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MANUFACTURE OF PRESSURE VESSEL FOR NUCLEAR POWER REACTOR

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I. DESIGN AND SPECIFICATIONS OF PRESSURE VESSEL

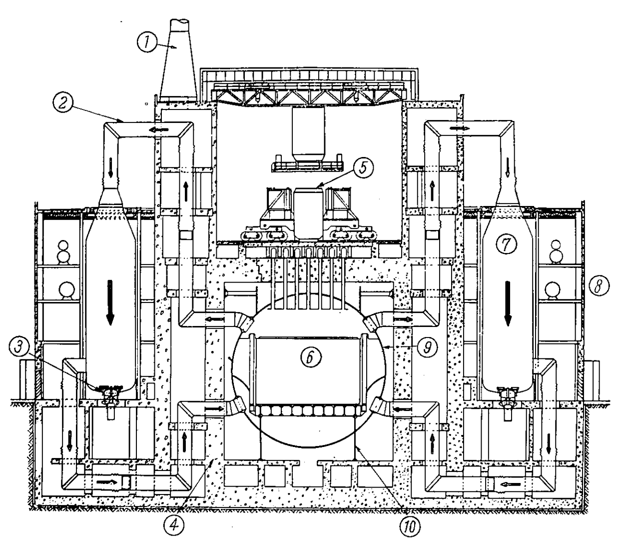
This pressure vessel is designed for use as an exterior wall of the central portion of Japan's first commercial nuclear power generating reactor (electric output 166,000 kw) of Tokai Atomic Power Station, Japan Atomic Power Company. The problems encountered in manufacturing this vessel are in its great size, plate thickness and the absolute requirements of safety and reliability associated with this relatively new field of atomic energy.

The exterior wall of this vessel forms a sphere with the outside diameter of about 18.5 m consisting of segments of aluminum-killed fine grain steel plate with the thickness of 80 to 92 mm numbering 101 pieces and a great number of forgings welded together. Welding is all of butt welding. The designed pressure for this vessel is 16.2 kg/cm^2 (maximum pressure to be applied being 14.4 kg/cm^2). This spherical wall is supported at its upper part by a cylindrical skirt with diameter of 12.5 m and thickness of 62 mm and by a similar cylindrical plate at its lower part also in order to protect the wall from earthquakes. The weight of the pressure vessel with all its equipment is about 4000 tons, of which the weight of the spherical wall itself is about 1000 tons.

Special consideration is paid to thermal insulation in order to maintain the temperature of the spherical wall during the operation of the nuclear reactor about 230°C.

Accuracy stipulated for manufacture is ±40 mm for the sphere diameter and less than 3 mm for the difference in the butt welding of the plates.

These materials are essentially different from those of ordinary pressure containers or vessels. In other words, since the present vessel is intended to contain radioactive material for nuclear reactors, it needs to be taken into consideration that the materials used will be subjected to change due to radiation of neutron and, therefore, their inspection and maintenance during the reactor operation will be difficult.



① Stack
② Hot gas duct
③ Gas circulator
④ Biological shielding
⑤ Charge-discharge machine
⑥ Reactor core
⑦ Steam raising unit
⑧ Steam drum
⑨ Pressure vessel
⑩ Support skirt

Fig. 1 Cross-section of reactor structure

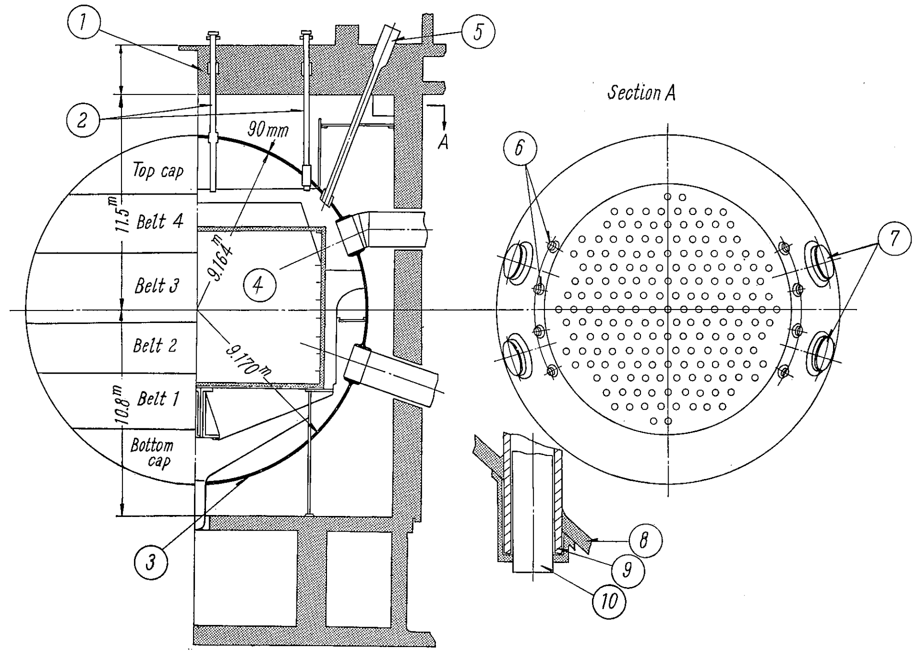
II. SPECIFICATIONS AND INSPECTION OF STEEL PLATE

1. Specifications

The following qualities are required of the steel plate used for the pressure vessel:

(1) That the transition point should be sufficiently low so that even when the reactor operation is stopped the crack will not spread;
(2) That the plate should be least liable to the radiation injury;
(3) That the creep characteristics should be superior;
(4) That the plate should have sufficient tensile strength;
(5) That the plate should have good welding characteristics;
(6) That the plate should have good anti-corrosion characteristics against the cooling gas in the reactor;
(7) That the reactor system should be stable in operating condition;

Thus, Coltuf 28 type steel plate is taken to meet



① Primary shield
② Stand pipes
③ Reactor shell
④ Reactor core
⑤ B.C.D. stand pipes
⑥ B.C.D. nozzles
⑦ Hot gas duct
⑧ Nozzles
⑨ Stand pipe
⑩ Reactor shell

Fig. 2 Basic dimensions of reactor vessel

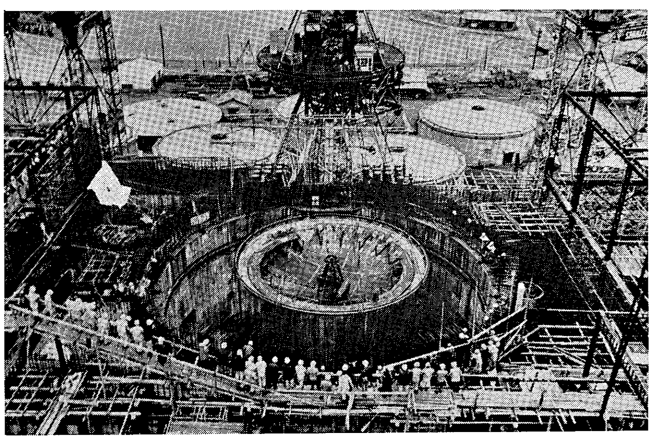


Fig. 3 Installation of pressure vessel

***Table 1* Specifications of Steel Plate**

Materials	Made from open-hearth furnace or electric furnace and suitable for welding
Chemical Composition	C<0.16, Si<0.1/0.3, Mn<1.40, S<0.05, P<0.05. Add aluminum of stipulated amount
State of Delivery	Steel plate shall be delivered in the state of annealing
Mechanical Qualities	Tensile strength 28/33 t/in^2; yield point 16 t/in^2; extensibility over 25%; impact value V notch chalpy 15ft-lb or over at −40°C
Crystal Grain	6∼8 (ASTM)

these requirements. The steel plate has the thickness of 82 mm and 94 mm. About 934 t, 106 pieces including spares, is made by Nihon Seiko. The specifications are as in *Table 1*.

2. Examination and Test

(1) Test to confirm technique in steel making method

The following tests were made regarding open-hearth furnace method and electric furnace method of making steel.

(a) Ultrasonic test for all surfaces

When defects were detected, the defective sections was cut off and microscopic tests was carried out.

(b) Magnetic flaw detection and coloring flaw detection test

Cut the surrounding and central parts with gas, and then finish by grinding, followed by tests.

(c) Mechanical tests

Pull, bend, impact, hardness, micro, sulpher print, and crystal grain tests were made.

(d) Special tests

Part of the plate used for the above tests was kept and re-tested in two months.

(2) Steel plate delivery tests

Steel plates manufactured through the processes confirmed by the above-mentioned tests were subjected to the following tests at delivery.

(a) Ultrasonic wave test
(b) Magnetic flaw detection test
(c) Mechanical tests (pulling, bending and impact test)
(d) Sampling special test
  a. Magnetic flaw and steel making method to be reconfirmed
  b. Test in two months

(3) Tests after hot press

It is anticipated that a steel plate subjected to the hot press has its mechanical characteristics changed, so after the press pulling, bending and impact tests were made.

After these numerous tests, only steel plates with good quality were sent to the site.

III. HOT PRESS AND CUTTING

The steel plate was subjected to the hot press by a 5000 ton press within the range of annealing temperature and was formed into a sphere. The accuracy curvature at this time was held down to 3 mm.

Even a slight error on size of the steel plate has far-reaching influences on the size of the whole when a sphere is made up of these steel plates put together. Take the belt 3 for example. Since a belt is made up of 18 steel plates welded together, even if each plate is longer by 1 mm it becomes 18 mm long around the circumference and 2.8 mm in radius, or just about the tolerance limit. When we consider the error that might arise out of shrinking of the welded portions, it is very difficult to make a belt with its radius error within 3 mm. Consequently, the mark-out size test was done in a double checking system and the error was contained within 1 mm.

In order to meet these severe accuracy requirements, the following steps were taken to keep size accuracy. First, the steel plate was cut with a special automatic gas cutter with magnetic wheel, and, since it was not possible to obtain the accuracy of 1 mm with gas cutting, the cutting was done leaving an allowance for finish of 2 mm to 5 mm. After this, the surface was precision-finished by a chipping hammer and a grinder.

Thus, the root gap and opening angle were kept uniform. This not only makes assembly work prior to welding easy but prevents defects at welded portions from arising, and, further contributes to making the amount of shrinkage uniform and making irregular deformation impossible.

IV. WELDING OF VESSEL AND SIZE ACCURACY

1. Training of Welding Engineer

About a hundred welding workers were trained at a welding school set up at Kawasaki Factory for a year prior to their welding of the pressure vessel. The training took place for 24 people at a time, and both lectures and practices were given them for about three months. During the training period, one trainee welded about thirty plates of 600 mm length with three different thicknees of 25, 50 and 84 mm. The welded test pieces were subjected to X-ray examination and macrography, and, on the basis of these tests 77 welders of good results were selected. The fact that there was so low a repairing rate for defective production welding of the pressure vessel is due largely to this training.

2. Assembly and Welding

The pressure vessel was welded together from the six parts welded at the site work shop: the bottom cap, belt 1, belt 2, belt 3, belt 4 and top cap. They were lifted into the reactor building by a 150 ton derrick crane and followed by the welding of the periphery.

As for the bottom cap and the top cap, steel plates were arranged on the welding stand of sphere, and finally were trimmed around the periphery with an automatic gas cutter.

Each belt was welded with allowance for shrinking

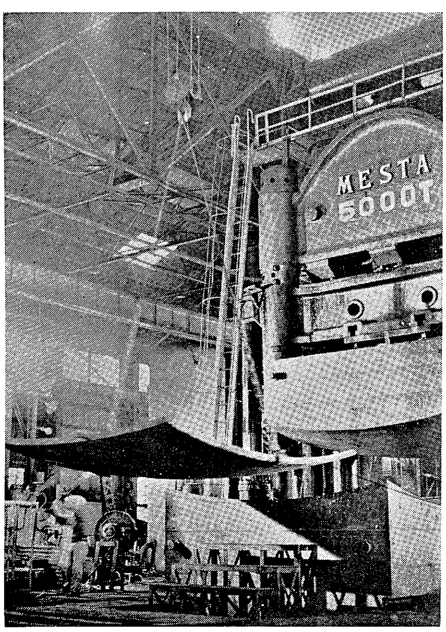


Fig. 4 Hot pressing

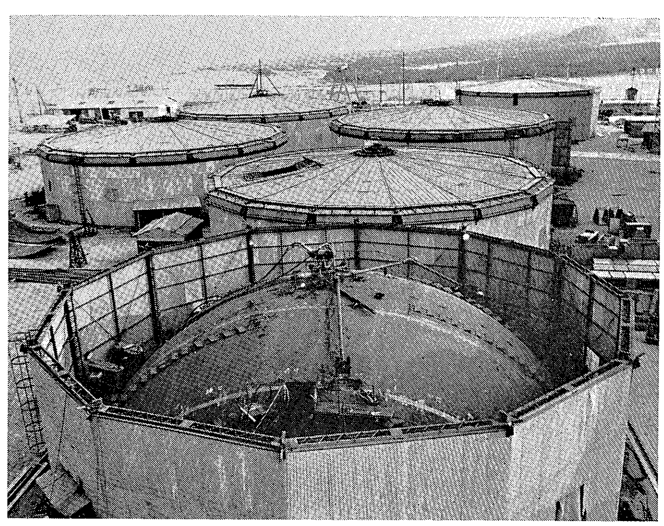


Fig. 5 Prefabrication tank under construction

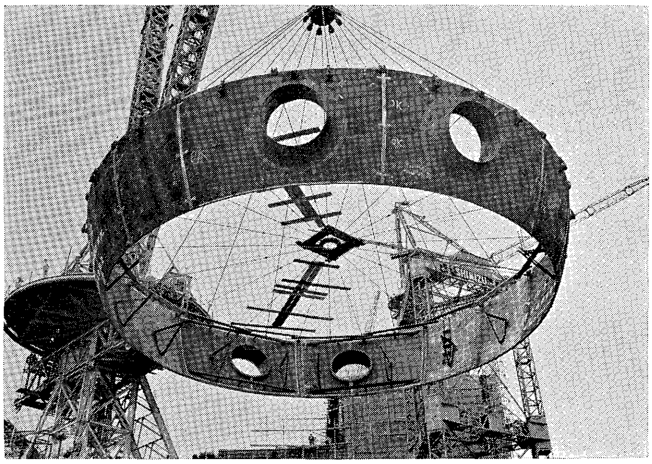


Fig. 6 Belt 2 lifting into the reactor

caused by welding. Suppose shrinkage should be of 1 mm per 1 seam, for belt 3 it would be 18 seams and so the difference would be 18 mm around and 2.8 mm in radius. Since the maximum discrepancy allowed in periphery welding of each belt is 3 mm, it is very difficult to maintain accuracy on radius of ± 3 mm when the curvature error of steel plates and angular deformation caused by welding are considered. For this reason, a number of tests were made of full size test plates to determine the value of shrinking. Many other tests were also made to investigate welding conditions, relationship between welding method and deformation, and relationship between welding method and notch ductility of the welding portion. It was possible to manufactue every belt with the accuracy within 3 mm when welding was executed on the basis of the well experimented tests.

Welding of the periphery was done by 15 to 25 welders at a time, with the entire suface preliminarily heated to 100°C~150°C with propane gas burners. While the working conditions were bad for periphery welding in site, an X-ray test showed that the repair factor was only 5.7% for the total welding length of 287 m.

When the pressure vessel sphere was completed, 185 charge/dicharge (C/D) nozzles were welded to the top cap. This was done very carefully with the 185 nozzles divided into 9 zones so as to prevent the shrinkage of the top cap by the C/D nozzle welding, its drop and dislocation of the nozzles previously welded or its inclination. The pressure vessel, furthermore, was made bigger in anticipation of the drop, so that the error on diameter immediately after the C/D nozzle welding was +4 mm in polar direction and +2.8 mm in equator direction.

After the C/D nozzle welding process, the pressure vessel was given a welding of about 10,000 pieces of stud for accommodation of heat insulating materials and thermoelectric couple in preparation for subsequent annealing. Sufficient tests were made to determine welding conditions in advance, and welding finished in a very short time with the use of two sets of Nelson stud guns.

In the middle of June, 1963, annealing was over, after which 185 pieces of charge-discharge stand pipes were welded on to the nozzles. It was not easy to weld stand pipes of 338 mm in diameter and about 9 m in length while maintaining such high accuracy as ± 1.5 mm for nozzle location and ± 3 mm for upper and lower ends of the pipe. However, a special set jig was used and two welders were situated symmetrically to one another to measure the inclination while welding. As a consequence, very good results were obtained.

3. Welding Rod

The welding rod for the pressure vessel, LB-55, is a low hydrogen type welding rod of Mn–Si system manufactured by Kobe Steel Works Ltd. Since the impact value of V-notch chalpy of deposit metal was stipulated to be more than 20 ft-lb at −40°C, many experiments were conducted with emphasis upon notch ductility at low temperature. Since the content of Mn and Si has the greatest effect upon the impact value, various experiments were attempted varying this proportion. It was found as a result that the low content of Mn and Si shows remarkable drop in the impact value at low temperature and that the impact value would improve at low temperature even if the content of Mn and Si is high, even as " welded " and annealed and stress relieved. About 5000 chalpy impact test pieces were made for the testing of welding rods LB–34 and SL–55 selected for these experiments and for spares.

Table 2 shows the chemical composition of deposit metal of LB–55 and an example of mechanical qualities.

Table 2 **Chemical Contents and Mechanical Characteristics of LB-55 Welding Metal**

Chemical Contents					Yielding Point	Tensile Strength	Ductility
C	Mn	Si	P	S	(kg/mm^2)	(kg/mm^2)	(%)
0.07	1.09	0.53	0.013	0.009	44.4	52.6	29.1

V. ANNEALING

The pressure vessel was annealed after the completion of internal construction assembly of sphere wall, reactor supporting stand, reactor restricting cylinder, gas seal, etc.

As a heating source, nichrome wires and heater consisting of 56 elements were employed and installed inside the sphere wall. The electric power required for heating was about 3.5 Mw.

The exterior surface of the pressure vessel was heat-insulated by a rock wood board of thickness

150 mm～300 mm in order to protect loss of thermal radiation and overheating of shut-off walls.

For the measurement of annealing temperature, 317 thermoelectric couple thermometers were used, and the temperature recorded by an automatic recording device.

Control of the annealing temperature was done from 107 thermometers fitted to a quarter of the sphere body, and as the other parts form a structural symmetry only differences of temperature were measured. Output of each heater element was individually controlled and heating, maintenance and cooling operations followed it.

The annealing work ended in about twenty days at the passage of the following temperatures:

Heating rate	3～6°C/hr
Soaking temperature	540～575°C
Cooling rate	2～3°C/hr
Soaking time	15 hr

The temperature transition was sufficient to meet the Nuclear Power Generation Safety Standards and UPC standard values.

After the annealing, tensile tests and impact tests were made of test pieces consisting of totally deposited iron and mother material in order to confirm mechanical characteristics of the material. The test pieces used were placed in the pressure vessel and annealed together with the vessel at the same time. Results of traction tests with these test pieces were compared with similar material annealed to eliminate stress in the standard manner (soaking temperature 600°C, soaking time 1 hr, plate thickness 1 in.) and no appreciable difference was recognized. As for the impact value, there was an increase in the transition temperature of about 10°C as compared with the transition curve in a normalized condition that the material itself had, but the transition temperature of the mother material itself was remarkablly low and vTr = −66°C even after annealing. This may be termed as a sufficiently low temperature for brittleness breakage.

Satisfactory results were derived from bending tests and non-destructive tests of the welded portions.

VI. PRESSURE TEST

For about a week from January 22, 1964, pressure and leakage tests of the pressure vessel were conducted in the presence of the Lloyd Vessel Association and the Ministry of International Trade and Industry (MITI).

These tests were made of a total cubic content of about 3930 m³ centering around the pressure vessel and including part of the main gas duct.

In the interest of safety even in the event of an earthquake, these tests were made with atmospheric pressure rather than with water pressure.

The test of compression was primarily intended to pass the intermediate leakage and compression tests of the Lloyd Association and the MITI, but as the tentative requirement of Lloyd was severer and more concrete than the safety standards of the MITI, the Lloyd's tentative criterion was followed and it was made 25.0 kg/cm² according to the following formula:

$$1.5 \times \left(\text{designed pressure} \times \frac{f_a}{f_t} \times \frac{t}{t-c}\right)$$

f_a: designed stress at test temperature
f_t: designed stress at designed temperature
t: nominal shell plate thickness
c: allowance for corrosion

During the compression, a stage was provided at 20.3 kg/cm² (16.2 kg/cm² × 1.25) for MITI purposes, and, in conformity with the provisional demand of Lloyd, the leakage test was made 1.1 times the designed pressure or 17.8 kg/cm².

The tests made included compression test, mesurement of stress, of displacement and leakage test, as well as exterior appearance test. The Lloyd Association made stress measurements at about 186 places of interrupted sections representative of the pressure vessel at each stipulated pressure stage of 4.0, 7.0, 12.0, 16.2, 20.3, 22.5 and 25 kg/cm². The displacement measurement was taken at about 24 places.

The leakage test was performed to test the existence of leakage at the following sections, and no leakage was detected.

1. Welded portions not subjected to radiation tests
2. Corner welded sections and parts welded to stop leakage.

VII. POINTS ON WHICH LABORIOUS EFFORTS WERE PAID

In the manufacturing of the pressure vessel, the welding of C/D nozzles and C/D stand pipes was the most difficult. The C/D nozzles were welded to

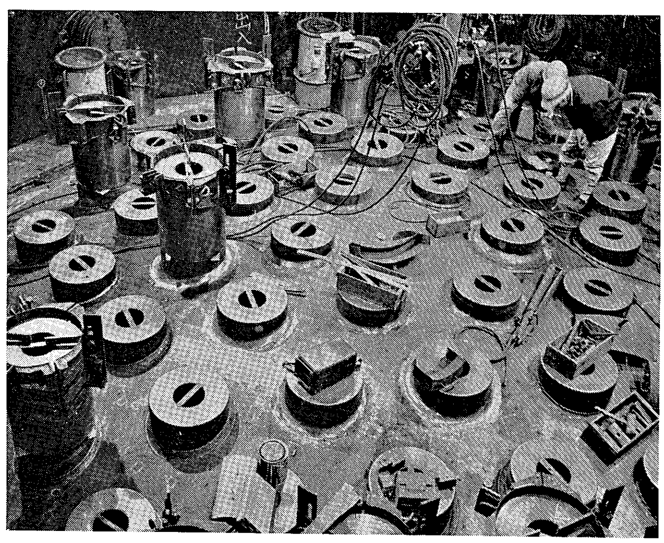


Fig. 7 Installation of C/D nozzles

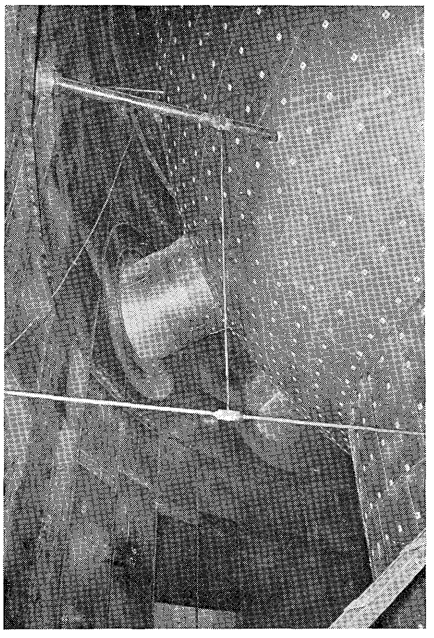


Fig. 8 The bottom of main part of the vessel

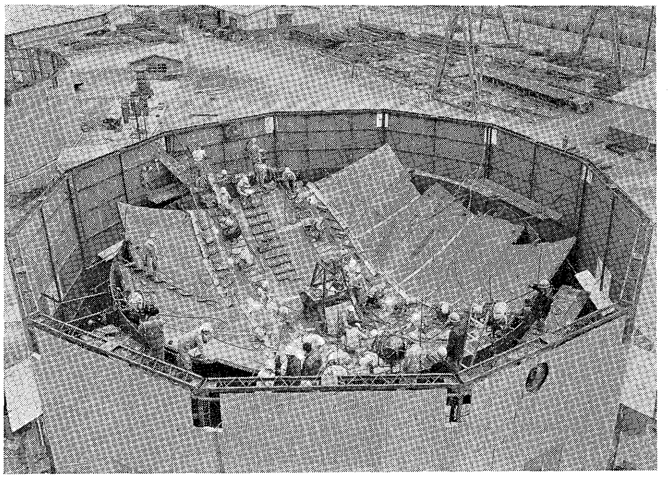


Fig. 9 Welding of bottom cap

the plate of the sphere and the fitting accuracy was far beyond the common sense of welding but still it had to be completed in such a short period of time. These nozzles, even if set vertically, incline by their own welding, and the position moves by the effect of the next zone's welding and still the next one, and the degree of inclination also changes. It was by no means easy, therefore, to keep the correct vertical position of all the nozzles when they were all welded. For this reason, 185 nozzles were divided into 9 zones, and as soon as a zone was welded all the nozzles were measured for movement and inclination and anticipation was made as to how to preset and pretilt the nozzles of the ensuing zone, and work was carried on very carefully.

In spite of such careful work, the work completed in 5.5 months with 48 welders for C/D nozzles, 24 chippers, 6 gas cutters, 8 canners and 8 inspectors for two shifts through night and day.

Final inspections following all welding work indicate the tilting of 1.8/100 for the 185 nozzles and deviation of position within 5 mm. All the welded portions were subjected to magnetic flaw inspection, but no flaw was detected.

Finally, we believe it is to Japanese technological credit that for the first time in Japan this nuclear reactor pressure vessel with severe specifications met all the required quality conditions of international standard and that the stress relieving work came to a close in 24 months from the beginning of the order of steel plate and the pressure test in 31 months, or relatively short time.