

## FURTHER FIELDS OF APPLICATION FOR PRESTRESSED CAST IRON PRESSURE VESSELS (PCIV)

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### SUMMARY

The redundancy of the prestressing system of prestressed structures as well as the clear separation of sealing and load-carrying functions of prestressed cast iron pressure vessels offer substantial advantages over conventional welded steel pressure vessels. Because of the temperature resistance of cast iron up to 400 °C it is possible to build prestressed pressure vessels commercially as hot-working structures. The compressive strength of cast iron, which is 25 times as high as that of concrete allows for a very compact design of the PCIV. Further specific properties of the PCIV like pre-fabrication of the vessel in the production plant—made possible by a structure assembled from segments—short assembly periods at the construction site etc., may open more fields of application.

— PCIV as pressurized storage tanks for the emergency shut down system in nuclear power stations:

For the control rod drives in the case of an emergency shut down of light-water and high temperature reactors gas or water of high pressure will be needed. The first one of these vessels of the PCIV concept for a reactor emergency shut down system is presently in production. Its volume is 17.5 m<sup>3</sup>, the operating pressure of the stored helium gas is approx. 230 atmospheres.

— PCIV as high pressure vessel for the chemical industry:

For numerous chemical processes, for example for the production of ammonia, carbamide, methanol and polyethylene PCIV's can be used because of their large diameters and lengths in comparison to steel vessels. The relatively thin liner of the PCIV is an economical protection of the supporting structure against aggressive substances.

— PCIV as energy storage:

Uninterrupted availability of electrical and thermal energy necessitates the planning for peak loads. The PCIV offers new possibilities for the storage of steam, hot water and compressed air due to manageable sizes as well as cost advantages.

— PCIV for light water reactors:

Apart from the development of PCIV's for high temperature reactors, the application of PCIV's for light water reactors has been investigated. PCIV's can be designed for light-water reactors of larger capacities than those constructed up to the present time.

— PCIV as burst protection:

Against the background of the discussion whether or not welded steel pressure vessels for light water reactors are sufficiently safe against bursting, Siempelkamp has made some preliminary investigations of the possible use of prestressed cast iron structures as burst protection for these steel reactor pressure vessels. When comparing prestressed cast iron structures for burst protection with prestressed concrete structures designed for the same purpose, it is evident that cast iron structures require substantially less space.

In summary it can be concluded, that the application of prestressed cast iron promises to be successful where either structures with large volumes and high pressures and/or temperatures are required or where aspects of safety allow for efficient use of prestressed structures.

1. The prestressed cast iron vessel (PCIV)

1.1 Main vessel components and their functions:

(Fig. 1)

The prestressed cast iron vessel (PCIV) consists of 3 components, each of which has separate functions. This way it is possible to optimally adapt the material for the individual components.

(Siempelkamp) [1] (Beine)[ 2 ]

The actual cast iron body of the PCIV is manufactured in segments, i. e. the cylindrical part of the vessel is horizontally divided into rings. The rings in turn can be subdivided into segments, depending on the size of the required vessel. Bottom and lid of these structures are divided into individual parts as well. In joining positions between the cylindrical part of the vessel and the bottom or the lid and in positions of break-throughs, special blocks may result. (Fig. 2)

All parts in the area of bottom and lid as well as in the cylindrical area are joined by moulded elements (fitting keys, fitting bushes, etc.). (Fig. 3)

The material used for the support system is grey cast iron with a minimum tensile strength of approx. 20 kp/mm<sup>2</sup> and a minimum compressive strength of approx. 80 kp/mm<sup>2</sup>. Thanks to the temperature resistance of the cast iron material up to temperatures of approx. 400° C there is a possibility of designing prestressed cast iron vessels profitably as hot-operated structures as well.

The compressive resistance of cast iron, which exceeds that of concrete by the factor 20 - 25, results in very compact structures in comparison with prestressed concrete reactor vessels (PCRv).

The walls are constructed under consideration of the following main aspects:

- Strength
- Limitation of block weight
- Consideration of casting technique
- Guarantee of checkability
- Shielding effect

The basic vessel body, which is made of cast iron, is non-positively placed under compressive stress by means of a circumferential and axial tensioning system. The tensioning system is subjected to tensile stress in this manner.

The tensioning system is made of prestressed steel with a tensile strength of 170 - 180 kp/mm<sup>2</sup>. This material was especially developed for prestressed constructions and has already been used in a large number of concrete structures.

In addition to component 1, basic body of cast iron, and vessel component 2, circumferential or axial tensioning system, we have a third vessel component, the liner. The liner covers the inside and is normally made of steel. The liner does not take on any support function but is braced by the cast body. It has merely a sealing function and

prevents thus pressure reduction inside the vessel.

### 1.2 Function of the support system

The power path diagram (Fig. 4) for the prestressed system shows the interdependence of stress system and cast iron support system for the various operating situations of the vessel.

In the following I shall explain the essential differences in comparison with the steel vessel.

- The walls of the PCIV are not subjected to tensile stress. Contrary to a steel vessel, which is subjected to tensile stress, the supporting cross-section will not be reduced in the case of possibly occurring cracks. As a result, we achieve a much more favourable crack propagation behaviour.
- Tension wires, which are subjected to tensile stress, are provided in large number. Failure of individual components leads to negligibly small changes in the remaining tension wires. Consequently propagation of a fault in the tension system is prevented.
- While, in the case of a steel vessel, the vessel wall goes through a tension change between no-load and load-drop tension in every load cycle, the tensile stress in the tensioning system is only increased by fractions of the prestress values in case of internal pressure increase from 0 to operating pressure in the case of a cast iron vessel. The cast iron support body, in turn, experiences a reduction in compressive stress (Fig. 4).

If the vessel volume becomes so large with the required operating pressures that steel vessels subjected to tensile stress are no longer adequate, the only solution is to be found in prestressed designs. In addition to the safety technology aspects, prestressed vessel designs under compressive stress and made of cast iron will render direct cost advantages in comparison with structures made of other materials.

In addition to these direct advantages, further indirect cost advantages may be expected on account of the specific features of the PCIV, i. e. thanks to prefabrication of the individual vessel blocks at the manufacturer's works, consequently reduced building periods, respectively favourable dismantling after shut-down, etc.

Thanks to the technology of the PCIV and the described advantages, various interesting fields of application can be expected for these designs.

### 2. Possible applications of the PCIV for reactor systems

In the Federal Republic the prototype of a high-temperature reactor with a power of 300 MWe is under construction. Based on the concrete vessel developed for this reactor, a prestressed cast iron construction has been designed (Fig. 5 and 6).

(Siempelkamp) [ 1 ]

Based on this design, a 1 : 7,5 model was developed, built and tested in 1973. The feasibility of building this design was proved in principle. Furthermore, very good conformity of the deformation values actually measured in practice and the arithmetically calculated values was achieved. (Beine, Gross, Schilling) [ 3 ]

Since 1976 the Federal Republic has been running a development programme in order to prove the technical and economic feasibility of a PCIV for high-temperature reactors of the presently common dimensions between 1200 and 1300 MWe. The targets of this programme as well as results obtained up to date are treated in separate lectures.

PCIV model (Fig. 7)

In addition to these developments for high-temperature reactors, the application of PCIV for light-water reactors was also examined. Studies covering the application of such designs for boiling- and compressed-water reactors have been prepared.

The principal set-up of such a vessel concept for a boiling-water reactor of the 1450 MWe type is shown in figure 8.

As a further development example the possibility of a PCIV for a process heat reactor with 3000 MW thermal, pod boiler design, is shown (Fig. 9).

### 3. Prestressed cast iron pressure design as burst and fragment protection for reactor pressure vessels from steel

In the course of the development work done in the field of prestressed cast iron pressure vessels, the question arose, whether the design principle used for the cast iron pressure vessels might be applied to burst protections and fragment protections of welded steel pressure vessels.

Compared to a good quality concrete the compressive strength of cast iron is about 20 times higher; this leads to far thinner walls using prestressed cast iron structures instead of prestressed concrete structures.

#### 3.1 Burst protection

The most important requirement a burst protection has to meet in the postulated case when a steel pressure vessel fails either by a circumferential or a vertical crack are:

- To limit the crack with such that the core integrity is maintained. (That means, flowing forces and pressure differences caused by the steam or water being pressed out of the gap have to be reduced to such an extent that the core geometry is not damaged so far that the residual heat cannot be removed.)
- To limit the crack with such that the permanent residual heat removal is possible. (That means, it must be possible to press more water into the vessel than that running out of the gap.)
- The burst protection must retain fragments of the vessel so that these fragments cannot destroy safety related equipments and especially the containment shell

(Fragment protection).

- The steel pressure vessel should be influenced as little as possible in its stress-strain behaviour by the burst protection.

A prestressed cast iron burst protection for a boiling water reactor is shown on figure 10.

The cylindrical part that serves for the limitation of vertical cracks consists of 4 stacked rings. A ring itself is subdivided into 12 elements.

In the walls of the elements, opening are provided to house the vertical prestressing cables and the air cooling system. Because the type of steel vessel regarded is required to be inspectable from its outside surface, a gap has to be provided between the outside surface of the vessel and the inside surface of the burst protection. During operation of the reactor this gap is filled with cell structured cast iron plates, the cells of which are filled with energy absorbing, and at the same time insulating material or with metal clad, light weight concrete elements.

That part of the burst protection that limits or even suppresses horizontal cracks consists of the additional top and bottom lids connected to each other by the vertical prestressing system. It is easily imaginable that this part of the system can be regarded as completely separated from the cylindrical part of the burst protection.

The prestressing tensile forces in the vertical cables cause compressive stresses in the wall of the steel pressure vessel in vertical direction but of course additional tensile stresses in circumferential direction. Only partial prestress should be applied on the cold vessel; full prestress in the cables would result from the thermal and pressure induced vertical elongation of the pressure vessel.

This design would suppress circumferential cracks but would also intensify the tensile stresses in circumferential direction which is the most important disadvantage of this solution. The second problem that cannot be solved perfectly with this structure is the necessity to take care of the tolerances of the vessel and the insulation material. These tolerances might give rise to the acceleration of fragments breaking out of the wall of the vessel and the resultant kinetic energy might cause very high stresses in the burst protection.

A burst protection design for a BWR that avoids these disadvantages is presented on figure 11. The cylindrical part is again subdivided into single block units and prestressed in circumferential and vertical direction. The vertical prestressing system is - that is one of the differences to the structure presented before - only acting on the cast iron cylinder and not on the steel pressure vessel. The clearance between the cold vessel and the top lid is designed to accommodate the thermal and pressure induced vertical elongation of the vessel. The forces acting on the secondary lids in the case of a horizontal crack are transmitted by studs to the cylindrical part of the burst protection and of course to the load carrying vertical prestressing system. After removing the

studs from the bottom lid, this lid can be lowered to provide outside inspection of the bottom of the pressure vessel.

A burst protection design for a PWR based on the same principles as described before is shown on figure 12

### 3.2 Fragment protections

The design of a fragment protection has to meet in general only one requirement:

To retain fragments or parts of the structure it surrounds, so that these fragments cannot damage the containment shell or important piping system etc.

In figure 13 a fragment protection, that can be dismantled in the case of limited repair work is shown. The rings in the cylindrical part are subdivided into 3 shell elements (fig. 14) which at their point of contact are screwed to T-profiles. So each third of a ring can be dismantled separately after having dismantled the vertical and circumferential prestressing systems. The rings are not prestressed in circumferential direction, the prestressing system is only clamped to the outside surface and only becomes strained when the outer shell of the heat-exchanger fails.

Fragments of the top and bottom lids of the heat-exchanger are retained by the secondary cell structured lids which are connected to each other by the vertical prestressing system.

The space between the heat-exchanger and the fragment protection is filled with insulating energy absorbing, light weight concrete.

Another possible design of this type of fragment protection is shown on figure 15. The cylindrical part is consisting of rings which are not subdivided. The circumferential prestressing system may be strained only clamped to the outside surface of the rings respectively. Dismantling of this type of fragment protection is only possible by taking complete rings from the structure.

### 3.3 Conclusion:

The investigations carried out with regard to burst and fragment protection designs and the prepared design drafts resulted in the finding that the various requirements which must be set for such burst protection constructions can be fulfilled to a high degree by prestressed cast iron structures.

A comparison of prestressed cast iron constructions for this type of application with prestressed concrete constructions for the same purpose shows again that the prestressed cast iron construction requires considerably less space and that changes in the containment or the overall installation of a light-water reactor are consequently kept within acceptable limits. In addition to direct and indirect cost advantages, which can be expected, the burst protection also takes on an additional shielding effect.

#### 4. High-speed shut-off vessel of prestressed cast iron pressure design

Driving of the shut-off and control rods of light-water and high-temperature reactors requires for an occurring case of rapid shut-off highly prestressed gasses or water under high pressure, respectively.

Due to the great importance of this equipment from a safety technology point of view, prestressed cast iron constructions lend themselves to application in these systems thanks to the explained structural aspects and as result of the definitions of failure safety of this construction.

A first order for a high-speed shut-off vessel of PCIV design is in production at the moment. It is intended for the prototype of the high-temperature reactor THTR in the Federal Republic. (Fig. 16) The vessel is planned for a branch of the high-speed shut-off system. The storage medium is helium, the volume of the vessel amounts to 17,5 m<sup>3</sup>. The max. operating overpressure amounts to 230 bar.

(Beine)[ 2 ]

The vessel is divided into several rings in axial direction. These rings are not further subdivided in circumferential direction. In axial direction the cast iron rings bear bore holes to hold the axial tensioning cables by means of which lid and bottom are joined to the cylindrical rings.

In the detailed development of this high-speed shut-off vessel systems for checking repetition behaviour of this vessel system were developed which can also be used for continuous operational supervision of such a vessel system.

The design of the prestressed cast iron pressure vessel offers the possibility of, for example, providing some cables in the axial tensioning system with pressure measuring gauges which in turn permit continuous supervision of the tensioning condition in this system. In the case of failure of individual wires in the cable or in the case of assumed failure of the entire cable the consequently occurring power changes would be indicated and the resulting measuring signals could be used for preliminary warning or, in borderline cases, for opening an overpressure valve and venting of the vessel.

For the axial system, but preferably for the circumferential system it is also feasible to have supervision systems which operate on the basis of measuring elongation distances. Changes in the circumferential tensioning system could be registered via DMS or via inductive transmitters opposed to a non-power measuring wire. The resulting measuring signals can be used as warning or pressure relief signals as described before.

The safety against spontaneous failure which is, on principle, inherent in the prestressed cast iron construction is made redundant by using these types of supervision systems. Erection sites for such vessel within the region of other elements or subunits which are significant for proper functioning, e. g. inside reactor buildings, may thus be chosen without hesitation.

The described high-speed shut-off vessel for the THTR nuclear power plant in the

Federal Republic is subject to the Approval Procedure of the Nuclear Power Act of the Federal Republic of Germany. On account of the positive evaluation in this procedure, the use of prestressed cast iron constructions should also be taken into consideration instead of other welded and tensile-stress-subjected steel pressure vessels. As an example supply water vessels should be mentioned.

Prestressed cast iron pressure vessels of smaller volumes and with medium to high pressures are also suited for use in a number of conventional applications.

As an example we should mention high-speed starting of gas turbines by means of air reservoirs of prestressed cast iron pressure design.

Open gas turbines can be accelerated very quickly but only with a simultaneous reduction in their service life. In practical application high-speed starting is therefore avoided if possible, so that transitional power is required for the period until the full load of the gas turbine has been achieved. The high-speed start air reservoirs with high pressures, which are required for this purpose, can be advantageously designed as prestressed cast iron pressure vessels. That way, the rated power of such an energy set becomes instantaneously available.

For a lay-out example of a line of 100 MW and 10 minutes start-up period, a vessel was determined which must have a required volume of 9,2 m<sup>3</sup> per MW, i. e. for 100 MW 920 m<sup>3</sup> volume with 165 bar. If we take the ratio of diameter : length to be 1 : 5, the clear height with a diameter of about 6 m would be 32 m for this starting vessel.

Rough cost calculations have shown, that this type of transitional reservoir would raise the installation costs per installed kW by about 20 %. It is definitely thinkable that there are situations and conditions where such an increase in investment costs would be justifiable from an economic point of view.

##### 5. The PCTV as energy storage, used in power stations (Goldstern) [ 4 ] (Siempelkamp) [ 5 ]

The operation of a power station is connected with the problem that fluctuations in steam demand or steam supply occur by days or by seasons and this applies both for the supply of consumers of electric energy and heat energy. This problem gave rise to tests which should make it possible to make industrial heat storage on a large scale a reality.

The first considerations concerning automatic steam storage go back as far as the 19th century. For example, the methods used nowadays in the Federal Republic for storing steam are essentially based on the developments of Dr. Ruths. In addition to some uses in power stations, steam storages are known in those industries where heat consumption is subject to great fluctuations and often caused by heating-up or boiling processes. Example for this are breweries, cell wool factories, dyeing plants etc.

The application in power plants serves, in most cases, to overcome the highest and shortest peaks. A second and important case of application is, however, the existence of an instantaneous reserve for cases of failure of specific units. This instantaneous reserve

may serve for keeping up a normal supply, but in the case of small-scale power stations it may also be of great importance and significance to keep up vital functions.

The energy crisis has, no doubt, given new impulses to all questions related to storage possibilities, also under the aspect that realisation of such methods will finally lead to savings in the fuel used. Furthermore, fuel costs would be substituted by capital costs and the foreign exchange expenditure for the overall reduced consumptions of primary energy-carrying agents, which must be imported, would also be reduced.

If we look at energy storage based on the example of steam storage, we have the following task: steam is stored when there is an excess in steam and steam is generated as soon as more steam is required.

Consequently a steam storage must fulfil the function of storing. But the use of the stored steam may serve very different purposes. A short outline is to show the multitude of possibilities:

- a) balancing of fluctuations in steam demand
- b) balancing of fluctuations in steam supply
- c) adaptation to differently fluctuating supply and demand
- d) covering of extreme demand peaks
- e) taking on extreme supply peaks
- f) instantaneous reserve for bridging the starting period of reserve installations when steam supply is interrupted.

All cases of demand are applicable for consumers of electric energy and direct heat consumers.

The two principal methods of steam storage are

#### 1. Gradient storage

In this case the excess steam is condensed during loading and transfers its heat to the storing agent (water), the temperature and pressure of which rise. Upon discharge part of the water is evaporated again by lowering the pressure and the temperature. The storing volume remains essentially constant during this process except for the additional condensate, while the specific heat capacity changes according to the pressure limits.

#### 2. Constant-pressure storage

In this case temperature and pressure are kept constant. The excess steam serves for preheating the supply water which is stored in the reservoir. During loading the water level of the hot water in the reservoir rises, while less or no supply water is being preheated with dropping hot water level upon discharge; this way an additional amount of steam is set free and made available for the consumer.

A realisation of energy storage requires storage vessels which will fulfil certain requirements. The essential characteristics of energy storage by means of steam storage are the following:

- a) Decisive is the storability or storage capacity, i. e. the quantity of steam supplied or demanded within a time unit. Pressure and temperature of the storing medium or pressure and temperature gradient, respectively, are essential factors for the lay-out of a storage vessel.
- b) Duration of the loading or discharging process are of significance. This means the time which is available for the loading or discharge capacity.
- c) Required volume or storage capacity of a vessel. For this values must be achieved which correspond to the storage capacity and the loading or discharge duration.
- d) Furthermore, the storage vessel must be designed to comply with the pressure and temperature values or the gradient values, respectively.
- e) The costs of the entire storage installation including control system. This results in an increase in line costs in order to realise the required energy storage and consequently the profitability as long as the definitely required existence of an instantaneous reserve does not put these economic questions into the background.

The use of the energy storage system is feasible both for conventional and nuclear power stations. In addition, it could also gain importance for the storage of sun energy, which is under discussion.

The prestressed cast iron pressure vessel is suited to solve the problems of energy storage with regard to the required storage vessel. (Fig. 17)

The development of the PCIV for reactor pressure vessels of high-temperature reactors has already made essential categories of stress and geometric conditions known. Vessels for these applications are characterised by large volumes, sizes of several  $1000 \text{ m}^3$ . The operating pressures to which these vessels are subjected lie between 40 and 60 bar. The concept of the hot-operated vessel leads to the development of the hot vessel wall with temperatures between  $310 - 340^\circ \text{C}$ .

For storage units in the field of energy storage, reservoirs with a holding capacity of  $8 - 10.000 \text{ m}^3$  are the presently discussed max. size. The temperature requirements lie within the limits between  $140$  and  $250^\circ \text{C}$  with pressure requirements not exceeding  $50 - 60$  bar, depending on the application.

Although there is still a number of problems to be investigated, as for example the design of the inlet and outlet openings, the question of vessel behaviour in the case of a travelling temperature front when using the constant-pressure storage, overall questions of insulation and thus reduction of heat losses etc., it is already quite clear to see that the prestressed cast iron pressure vessel will be a suitable storage vessel for energy storage on a large scale.

First drafts for small-scale vessels for this specific application and a volume of about  $150$  and for further vessels with a volume of  $1.500 \text{ m}^3$  holding capacity have been prepared.

6. The prestressed cast iron pressure vessel and high- and maximum-pressure vessel in the chemical industry and process technology

Finally it should be pointed out that numerous chemical processes require vessels of larger volumes as well, vessels which must guarantee the respective process pressures and process temperatures. This is, for example, the case in the production of ammonia, carbamide, methanol, polyethylene, etc.

In this case two further structural advantages of the PCIV come to bearing in addition to the previously mentioned properties. The ring-shaped set-up of prestressed constructions offers the possibility of assembling such prestressed containers to comparatively great lengths. The segmentary construction of the individual rings results relatively unproblematically in vessel diameters which exceed the makeable diameters of previously employed steel pressure vessels. A second and considerable advantage lies in the fact that the PCIV receives with the thin special liner, which is chosen according to the process, an inner coat which protects the cast iron walls specifically against the medium inside the vessel. This way the support structure cannot be attacked. With regard to material and wall thickness, the liner can be optimally made according to the chemical reaction and the size of the vessel.

A further important application for the PCIV in the future could be gas storage, if in conjunction with high-temperature reactors for the production of process heat - the projects of brown coal and coal gasification become reality, processes whose development is under way and whose realisation can be expected as early as in the eighties.

(For this refer to figure 18)

7. Summary

The lecture was intended to give a short outline of the technical and functional structure of a PCIV. Several possibilities for application in different types of methods and processes have been introduced. With this lecture we wanted to explain that the use of prestressed cast iron constructions promises success in all those cases where large volumes with respectively high pressures are required. In addition to room-or slightly raised temperatures, the vessel can be used for processes where high temperatures of up to 400° C become necessary. Furthermore, the lecture was to show that the basic structure of the prestressed cast iron pressure construction offers safety-technology advantages with the process-determined pressure and temperature conditions, as these constructions can be regarded as safe against failure within the range of the laid-out pressures as far as spontaneous failure under operating conditions is concerned.

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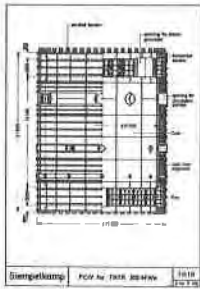


Fig. 1

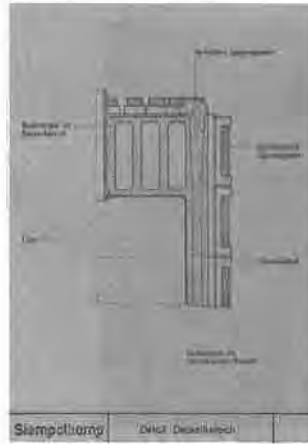


Fig. 2

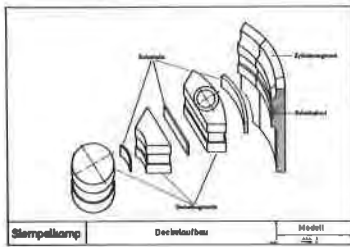


Fig. 3

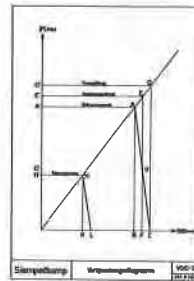


Fig. 4

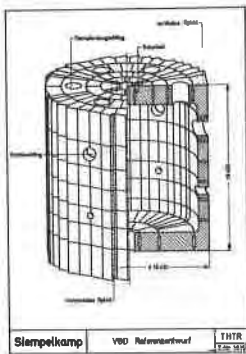


Fig. 5

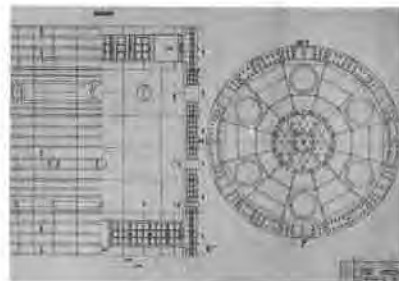


Fig. 6

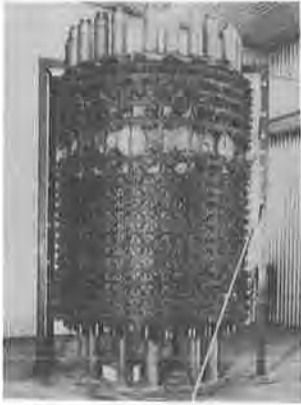


Fig. 7

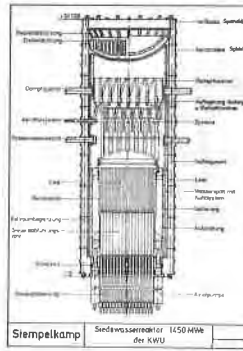


Fig. 8

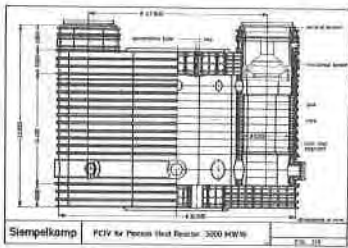


Fig. 9

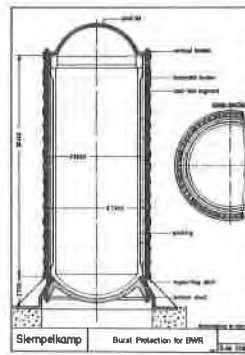


Fig. 10

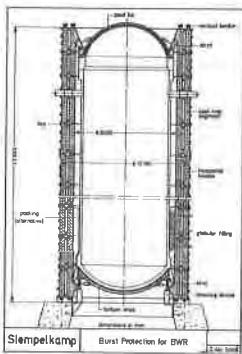


Fig. 11

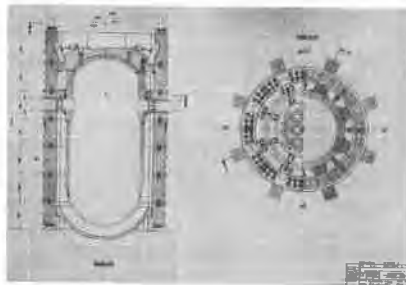


Fig. 12

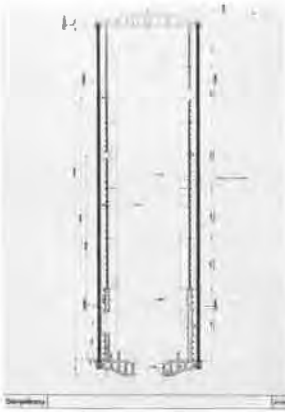


Fig. 13

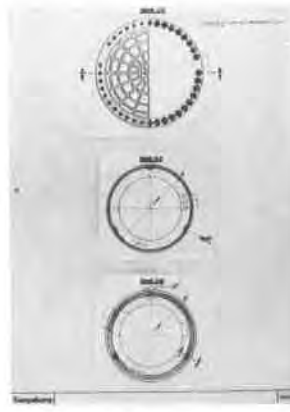


Fig. 14

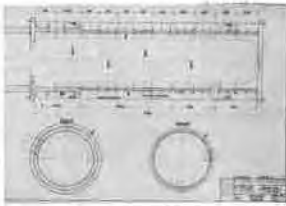


Fig. 15

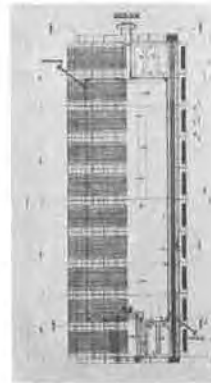


Fig. 16

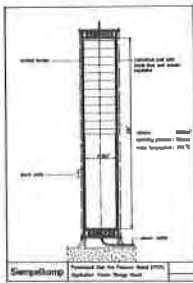


Fig. 17

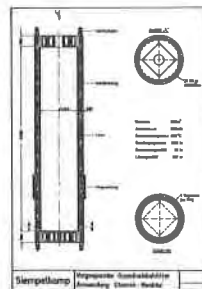


Fig. 18