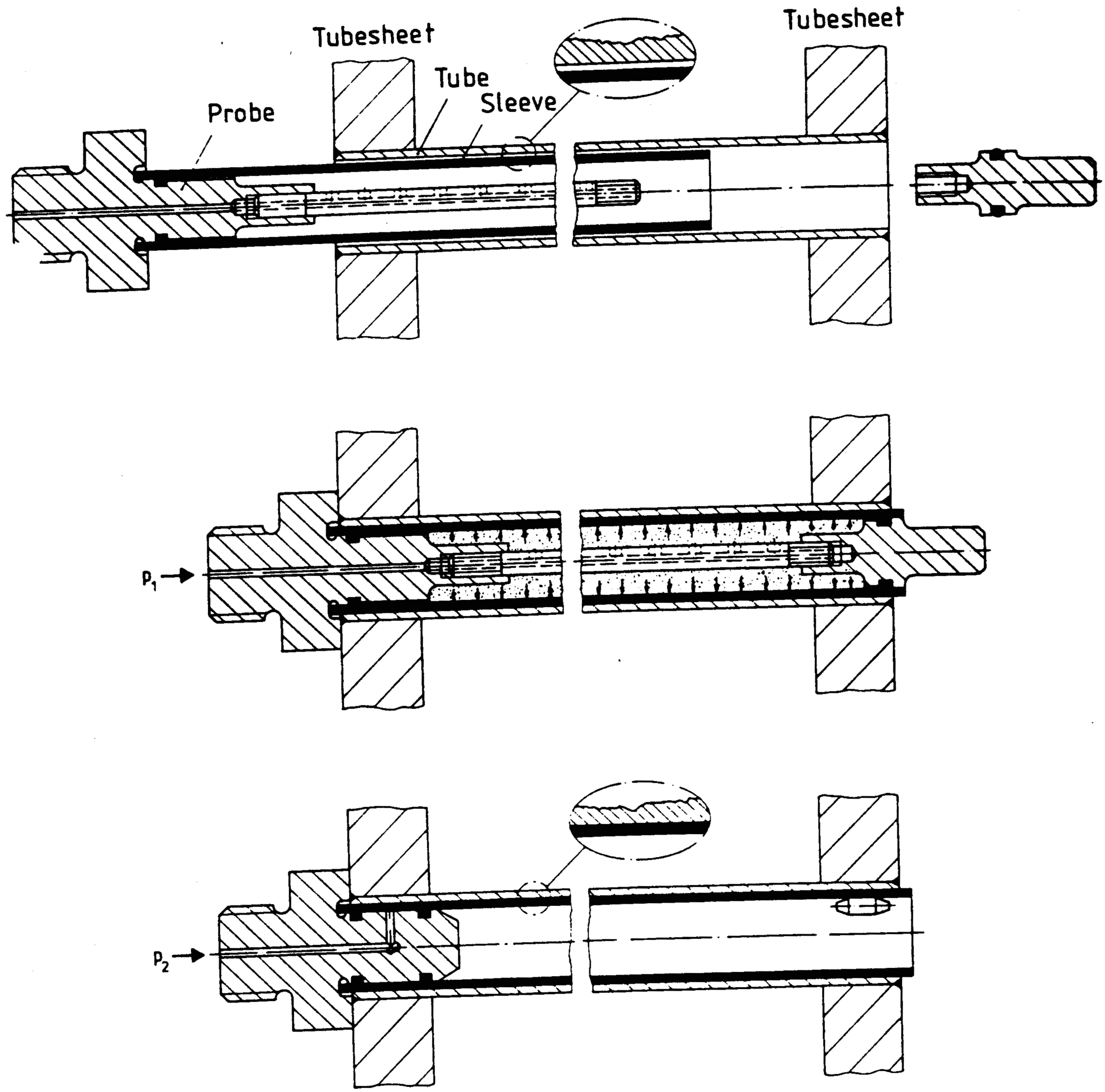


Fig. 15 HYTEX sleeving