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Underwater Plasma Arc Cutting of In-Reactor Tube of In-Pile Creep Test Facility

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The in-reactor tube of the In-Pile Creep Facility had been irradiated periodically for over 6 years in the Japan Materials Testing Reactor (JMTR) up to the end of 1978 under an operating condition of high temperature and high pressure identical to that of the Prototype Advanced Thermal Reactor, FUGEN, to gain the basic data for estimating the amount of creep which would occur in the pressure tubes of FUGEN.

Following the removal of the in-reactor tube out of the JMTR, the test sections in the tube which were to be subjected to post irradiation examination were cut out. Underwater plasma arc cutting was employed to prevent the spread of contamination to the work area, to confine the heat affected zone in the test pieces to a minimum and to simplify disposal of the unneeded portions of the pressure tube.

Setup of the cutting machine, cutting operations, radiological conditions during cutting of the highly radioactive portion of the tube and disassembly of the cutting equipment are described. In addition a brief description of the underwater plasma arc cutting machine is presented.

The hot-cutting operations were done remotely to control personal exposure. The containment envelope prevented the spread of contamination

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to the environment and radioactive particles deposited on the cutting machine were removed without any difficulties. External exposure received by cutting personnel was small. Internal radionuclide deposit examinations were conducted, determining no crew member inhaled radioactive substances. Contamination spreads to the work area were minimal and release of radionuclide was well controlled.

Keywords : Underwater Plasma Arc Cutting, In-Reactor Tube, In-Pile Creep Test Facility, JMTR

内圧クリープ照射試験装置炉内管の水中プラズマアーク切断

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（1988年9月12日受理）

新型転換炉の原型炉「ふげん」の炉心部に使用されているジルコニウム合金製圧力管の中性子照射下でのクリープ歪量を確認する目的で，JMTRに設置された上記圧力管と同材質の内圧クリープ照射試験装置炉内管は1978年まで7年間照射試験に供された。照射試験終了後，撤去された炉内管の廃棄のための切断および照射後試験に供されるテストセクション部の切出し作業が1981－1982年に掛けて実施された。

切断作業は大別して (1) 非放射化部で，かつ汚染密度の低い部分の空中切断，(2) 放射化部を含む汚染密度の高い部位の水中プラズマアーク切断，および (3) ホットセル内での機械切断の3とおりである。

本報告書は空中切断に続いて行われた水中プラズマアーク切断について，今後同様な作業を計画する場合の参考と成り得るデータ等を収録する目的でまとめられた。

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1. INTRODUCTION

The in-reactor tube of the In-Pile Creep Test Facility, similar to the pressure tubes being used in the Prototype Advanced Thermal Reactor, FUGEN, owned by the Nuclear Fuel and Power Reactor Development Corporation (PNC) was removed from the Japan Materials Testing Reactor (JMTR) at the Japan Atomic Energy Research Institute (JAERI) Oarai Research Establishment in December 1978 due to a malfunction which developed in the in-reactor tube temperature measurement system. The In-Pile Creep Test Facility was built by Ishikawajima Harima Heavy Industries Co., Ltd.(IHI) under a PNC contract as a part of the PNC's advanced thermal reactor development program. The aim of the In-Pile Creep Facility was to estimate by analogy the amount of creep which would be induced in the pressure tubes being used in FUGEN by the time of their removal by measuring at regular intervals the growth rate of the creep generated in the in-reactor tube of the In-Pile Creep Test Facility in the JMTR.

The in-reactor tube (Fig.1-1) had been irradiated periodically for over 6 years by JAERI at the request of the PNC who installed the test facility in the JMTR rated 50 MW(th) in December 1972. The data on the creep behavior gained through the In-Pile Creep Test Facility was satisfactory for the above purpose. Therefore the in-reactor tube was removed from the JMTR in the middle of December 1978 when a thermocouple for measuring the tube temperature was found to be out of order.

Three chief parts, the in-reactor tube, electric heater, and partition tube, composed the in-reactor portion of the test facility. The heater was inserted coaxially into the in-reactor tube and the partition tube was mounted around the heater. The in-reactor tube (Fig.1-2) consisted of both the inner tube of zirconium-(2.5% wt)niobium alloy and the outer tube of zircaloy-2. The large-diameter tube, 74 mm outside diameter, 3.1 mm thick and the small-diameter one, 57 mm, 2 mm thick, were welded end to end to form a 6.9 m long inner tube. There were two test sections 500 mm in length on the inner tube, one in the region surrounded by the reactor core and the other outside of the core area. Their purpose was to evaluate the effect of neutron irradiation on the creep characteristic of zirconium-(2.5% wt)niobium alloy by means of comparing the amount of creep which occurred in each section. At each test section, to accelerate the growth of the creep, the wall thickness was reduced to 1.5 mm, thinner than the other region by 0.5 mm.

The outer-tube was also made of tubes having different diameters and thicknesses in the same fashion as the inner-tube. By employing a reducer to accommodate the difference in the diameters, a tube of 69 mm outside diameter, 3.9 mm thick was welded to a tube of 92 mm outside-diameter, 5.1 mm thick to make a 7 m long outer tube. The inner-tube was inserted into the outer-tube coaxially to allow them to be welded at the tops in order to complete the in-reactor tube.

During the operation of the In-Pile Creep Test Facility while the reactor was in operation, a pressure of 87.6 kg/cm^{2}G, identical to the pressure generated inside the pressure tubes of FUGEN, was applied inside the inner tube by heating up the water in the tube with an electric immersion-type heater having a maximum output of 20 KW. To generate the desired pressure of 87.6 Kg/cm^{2}G, the water in the tube had to be maintained at a temperature of 300°C.

The major functions of the outer-tube were as follows: (1) to prevent damage when the inner-tube broke due to the pressure inside, and (2) to reduce the heat conduction from the inner-tube kept at 300°C to the reactor primary coolant about 40°C which flows along the outside of the outer-tube to maintain the desired temperature of the water in the inner-tube by providing a thermal insulating space between the inner-tube and the outer one. The presence of the thermal insulating jacket prevented excessive thermal stress across the inner-tube wall. When the test facility was in operation, the thermal insulating jacket was swept continuously with helium gas to detect the presence of moisture in the jacket which could be caused by water leakage into the jacket through an unexpected break in the inner-tube or the outer-tube.

The 7.2 m long electric immersion-type heater was fabricated from 23 mm O.D., 1.5 mm thick, type SUS 32 stainless steel tubing. The electric heater elements and magnesia insulation were put in the tube. The partition tube was placed coaxially around the heater. The function of the partition tube was to guide the circulation of the water in the inner-tube. The water is circulated by convection generated by the heat from the heater. The purpose of the circulation was to reduce the difference in the temperature between the water at the top and the water at the bottom of the inner tube. The type SUS 32 upper portion tube, 46 mm O.D., 1.65 mm thick, and the lower portion tube of the same material, 34 mm O.D., 1.65 mm thick, were welded together with a reducer between them to adjust the diameter difference making the complete partition tube having an overall length of 6.3 m.

Prior to the installation of the facility, an agreement was reached between the staff concerned that the in-reactor tube would have to be withdrawn from the JMTR under at least one of the following circumstances; (1) the amount of the creep taking place in the test section was above 1%, and (2) the total fast neutron flux on the test section exceeded 10^{21} nvt. At the time of the malfunction of the temperature measurement circuit, the above two requirements were almost satisfied, therefore, it was decided to remove the In-Pile Creep Test Facility from the reactor in the middle of December 1978. After having been withdrawn, the in-reactor tube was laid underwater at a depth of 6.2 m on the bottom of the canal attached to the reactor and was kept there for 2 years and a half until June 1981 when the preliminary cutting operation of the in-reactor tube began.

In June 1981, as preparatory work for conducting the underwater plasma arc cutting job, the in-reactor tube was cut at the top in the air in order to sever it into two pieces, the inner tube and the outer tube, by employing a hand-operated tube cutter with the radioactive portion of the tube submerged under water with a view to protecting the work crew from excess radiation exposure. This cutting was done in the canal and reactor cavity. After being separated, each tube was further divided into two parts by being cut at about the center in the same fashion. Both the partition tube and the heater were cut manually in the same manner as the in-reactor tube, with the active region being kept underwater. Because the radiation level of the partition tube and heater was higher than that of the in-reactor tube, in the preliminary cutting, a shielding device specially designed for this particular job was employed with the aim of lowering the radiation level.

Through the preliminary cutting operation, the items prepared for the scheduled underwater plasma arc cutting were as follows; (1) the lower half of the inner tube, (2) the lower half of the outer tube, (3) the upper half of the partition tube, and (4) the lower half of the partition tube. The upper portions of the outer and iner tubes were disposed of using in-air mechanical cutting because of their low radiation intensities. The heater elements were cut in the hot cell at the JMTR as planned. All the above work items except item (3) were highly radioactive, however the upper part of the partition tube was contaminated to a large degree with radioactive crud. In the end, the cutting of all the items, except the lower half of the partitin tube, was satisfactory. The lower portion of the partition tube was segmented by means of a hack saw in the hot cell.

2. RADIOACTIVE INVENTORY AND RADIATION LEVELS

In order to design capable cutting equipment with the necessary shielding devices, the radioactive inventories in the items to be cut and the resulting dose rate from each item had to be determined before the designing step commenced. After being installed in the JMTR in October 1972, the in-reactor tube was irradiated periodically at an operating pressure of 87.6 Kg/cm^2 G and an operating temperature of 300°C with the reactor operating at its rated power of 50 MW(th) until the removal of the in-reactor tube from the reactor in December 1978. The total length of operating time of the In-Pile Creep Test Facility was 7,300 hours and the total integrated fast neutron flux on the in-reactor tube came up to 9.03 x 10^{21} nvt.

After being removed, the in-reactor tube and heater assembly were kept at 6.2 m in the pool adjacent to the reactor cavity for 2 1/2 years. During this period, the radiation levels at the surfaces of the in-reactor tube and the immersion heater together with the partition tube were measured at an interval of 100 days with a gamma-ray dose rate meter designed for underwater use to get the data comprising the basis for designing the cutting machine. Along with this measurement, calculatins of both the reactor-originated radioactivities and the resulting dose rates from each component were done to determine what amount of the significant nuclides, like Co-60 and Fe-55, survived till the time of the execution of the underwater cutting operation in February 1982. The calculated radioactivities in the components were as follows; (1) 2 Ci in the inner tube, (2) 4 Ci in the outer tube, (3) 330 Ci in the partition tube, and (4) 170 Ci in the heater.

In Fig.2-1 the above mentioned radiation intensity of the in-reactor tube is shown together with the calculated one based on the reactor-originated radioactivity. Fig.2-2 gives the corresponding radiation values for the heater and partition tube combined.

3. DEVELOPMENT OF UNDERWATER PLASMA ARC CUTTING EQUIPMENT

The malfunction that developed in the temperature measuring device of the in-reactor tube toward the end of 1978 promptly led to the removal operation of the tube since the above mentioned criteria (amounts of both

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3. DEVELOPMENT OF UNDERWATER PLASMA ARC CUTTING EQUIPMENT

The malfunction that developed in the temperature measuring device of the in-reactor tube toward the end of 1978 promptly led to the removal operation of the tube since the above mentioned criteria (amounts of both creep and neutron flux) for withdrawing the in-reactor tube were nearly fulfilled by that time. Taking into consideration the length of time needed to develop the cutting machine for the irradiated works, in the middle of 1977 we began a basic study on the possibility of conducting the underwater cutting job.

The development of the plasma arc cutting facility was carried out by the three organizations concerned, the PNC, IHI, and the JAERI. The PNC sponsored the program and provided the major guidelines to follow. IHI, in accordance with the policy given by the PNC, conducted the basic research, safety research, the design of the cutting equipment, manuacturing the facility, and the cutting job. The JAERI took part in realizing the program because the JAERI had irradiated the in-reactor tube in the JMTR for over 7 years. It was responsible for the disposal of the radioactive items as well as the unneeded portions, and supervised the cutting operations and radiological conditions.

The basic study and safety research comprised the following items: (1) the requirements for igniting the plasma arc - (a) the influence of torch stand-off (torch-to-work distance), (b) the kinds of working gas, (c) the gas flow rate, (d) the amperage of the arc current when igniting the plasma arc; (2) the influence of the cutting conditions on the width of the kerf, on the surface roughness, and on the extent of the heat affected zone - (a) stand-off, (b) the cutting speed, (c) the working gas flow rate, (d) the kind of working gas, (e) the cutting amperage; (3) the amount of exygen and hydrogen dissolved in the vicinity of the cut and their distribution; (4) the magnitude of the deformation taking place around the cut by the thermal input; (5) the effect of the depth of water when igniting the arc; (6) the study on the slag generated in experimental plasma cutting - (a) the amount of the molten part, (b) the amount of slag particles and their diameters, and (c) the method for gathering the slag underwater; (7) the slag suspended in the water - (a) the effect of cutting conditions on the amount of slag suspended in the water, (b) the variation of the amount of slag suspended in the water over time, (c) the shape of the suspended slag particles, (d) the pH value of the water, (e) the conductivity of the water, and (f) the turbidity of the water; and (8) the size of the molten particles from the cuttings carried by the working gas. All the experiments were conducted using the transparent plastic tank (850 mm wide x 500 mm deep x 450 mm high) except item (5) which was done with the full scale mock-up facility (850 mm across x 3,500 mm high) at a workshop of IHI.

4. DESCRIPTION OF CUTTING MACHINE

The cutting equipment (Fig.4-1) was composed of the torch, plasma power controller, torch manipulator, work platform, scaffold, drive unit, water tank, envelope, water purification system, air purification system, control console, closed circuit television set, and diesel engine generator. The functions and characteristics of each component are briefly described below.

Torch and Plasma Power Controller

A commercially available 200 V, 250 A plasma arc torch with the tungsten electrode measuring 4 mm in diameter and 150 mm in overll length was modified to be used for this underwater cutting (Fig.4-2). While the torch was under water, argon gas flowing through the passage in the torch via the gas supply hose prevented the water from entering the orifice and kept the passage dry. The working gas of helium replaced the argon gas before the cutting procedure began. The torch was capable of cutting 17 mm thick type SUS 304 stainless steel underwater.

The plasma power controller was to control the electric power from the diesel engine generator in order to provide the torch with the desired amperage. The pilot arc circuit for igniting the arc was also contained in the plasma power controller. Equipped with the plasma power source were the meters to indicate the present values of the amperage, voltage and working gas flow rate.

Torch Manipulator

The 6.8 m long torch manipulator (Fig.4-3) which hung from the scafflod placed on the work platform over the SFC (spent fuel cutting) pool had the following functins; (1) vercical positioning of the torch (a range of 4.9 m in the vertical direction), (2) holding and rotating the item to be cut, (3) vertical positioning of the bucket to retrieve the piece that was cut off, and (4) adjustment of the torch-to-job distance (stand-off). On the plate at the top of the torch manipulator, the driving gears to fulfill the above functions were secured. The source for driving the manipulator was electricity.

Work Platform

The 4 m wide x 3 m deep work platform (Fig.4-4) was placed over the SFC pool with its legs on the main floor in order to accommodate devices such as the water tank, envelope, scaffold, water purification facility, and air purification system.

Scaffold and Drive Unit

The purpose of the 1.6 m high scaffold consisting of 6 vertical tubes arranged hexagonally with horizontal tubes connecting the vertical ones at two different heights was to hang the torch manipulator from the top plate on the scaffold (Fig.4-5). The bottom ends of the vertical tubes, 1.1 m apart from their opposite ones, were placed on the upper rim of the water tank at the location where the two walls of the tank met. On the top of the scaffold were fitted the driving mechanisms driven with direct current motors for rotating the work, positioning the torch vertically, and adjusting the atand-off.

Water Tank

To prevent the SFC pool from being contaminated with the radioactivity from the slag of the cuttings, the 6 m deep tank (Fig.4-6) was suspended from the work platform with the lower 5 m portion submerged in the water in the SFC pool and the upper 1 m part being above the water. Twelve type SUS 304 stainless steel plates, 0.55 m wide, 3 m long, were formed into one hexagonal tank having a width of 0.9 m across each of the parallel sides facing each other. Upper and lower hexagonal tanks were constructed and the two structures were bolted end to end to form the 6 m long tank with the bottom inclining toward the center in order to facilitate the collection of particles generated from the cutting. At the very bottom of the water tank a strainer was provided to collect large-diameter slag particles. The water in the tank was circulated through the strainer and the water purification system and returned through the top of the tank. One side of the tank was provided with a 0.2 m wide, 4.5 m long removable panel having transparent reinforced glass to allow a cutting personnel to observe what was going on in the inside of the tank. The panel was removed when the work to be cut was brought into the tank and when the pieces that were cut were taken out of the tank.

Envelope

For the purpose of collecting the gas coming out of the water in the tank during a cuttring operation, an envelope (Fig.4-7) of 2.5 m high was mounted over the opening of the tank, with the scafflod and the torch manipulator placed in it. The envelope was large enough for several cutting crew to perform their jobs inside.

The pressure inside the envelope was maintained 8 mm lower than the surrounding atmospheric pressure. The measuring device was a water gauge (w.g.). This was done by removing the air from the inside with an air purification system. To maintain a constant pressure difference even when a worker entered, a special room was attached to the envelope as an isolation room. This room acted as a barrier between the outside and the inside of the envelope. It was also used as a changing room.

The plexiglass windows in the five sides of the envelope and in the two sides of the isolation room allowed what was going on inside to be observed.

Water Purification System

To purify the water contaminated with tiny particles suspended from the work being cut, a water purification system was connected to the water tank. The system consisted of the water pump, water filters, resin ion exchanger columns, water flow meter, conductivity meter, pH meter and the piping which drew the water from the bottom of the water tank and sent it to the top of the tank.

Of these components, the pump and the resin ion exchange columns were placed at a depth of 1 m and 2 m respectively underwater to reduce the radiation level at the working area by letting the water above those components act as shielding for the accumulated radioactive particles in the components.

Air Purification System

The air purification system had an exhaust fan with a capacity of 550 l/min and a filtering system capable of removing most of the airborne contamination generated during the cutting operations.

The exhaust from the inside of the envelope was sent to a permanently installed ventilation system of the JMTR with the difference between the pressure inside and the atmospheric pressure outside maintained at 8 mm (w.g.).

Control Console

The control console (Fig.4-8) enabled the cutting crew to control the cutting procedure from a remote operating position. Procedures which could be controlled through the control console were as follows; (1) clamping and rotating of the work, (2) vertical movement of the torch, (3) adjustment of the stand-off, and (4) vertical movement of the bucket.

The control console was located at the side of the SFC pool at a distance of 3 m from the platform in order to reduce personnel exposure to radiation caused by the work.

Closed Circuit Television

To observe what was taking place in the tank during the cutting operation a closed circuit television was provided. The underwater TV-camera which could move along the transparent window in the guide tube to gain the same elevation as that of the torch inside the tank covering a range of 0.9 - 4.5 m underwater proved to be a very useful device for the cutting crew who could ascertain that the cutting was going as expected by viewing what appeared in the TV-set which was beside the control console.

Diesel Engine Generator

Since no commercial electric power was available near the site, a diesel-powered three-phase 200-volt generator, 250 A, 100 KVA was connected to the plasma power controller which controls the power in the predetermined mode. From the plasma power supply to the plasma torch, electric power was supplied through a power cable via the intermediate plasma power controller which served the same purpose as the plasma power controller and which had amperage and voltage displays. To avoid noise from the power cable to the control circuit, due consideration was paid. During the trial cutting some of the displays on the control console were destroyed by the noise induced in the control circuit. This problem was overcome by applying an electrical shield to both the power line and the control line and changing the positions of the cables and controller.

5. CUTTING OPERATION

The cutting operation fell into three major categories: (1) in-air cutting; (2) underwawter plasma arc cutting; (3) cutting with mechanical devices in the hot-cell.

The cutting operations and the jobs related to them are presented in chronological order.

In-air cutting

① Cutting of the in-reactor tube. May 18 to 20, 1981.

② Mock-up test for cutting the partition tube and heater. May 21 to June 10, 1981.

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② Mock-up test for cutting the partition tube and heater. May 21 to June 10, 1981.

③ Cutting of the partition tube and heater into two pieces each. June 8 to 10, 1981.

④ Disposal of the head of the in-reactor tube. June 10 to 24, 1981.

Underwater plasma arc cutting

① Setting up the cutting facility at the site. Nov. 4 to 19, 1981.

② Coordination of the facility and mock-up test with non-radioactive work. Dec. 7 to 18, 1981, Jan. 7 to 13 and 18 to 19, 1982, and Feb. 15, 1982.

③ Hot cutting operation. Feb. 17, 1982 to Mar. 1, 1982.

④ Dismantling of the cutting facility. Mar. 3 to 31, 1982.

⑤ Decontamination of the facility. Mar. 15, 1982 to May 28, 1982.

This chapter chiefly deals with the underwater cutting.

Before the cutting operation began in February 1982 the work of setting up the cutting equipment and the trial cutting of the non-radioactive items by the actual machine was carried out. After the plasma arc cutting job was finished at the beginning of March of the same year, all the equipment was dismantled and decontaminated at a decontamination shop of the Waste Management and Decontamination Division of the JAERI Oarai Establishment before being stored in a warehouse in the same complex at the beginning of June 1982.

The above operations were done intermittently because other scheduled jobs like the transportation of the spent fuel were conducted during this cutting work.

Setup

The setting up which began at the beginning of November, 1981 lasted 17 days. After the setting up, the adjustment and trial run of each component was performed, and then the trial run of the cutting machine as a whole was conducted in Decmber, 1981 and January, 1982 spending 7 days altogether to confirm that the equipment worked as expected.

The job of setting up began with placing the 2.3 ton work platform similar in shape to a table having four legs over the SFC pool by using a 30-ton crane installed at the site. The water tank was submerged into the pool through the opening at the center of the work platform until the six rims extending outwards from the top of the tank came into contact with the main beam of the platform. So the overall weight of the water tank, air purification system, water purification system, envelope and the platform itself was born by these four legs.

To prevent the leakage of contaminated water from the tank into the SFC pool, measures were taken. It would have been difficult to assemble the tank with satisfacatory watertightness at the site, so the tank was assembled at the manufacturer's workshop and was applied with a spray which hardened to a thin rubber-like coating in a few minutes at the locations that were likely to allow leakage. The assembled tank was transported by a truck from the workshop to the site.

The scafflod was placed on the platform with its legs on the rim of the water tank. The top plate of the torch manipulator on which the three electrical motors(stand-off adjustment motor, work clamping motor, and plasma torch drive motor) were secured was placed on the scaffold.

The control console was connected to the control mechanism on the top plate of the torch manipulator by the cables running thourgh the panel of the envelope. Also the power supply cable was laid thourgh the power controller to reach the torch underwater. To perform the underwater cutting safely it was found that some means for observing the cutting in progress was necessary. Fortunately enough we had a closed-circuit TV unit that had been made for a different purpose. So the tank equipped with a panel with transparent plexiglass was provided with a guide tube to accommodate an underwater TV camera of 40 mm in diameter. The TV set was placed beside the control console to view the cutting operation and to change the cutting parameters if the need arose. The usefulness of the TV set was so great that we couldn't have accomplished our aim without it. Both the air and the water purification systems were installed on the work platform. Some of the water purification system components, like the water filters, ion exchange column, and water pump were kept underwater by hanging them from aluminum frames attached to the work platform. However, the air filters were fixed above the work platform. The computer calculation of the radiation level showed that the expected dose rate from the filters would be below the acceptable level. To check the watertightness of the tank a water level difference of as much as 200 mm was made by removing water from the tank and observing the change in the water level. Although the water level difference varied from 200 mm to 195 mm in the first 24 hours, no change was detected afterwards. During the cutting operation lasting as long as 4 months, no water leakage hindered the cutting procedure.

Next, the envelope was placed on the platform completely covering the opening of the tank for the purpose of collecting the working gas containing radioactive fume from the job. A separate room, called an isolation room, was attached to the envelope to prevent the pressure inside from being disturbed by the outside doors being opened. The pressure of the inside of the envelope was kept lower than the atmospheric pressure by about 8 mm (w.g.) by drawing the air out of the envelope. This isolation room measuring 2 m wide, 1.3 m deep, 2.1 m high was enough to accommodate a few operating personnel and tools.

Since argon gas and helium gas used in this cutting operation, it was necessary to ensure that these gases did not reduce the concentration of oxygen in the envelope to a dangerous level for the working crew. The variation of oxygen density in the envelope was measured at various locations, and the gas fow rate was 60 l/m. From the above test it was confirmed that the amount of oxygen in the envelope never went down below the allowable minimum oxygen concentration level, namely 18 %.

It was decided prior to the cutting operation that cutting personnel would wear an air-supplied respirator in case the radioactive particle concentration in the air rose above 10^{-10} Ci/ml. Then it was necessary to keep the pressure in the envelope lower than the pressure outside to prevent the contaminated air with radioactive dust from flowing out into the surrounding area. To assure that the above requirement was met, air was supplied into the inside of the envelope at a rate equivalent to the consumption by the two respirators, and no change in the pressure inside the envelope was observed.

Mock-up Cutting Test with Non-radioactive Work

Upon completion of assembling and coordinating everything, the cutting job was performed with non-active materials identical to the radioactive items that would be cut later in order to find difficulties that would be encountered in the actual cutting operation (Fig.5-1). The circumstances and conditions in the trial cutting were made as close as possible to those of the actual operation. As a final step to ascertain the capability of the equipment and procedure for cutting the radioactive parts, a non-radioactive tube identical to the in-reactor inner tube (Zr - 2.5% wt Nb) was cut. It was proved that the facility worked as expected in every aspect. The materials cut during the trial are shown in Fig.5-2. The total length of the cuts in the mock-up test was about 1.2 m. The cutting parameters are tabulated in Table 5-1 and the cutting locations in the work are represented in Fig.5-3.

Cutting of Inner Tube

The paramount purpose of cutting the in-reactor tube was to dispose of the unneeded portion of the in-reactor tube and to obtain the necessary test pieces, which would be examined later. The non-radioactive upper half portion of the in-reactor tube was cut previously by a mechanical tubing cutter in the air. As mentioned earlier the induced radioactivity present in the tube was estimated at 6.0 Ci and both the measurement and computer calulation of the contact radiation levels were about 100 R/hr as of the beginning of 1981. The cutting parameters are shown in Table 5-2. The cutting positions in the work are presented in Fig.5-4. The maximum radioactivity measured in the air removed from the envelope and in the water in the tank agreed with the calculated values quite well. In this case the concentrations measured in the water and in the air were 6.9×10^{-5} Ci/ml and 5.7×10^{-8} Ci/ml, respectively. This was the cutting workers' first cutting job with radioactive material, so a rigorous monitoring of the water and the air was performed until a reasonable amount of data on these matters was gained. All the cuts were done with helium gas flowing at a rate of 20 l/min. The total length of the cuts in this job was 2.56 m, of which two cuts were welded portions and two were test sections. One of the test sections was situated at the vertical center of the reactor core and the other was outside the core.

Cutting of Outer Tube

The cutting parameters for cutting the outer tube are given in Table 5-3. Fig.5-5 depicts the cutting locations in the outer tube. The working gas used here was helium gas the same type as that used for the inner tube cutting. The total length of the cuts in this work amounted to 3.25 m.

Cutting of Partition Tube

The 6.3 m long partition tube was previously cut into two in the air to separate the activated portion from the non-radioactive part as well as to reduce the over-all length of the tube to make it short enough to be accommodated into the plasma arc cutting machine. On the outer surface of the partition tube the 1.6 mm O.D. thermocouples were installed for measuring the temperatures of the water and tube. Some thermocouples proved to be an obstacle because the torch came into contact with them when the partition tube rotated on its axis with the torch coming close to the outer surface of the partition tube. It was necessary to remove the thermocouples prior to the cutting. So these thermocouples were removed during the in-air cutting operation. The 2.74 m long upper-portion tube was segmented into 12 pieces by cutting it at intervals of 0.25 m with the total length of the cuts being 2 m. Table 5-4 gives the cutting parameters for cutting the upper-portion of the partition tube. The cutting locations in the work are illustrated in Fig.5-6.

After cutting the upper-portion of the tube, the lower half of the tube, the most radioactive part in this cutting operation, whose activated area had a contact dose rate of 6,000 R/hr, was subjected to underwater cutting. As mentioned earlier the tube had thermocouples along its outer surface. So it was necessary to remove these thermopiles to prevent the stand-off from varying as the material to be cut rotated. At first, the thermocouples were cut at the location of the reactor core center where the neutron flux was highest (Fig.5-7). A quarter of the circumference of the tube was automatically cut at the same time. The radioactive material released from the tube and thermocouples by the plasma was carried through the hollow part of the tube by the plasma working gas and came out of the water passing through the inside of the tube and finally entered the permanently installed exhaust system via the air filtration system.

Immediately after this cutting, the reading of the radiation level monitoring instrument which was located just below the work platform and which monitored the radiation level at the outer surface of the top portion of the water tank, read a much higher dose rate than expected. Later, the cause of the high reading was found to be the highly radioactive fine particles on the inner surface of the very top of the tube above the water surface and on the inner surface of the suspension device (Fig.5-8) which suspended the work from the scaffold. The suspension decvice chiefly consisted of four aluminum tubes measuring 40 mm in diameter at the thickest region and was adjustable in its overall length in order to adjust the changing depth of the water above the job to shield the work accordingly and was made of four umbrella-shaped connectors joined to each other by thin pins. The gaps between the connectors allow the water together with the plasma gas coming up into the hollow part of the work piece to flow out of the suspention devices and to return to the tank before it goes up further into the air filtration system. The highly radioactive fine slag left behind on the connectors produced a high radiation level in the working area. The total amount of slag was about 1 gram. The radiation level was around 40 mR/hr at 0.5 m from the material being cut. The immersion of the suspension device and the top portion of the work-piece into the water completely removed the slag instantly, restoring the radiation level around the work area to its normal level. Further cutting of the lower portion of the partition tube was suspended because the scheduled cutting operations would have unnecessarily exposed cutting personnel to further radiation.

Furthermore, a tight time table for the cutting job did not permit an extension of the scheduled cutting period. The underwater plasma arc cutting operation was brought to an end, sending the uncompleted work to the hot cell to be cut in the air by using a mechanical cutting device. The cutting parameters for cutting the lower half of the partition tube are given in Table 5-5.

6. DURABILITY OF TORCH TIP

From the experience gained in the underwater plasma arc cutting, it was concluded that little consumption of the torch tip occurred during the cutting process provided the stand-off was maintained in the proper range (3 - 5 mm). Contact between the torch tip and the work material was enough to make it unable to continue the cutting job. The extent of radioactive contamination of the tip by slag from the job largely depended on the specific activity of the work to be cut.

7. AIR FILTRATION SYSTEM

Some plasma gas and fume originating from the work came out of the water in the tank into the envelope and was drawn by the air filtration system into the permanently installed exhaust system. The other part of the gas and fume came out into the hollow part of the suspension device through the water inside the tube being cut and finally entered the exhaust system after being filtrated. Although a large portion of the radioactive substance carried through the water in the tank by the plasma working gas was trapped by the water, a fraction of the substance escaped out and mixed with the air in the envelope. As stated earlier the air pressure inside the envelope was maintained lower than the atmospheric pressure by about 8 mm (w.g.) to prevent the radioactive particles from going outside and to facilitate the suction of particles by the air filtration system. When it was necessary to enter the envelope after some radioactive material was cut, a cutting personnel was required to wear protective respiratory devices depending on the concentration of radioactive substances present in the air. Above 10^{-10} Ci/ml an air-supplied respirator was needed, between 10^{-10} and 10^{-13} Ci/ml a respirator was needed, below 10^{-13} Ci/ml no protective gear was needed.

In addition to the above requirement, it was decided to lower the concentration of radioactive susbstances present in the air inside the envelope below 10^{-13} Ci/ml before the removal of the envelope. A calculation of the concentration conducted prior to the cutting operation

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indicated that the concentration in the envelope would be of the order of 10^{-9} Ci/ml when the reactor tube was being cut and on the order of 10^{-7} Ci/ml the partition tube was being cut. Also the calculation showed a 45-minute-ventilation period would decrease the concentration by 1/10. The results obtained from the actual cutting proved these predictions were reasonably accurate. Owing to the high effectiveness of the air purification system, it was never necessary for a cutting personnel to wear an air-supplied respirator when entering the envelope. The highest concentration monitored during the whole cutting operation was 5×10^{-8} Ci/ml which was experienced during the cutting of the lower half of the outer tube. The length of time between each cut was long enough for the concentration to subside to the background level. Upon finishing the cutting operation, the final contact dose rate of the air filter read 7 mR/hr.

8. RADIOACTIVE SUBSTANCE CONCENTRATION IN THE WATER IN THE TANK

4.5 tons of water in the tank was circulated through the ion-exchange columns, millipore filters, and filters of mesh by the pump with a capacity of 2 tons/hr to recover the quality of the water consisting of the four requirements: (1) conductivity must be less than 2 $\mu\mho$/cm; (2) water turbidity must not be worse than that of pure water; (3) radioactive particle concentration must be less than 10^{-6} Ci/ml; (4) the pH must be between 5.5 and 7.0 before mixing the water in the tank with the water outside. Throughout the cutting operation the most prominent nucleus the water purification system had to dispose of was Co-60. After completion of the cutting job, it took about 45 hours to reduce the concentration from 6.9×10^{-5} to 2.2×10^{-6} Ci/ml. The pH fluctuated between 5.1 and 6.2. For the conductivity, the value never went beyond 2 $\mu\mho$/cm.

9. CONTAMINATION OF INNER SURFACE OF ENVELOPE

Throughout this cutting operation the contamination of the inside wall and the floor of the envelope with radioactive particles accompanying the plasma gas was amazingly small. In the course of the cutting process the highest contamination of the inside of the envelope was found to be 370 dpm/100 cm^2 (excluding the background) using the smear method. A few wipes with a cloth was enough to effectively remove the fine radioactive substance staying on the floor or the wall if the surface of the envelope was not rough. No problems surfaced in regard to this.

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4.5 tons of water in the tank was circulated through the ion-exchange columns, millipore filters, and filters of mesh by the pump with a capacity of 2 tons/hr to recover the quality of the water consisting of the four requirements: (1) conductivity must be less than $2\,\mu\mho$/cm; (2) water turbidity must not be worse than that of pure water; (3) radioactive particle concentration must be less than 10^{-6} Ci/ml; (4) the pH must be between 5.5 and 7.0 before mixing the water in the tank with the water outside. Throughout the cutting operation the most prominent nucleus the water purification system had to dispose of was Co-60. After completion of the cutting job, it took about 45 hours to reduce the concentration from 6.9×10^{-5} to 2.2×10^{-6} Ci/ml. The pH fluctuated between 5.1 and 6.2. For the conductivity, the value never went beyond $2\,\mu\mho$/cm.

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10. DISASSEMBLY OF CUTTING EQUIPMENT AND PERSONNEL EXPOSURE

The removal of the cutting equipment began immediately after finishing the purification of the water in the tank so as to lower the radioactive concentration in it. First, the radioactive pieces were transferred from the tank to a designated location outside, then the radioactive particles were removed with a cloth from the dry part of the cutting equipment situated inside the envelope and inner surface of the envelope. The wet parts of the machines were flushed with water from the water purification system when the machines were removed. To remove the radioactive particles from the inner wall of the tank the water from the purification system was sprayed against the wall by circulating the water in the tank through the pump on the purification system. In this phase of the job an unanticipated difficulty arose. On the bottom of the tank, some radioactive slag still remained even after the tank was carefully flushed with water from the pool into which the tank had been submerged. The bottom of the tank was inclined toward the center from both ends to facilitate the removal of the waste. This inclination and flushing did not allow the radioactive slag on the bottom to be completely removed. A contact radiation intensity at the bottom surface read 2 R/hr, at 0.4 m it read about 50 mR/hr. The radioactive slag was wiped off with a cloth to reduce the contact level to about 10 mR/hr at 0.4 m. It took only a few minutes to remove the radioactive material from the bottom plate. The total personnel exposure dose in this cleaning operation was 55 man-mR. Before this operation the bottom was unbolted from the tank. This job was done with a radiation field of about 50 mR/hr, requiring the expenditure of 105 man-mR of collective exposure. After the tank was removed, the pump, ion exchange column and filter unit on the water purification system were disconnected by being taken out of the water. The filter unit was disposed of as normal low-level waste. The pump was transported to the decontaminating shop for decontamination. The ion-exchange column was kept under water in the pool. The maximum contact dose rates of these components were 400 mR/hr for the pump, 110 mR/hr for the filter unit and 80 mR/hr for the ion exchange column. The exposure the workers received during the three days of the dismantling operation accounted for 35 % of the total 640 man-mrem received by the 13 crew members throughout the plasma arc underwater cutting job. The average external exposure during the cutting operation was 50 mrem while the maximum exposure received by any single workman during the same period of time was 180 mrem. Internal deposition of radioactive material in people connected with the underwater plasma cutting was estimated twice, right before the start of the job and immediately after its completion, using a whole body counter, to find no change in internal deposition in any working crew members. Before being transported to the decontaminating shop where the disassembling of the components and thorough decontamination were done, all the components of the machines were subjected to decontaminatioon at the working area in order to reduce the radiation level at the surface below 200 mR/hr and below 10 mR/hr at a distance of 1 m, a requuirement imposed by the authority. In fact, every component satisfied this requirement by a big margin except for the pump on the water purification system which read as high as 400 mR/hr at the surface. The radiation rate at 1 m from each component was far below that stated in the regulations. The dismantling operation including decontamination at the site and the transfer of the cut materials from the tank to the adjacent pool took one month, requiring 7 man working crews. The dismantled components were transported to the decontaminating shop in the complex by a truck. The components not kept in water were transported to a warehouse after being wiped by a cloth at the site. The decontamination operation at the decontaminating shop needed a man power of 255 man-days.

11. SUMMARY AND CONCLUSIONS

The underwater plasma arc cutting technique, which has a great potential as cutting method for dismantling nuclear reactors, was employed to cut the radio-activated tubes of zirconium-niobium alloy, zircaloy-2, and stainless steel.

Cutting of the in-reactor tube (with a maximum wall thickness of 10.5 mm) and the upper half of the partition tube have been successfully completed.

The test pieces were obtained from the lower half of the inner tube (two each from the in-core and out-of-fore portions). The remaining portion of the lower half of the inner tube was cut into pieces for disposal as redioactive waste.

The lower half of the outer tube and the upper half of the partition tube were cut into pieces for disposal as radioactive waste.

Cutting of the lower half of the partition tube was partially successful.

The cutting equipment and the operating procedures proved to be workable and practical.

The plasma arc cutting torch with minor modifications and associated equipment performed satisfactorily.

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The cutting equipment and the operating procedures proved to be workable and practical.

The plasma arc cutting torch with minor modifications and associated equipment performed satisfactorily.

The control console and the plasma torch manipulator proved suitable for underwater plasma arc cutting of the in-reactor tube and the partition tube.

There were no significant releases of radioactivity or excess radiation exposure to personnel.

ACKNOWLEDGEMENT

Many persons have contributed either directly or indirectly to this underwater cutting operation; we should like to mention some of them by name:

Mr. Kiyozumi Hayashi and Mr. Saburo Takahashi of the ATR Development Head Office, PNC, deserve many thanks for giving us the policy to follow.

Mr. Katusji Fujioka, Mr. Yoshio Kondo, and Mr. Hiraku Sawahata of Radiation Control Division, Management Department, supervised the control of radiological conditions at the work area and environmental affairs in the cutting operation, and were involved in the program from the preliminary stage, assisting in the design of the cutting equipment from a radiological view point.

Mr. Katsumune Yamamoto, Mr. Iichiro Yokouchi, and Mr. Isamu Hisa of Irradiation Division III, JMTR Project, conducted chemical analysis of the water in the plasma arc cutting system.

Mr. Kazuyuki Mishima, Mr. Tomoshige Oso, Mr. Takeshi Kashiwa, Mr. Tomoaki Sato, and Mr. Kazuo Katsuyama of Waste Management Division, Management Department, carried out the decontamination of the underwater plasma arc cutting machine as well as the disposal of the solid and liquid wastes generated in the course of the cutting job.

Mr. Susumu Hirohara and Seiji Inada of Reactor Division I, JMTR Project, assisted us by allowing us to use the work area, including SFC pool, and to discharge the gas and water into drainage and ventilation systems they were responsible for.

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3. Harada, K., and Hasegawa, T., "In-pile Creep Test Facility for the Power Reactor and Nuclear Fuel Development Corporation of Japan," IHI Engineering Review, Vol.13(4), July 1973, pp. 520 to 527.

The control console and the plasma torch manipulator proved suitable for underwater plasma arc cutting of the in-reactor tube and the partition tube.

There were no significant releases of radioactivity or excess radiation exposure to personnel.

ACKNOWLEDGEMENT

Many persons have contributed either directly or indirectly to this underwater cutting operation; we should like to mention some of them by name:

Mr. Kiyozumi Hayashi and Mr. Saburo Takahashi of the ATR Development Head Office, PNC, deserve many thanks for giving us the policy to follow.

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Mr. Susumu Hirohara and Seiji Inada of Reactor Division I, JMTR Project, assisted us by allowing us to use the work area, including SFC pool, and to discharge the gas and water into drainage and ventilation systems they were responsible for.

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1. Hayashi, k., et al., "Development of Techniques for Underwater Plasma Arc Cutting of the In-Reactor Tube of In-Pile Creep Test Facility in JMTR," PNC Technical Review No.35(1980)

2. Hayashi, K., et al., "Study on the Plasma Arc Cutting for Stainless Steel," IHI Engineering Review, Vol.15(3), July 1982, pp. 41 to 46.

3. Harada, K., and Hasegawa, T., "In-pile Creep Test Facility for the Power Reactor and Nuclear Fuel Development Corporation of Japan," IHI Engineering Review, Vol.13(4), July 1973, pp. 520 to 527.

Table 5-1 Parameters Resulting from Underwater Plasma Arc Cutting of Test Work

Cutting locations (see Fig.5-3)	1	2	3	4	5	6	7
Circumferential length of cut (mm)	176	176	176	176	176	176	176
Total cut length (mm)				(1232)			
Time required to cut (sec)	13	13	13	13	13	13	13
Cutting speed (mm/min)				880			
Axial lenth of work to be cut off (mm)	260	70	380	20	20	40	20
Water depth at the torch (mm)	1640	1570	1190	1170	1150	1110	1090
Wall thickness of work (mm)				1.7			
Arc current (A)				150			
voltage (V)				80			
Torch-work distance (mm)				3			
Plasma gas flow rate (l/min)				20 (He gas)			

Table 5-2 Parameters Resulting from Underwater Plasma Arc cutting of the Lower Half of the Inner Tube

Cutting locations (see Fig.5-4)	1	2	3	4	5	6	6[a]
Circumferential length of cut (mm)	179	179	179	179	179	179	179
Total cut length (mm)				(2560)			
Time required to cut (sec)	27	18	17	16	16	18	16
Cutting speed (mm/min)	900	1350	1350	1350	1430	1430	1430
Axial lenght of work to be cut off (mm)	25	110	222	700	234	-	251
Water depth at the torch (mm)	3010	2900	2678	2005	1771	1563	1520
Wall thickness of work (mm)	5	2	2	2	2	2	2
Arc current (A)	150	150	150	150	140	140	150
voltage (V)				80			
Torch-work distance (mm)	4	4	4	4	3	3	3
Plasma gas flow rate (l/min)				20 (He gas)			

Cutting locations (see Fig.5-4)	7	8	9	9[a]	10	11	12
Circumferential length of cut (mm)	179	179	179	179	179	179	232
Total cut length (mm)				(2560)			
Time required to cut (sec)	16	18	18	15	17	14	37
Cutting speed (mm/min)	1430	1430	1430	1430	1430	1430	460
Axial length of work to be cut off (mm)	220	235	165	50	700	250	110
Water depth at the torch (mm)	1300	1065	900	1935	1235	985	875
Wall thickness of work (mm)	2	2	2	2	2	2	10.5
Arc current (A)	150	150	150	150	150	175	210
voltage (V)	80	80	80	80	80	100	100
Time required to cut (sec)	16	18	18	15	17	14	37
Torch-work distance (mm)	3	3	3	3	3	4	4
Plasma gas flow rate (l/min)				20 (He gas)			

Table 5-3 Parameters Resulting from Underwater Plasma Arc Cutting of the Lower Half of the Outer Tube

Cutting locations (see Fig.5-5)	1	2	3	4	5	6	7
Circumferential length of cut (mm)	217	217	217	217	217	217	217
Total cut length (mm)				(3252)			
Time required to cut (sec)	23	22	20	20	20	20	20
Cutting speed (mm/min)	1000	910	910	910	910	910	910
Axial lenght of work to be cut off (mm)	250	250	250	250	250	250	250
Water depth at the torch (mm)	3040	2790	2540	2290	2040	1790	1540
Wall thickness of work (mm)				3.9			
Arc current (A)	170	160	160	160	160	160	160
voltage (V)	80	70	70	70	70	70	70
Torch-work distance (mm)				4			
Plasma gas flow rate (l/min)				20 (He gas)			

Cutting locatins (see Fig.5-5)	8	9	9[a]	9[b]	10	11	12	13
Circumferential length of cut (mm)	217	217	217	217	217	217	217	217
Total cut length (mm)				(3252)				
Time required to cut (sec)	21	21	21	20	30	21	22	27
Cutting speed (mm/min)	910	910	910	910	910	910	910	910
Axial length of work to be cut off (mm)	250	-	230	40	230	250	250	250
Water depth at the torch (mm)	1290	1040	1060	1020	790	1770	1520	1287
Wall thickness of work (mm)				3.9				
Arc current (A)	160	160	160	160	160	160	160	180
voltage (V)	70	70	70	70	70	70	70	90
Torch-work distance (mm)				4				
Plasma gas flow rate (l/min)				20 (He gas)				

Table 5-4 Parameters Resulting from Underwater Plasma Arc Cutting of the Upper Half of the Partition Tube

Cutting locations (see Fig.5-6)	1	1[a]	2	2[a]	2[b]	3	4
Circumferential length of cut (mm)	145	145	145	145	145	145	145
Total cut length (mm)				(2030)			
Time required to cut (sec)	12	18	7	18	17	19	16
Cutting speed (mm/min)	1010	1010	870	870	870	720	810
Axial length of work to be cut off (mm)	240	30	-	230	40	210	240
Water depth at the torch (mm)	3010	2980	2750	2770	2730	2540	2300
Wall thickness of work (mm)				1.65			
Arc current (A)	170	215	200	200	200	200	200
voltage (V)	100	100	100	100	100	100	100
Torch-work distance (mm)				4			
Plasma gas flow rate (l/min)				20(He gas)			

Cutting locations (see Fig.5-6)	5	6	7	8	9	10	11
Circumferential length of cut (mm)	145	145	145	145	145	145	145
Total cut length (mm)				(2030)			
Time required to cut (mm)	14	15	17	18	14	16	17
Cutting speed (mm/min)	980	720	720	720	720	720	720
Axial lenght of work to be cut off (mm)	240	240	240	230	240	240	100
Water depth at the torch (mm)	2060	1820	1580	1350	1110	870	770
Wall thickness of work (mm)				1.65			
Arc current (A)				200			
voltage (V)	100	80	80	80	80	80	70
Torch-work distance (mm)				4			
Plasma gas flow rate (l/min)				20 (He gas)			

Table 5-5 Parameters Resulting from Underwater Plasma Arc Cutting of the Lower Half of the Partition Tube

Cutting locations (see Fig.5-7)	1
Circumferential length of cut (mm)	27
Time required to cut (sec)	10
Cutting speed (mm/min)	480
Axial lenght of work to be cut off (mm)	505
Water depth at the torch (mm)	2800
Wall thickness of work (mm)	1.65
Arc current (A)	175
voltage (V)	90
Torch-work distance (mm)	3
Plasma gas flow rate (l/min)	20(He gas)

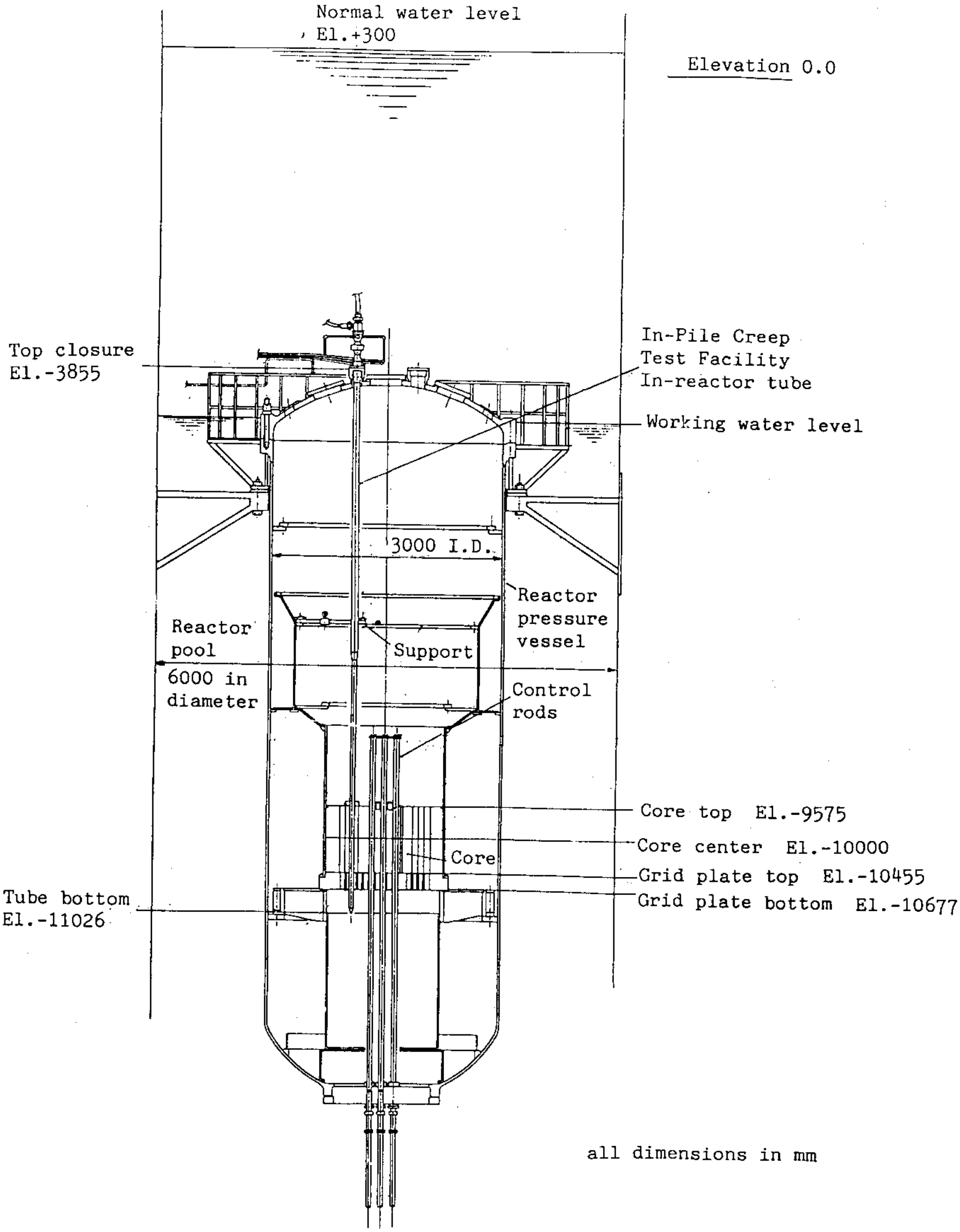

Fig.1-1 Arrangement of the In-Reactor Tube of the In-Pile Creep Test Facility in the JMTR

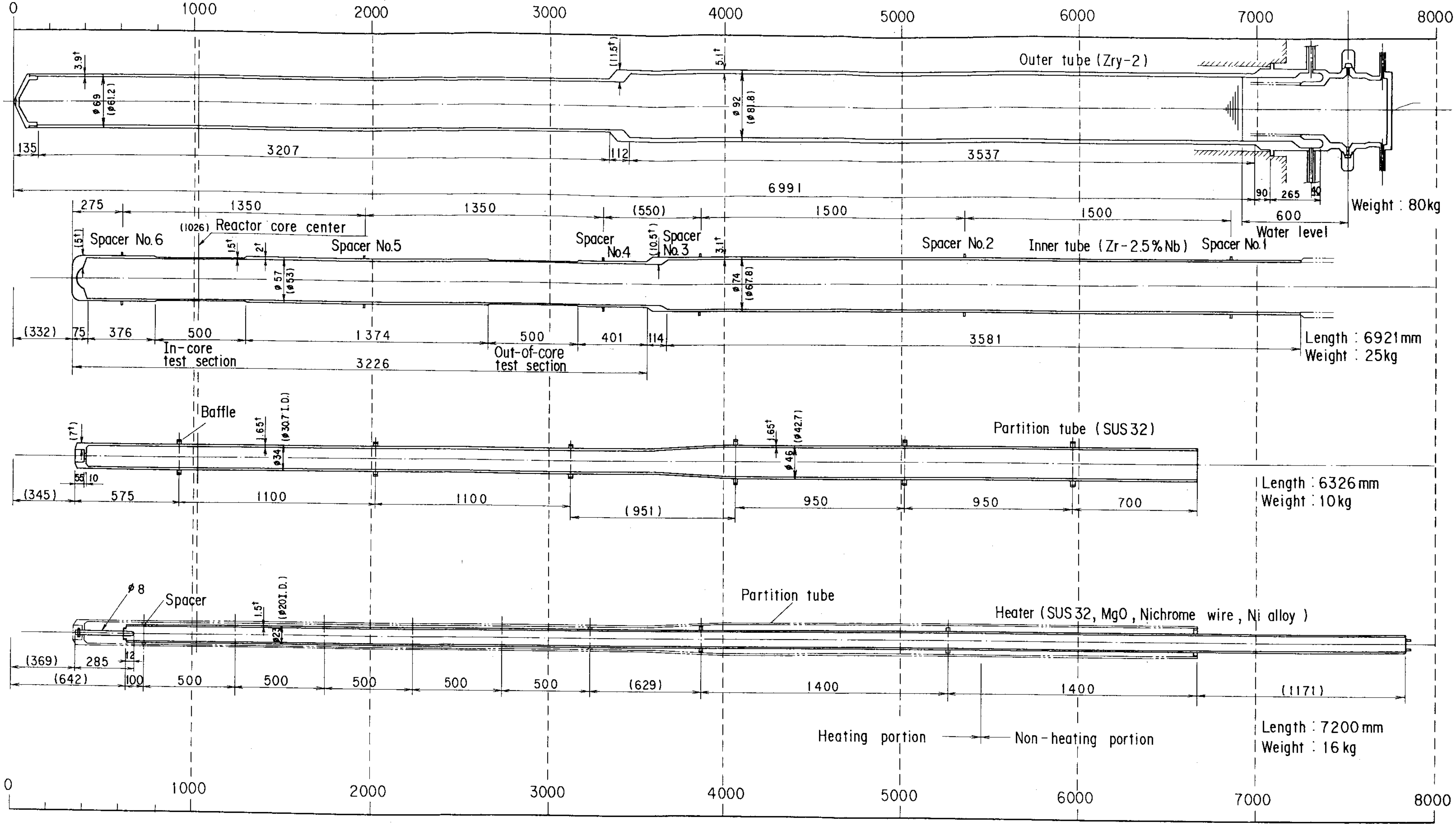

Fig.1-2 In-Reactor Tube, Heater, and Partition Tube

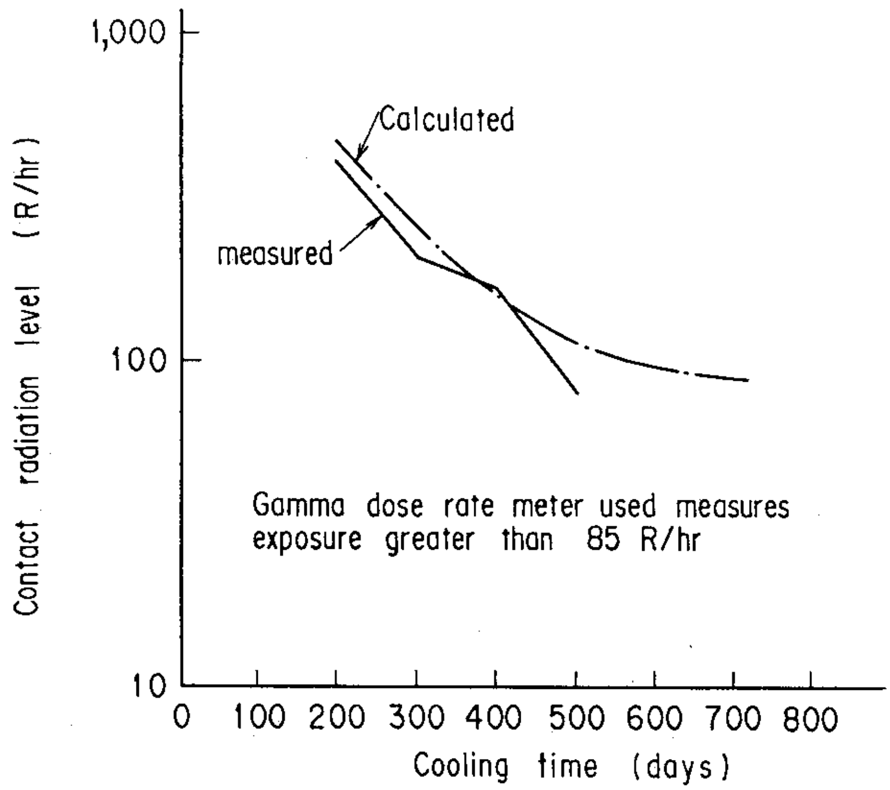

Fig.2-1 Contact Radiation Level from Radioactivity in In-Reactor Tube

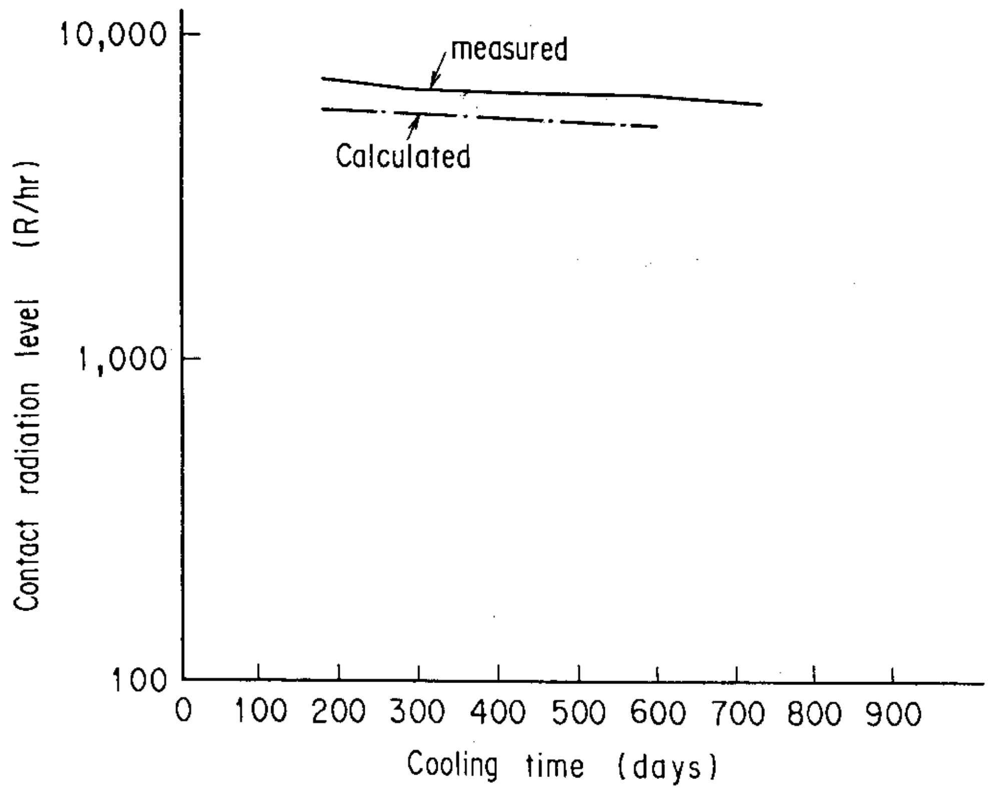

Fig.2-2 Contact Radiation Level from Radioactivity in Heater and Partition Tube Combined

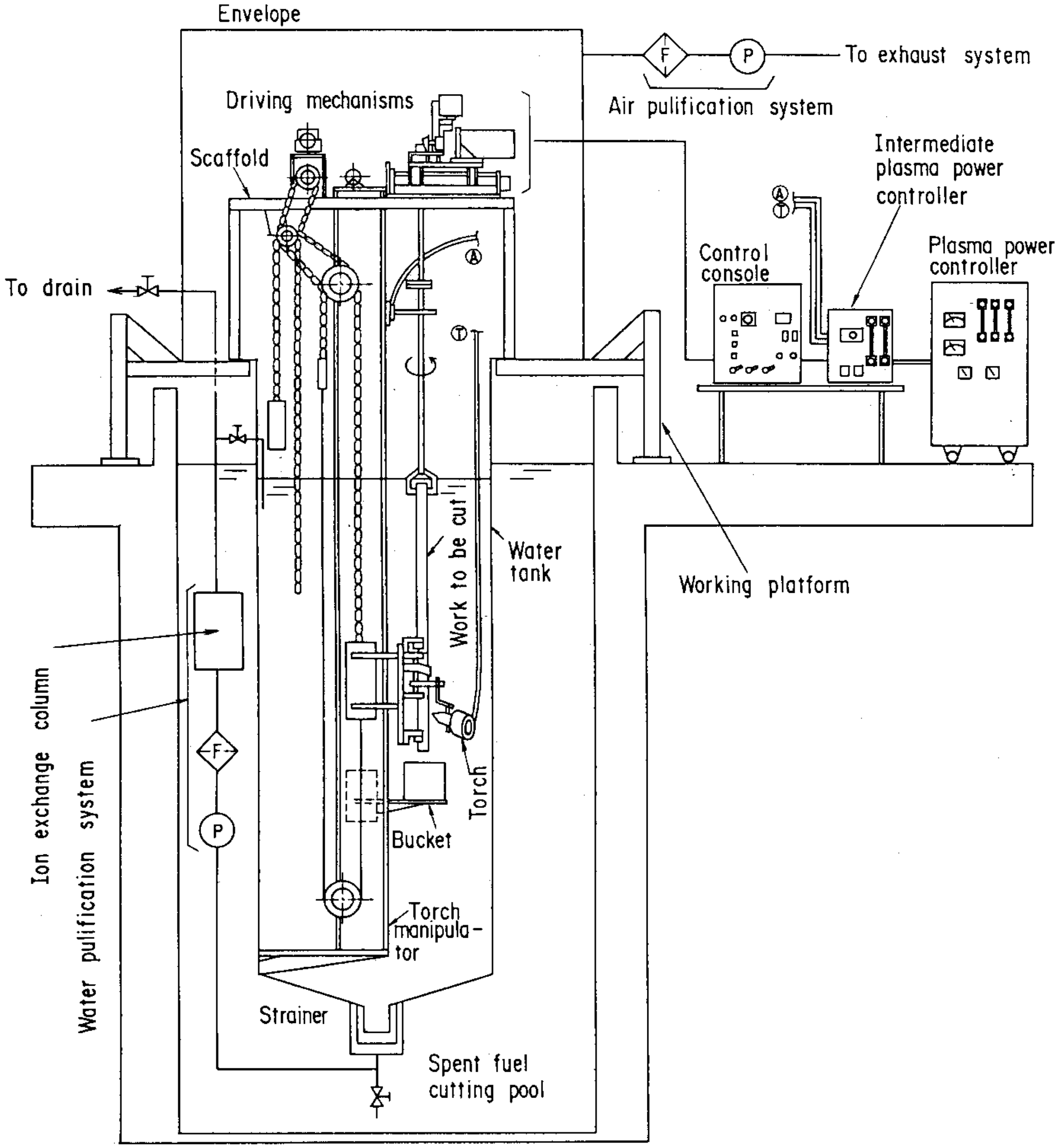

Fig.4-1 Plasma Arc Cutting Equipment

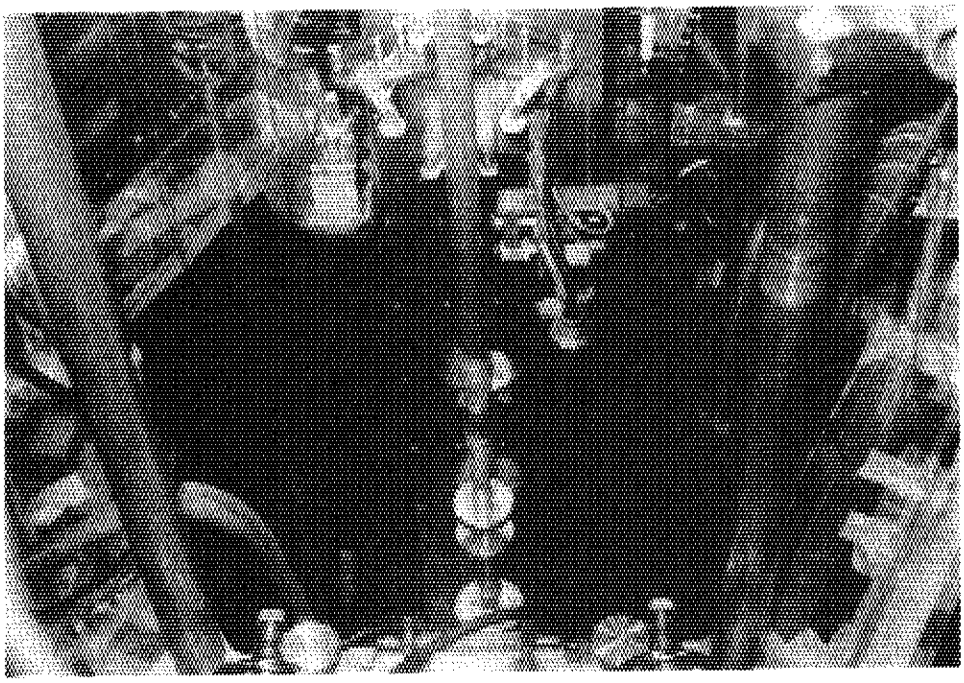

Fig.4-2 Plasma Arc Cutting Torch Prepared for Underwater Use

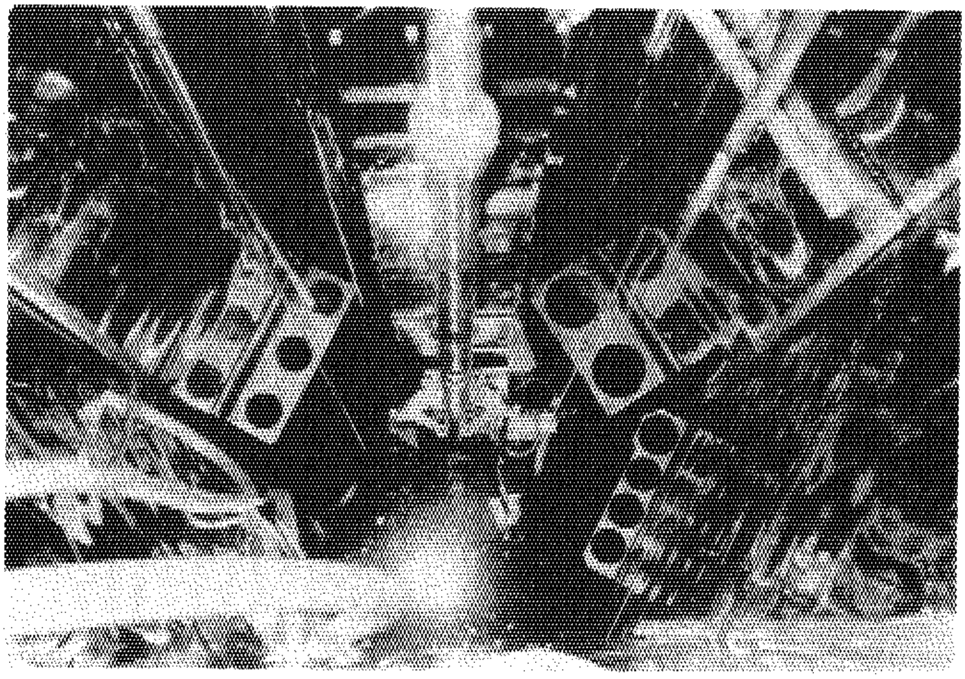

Fig.4-3 Plasma Torch Manipulator in the Water Tank

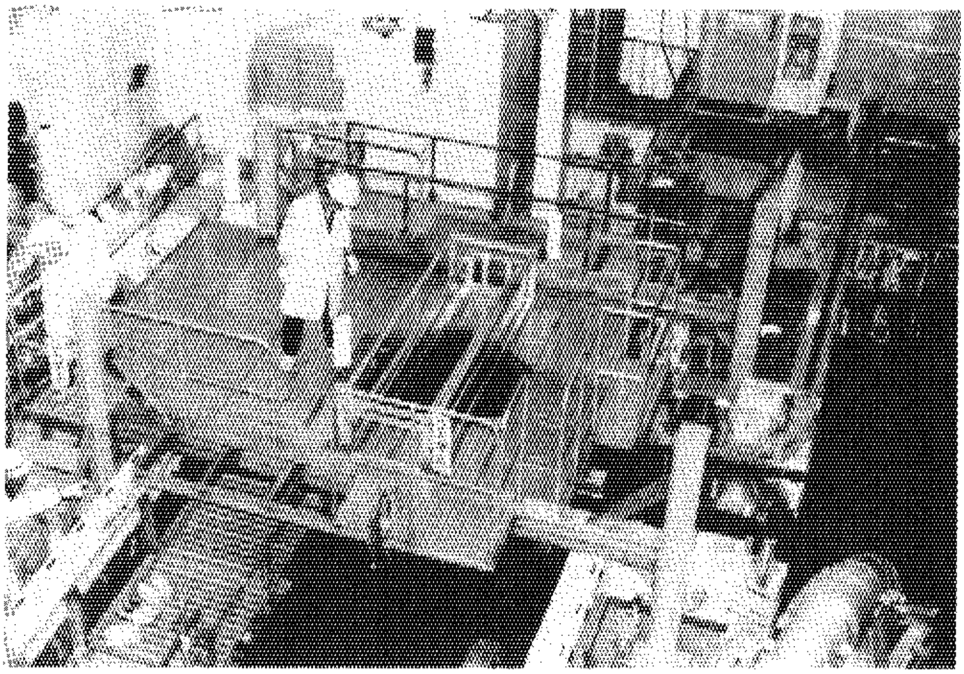

Fig.4-4 Work Platform

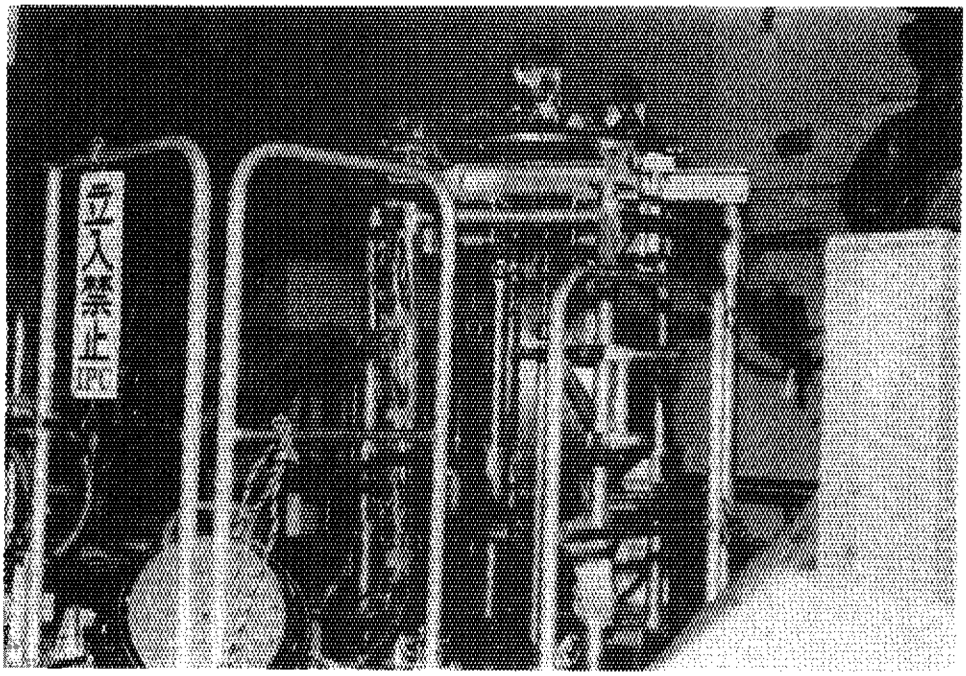

Fig.4-5 Scaffold with the Plasma Torch Manipulator on It

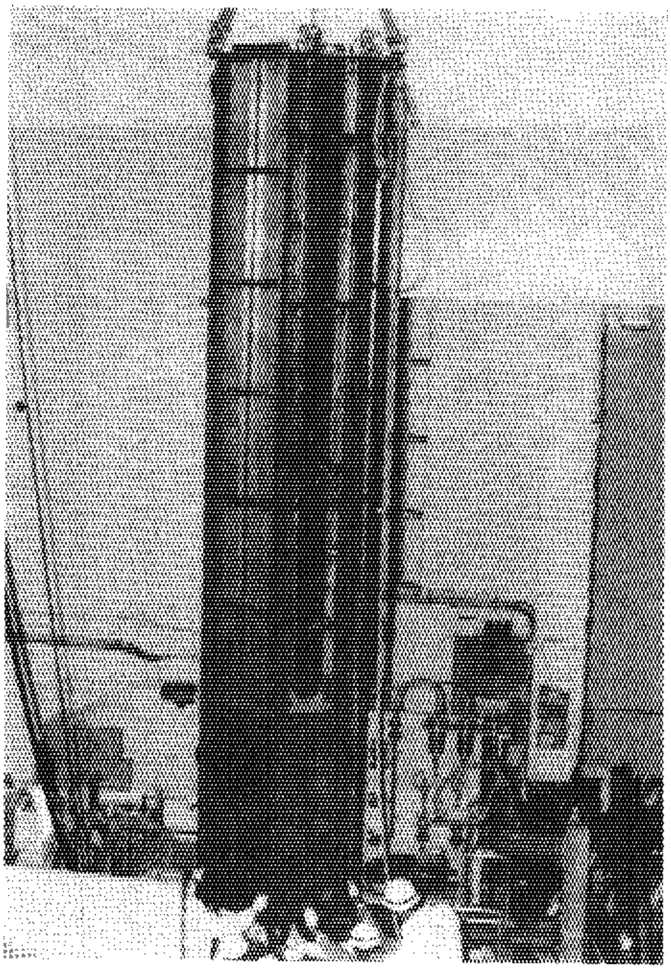

Fig.4-6 Water Tank

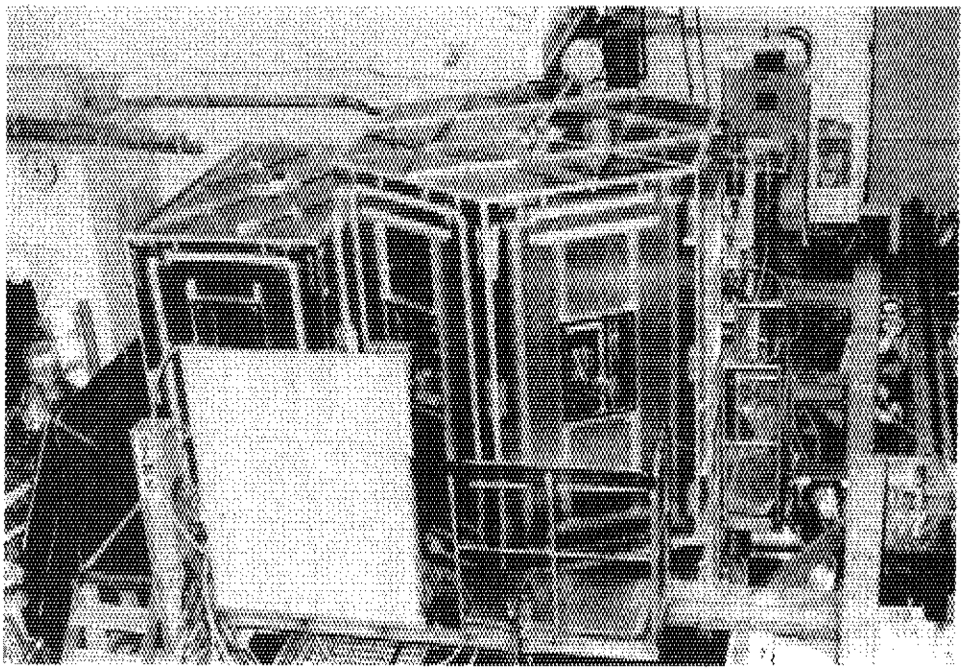

Fig.4-7 Envelope

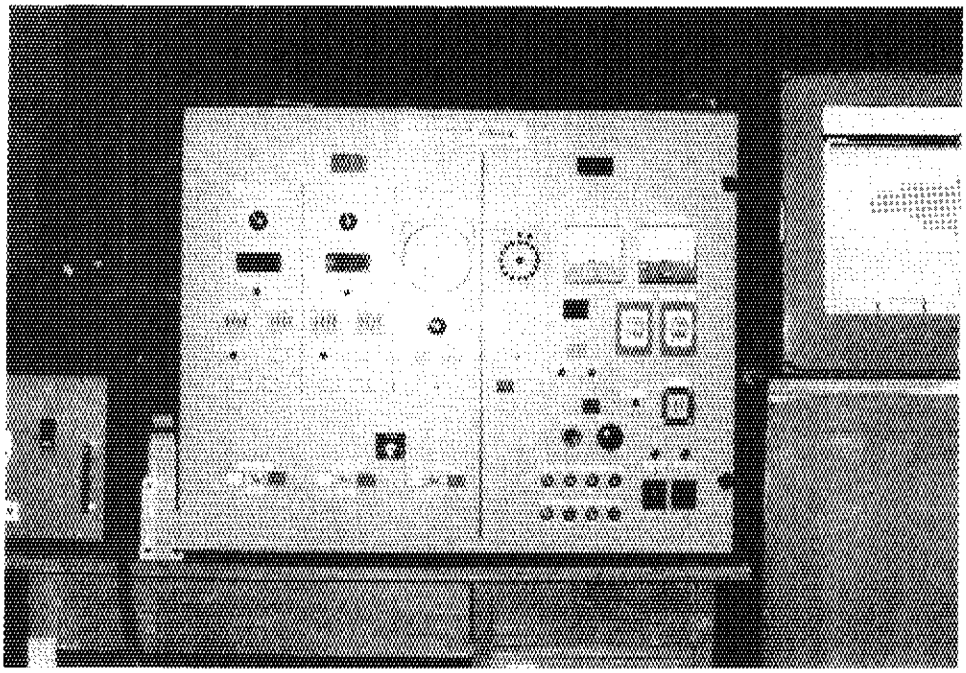

Fig.4-8 Control Console for Remote Plasma Arc Cutting

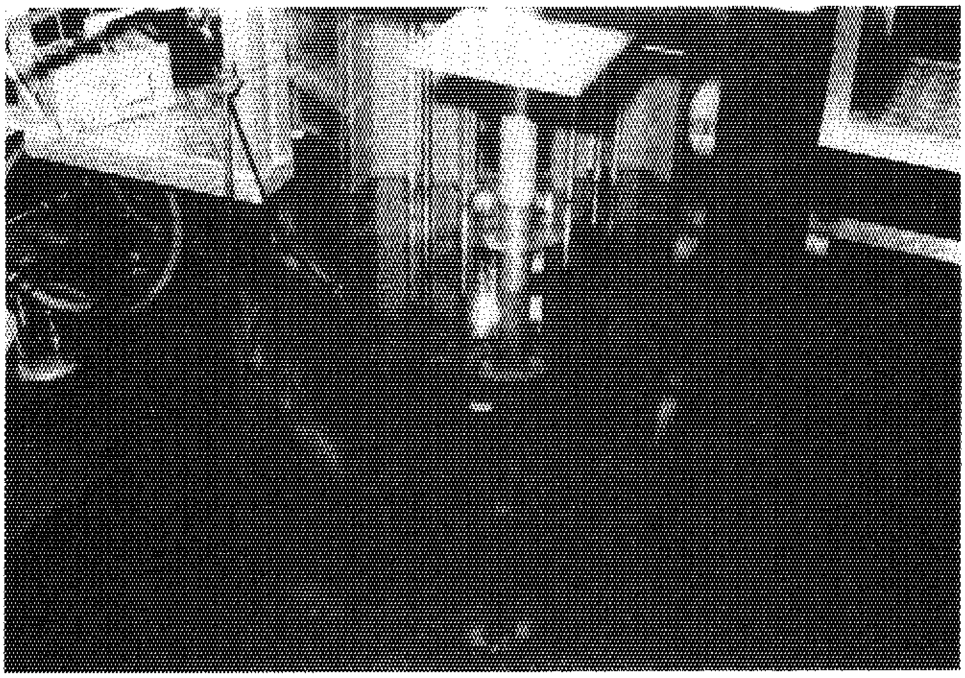

Fig.5-1 Mock-up Cuttting Test in Progress

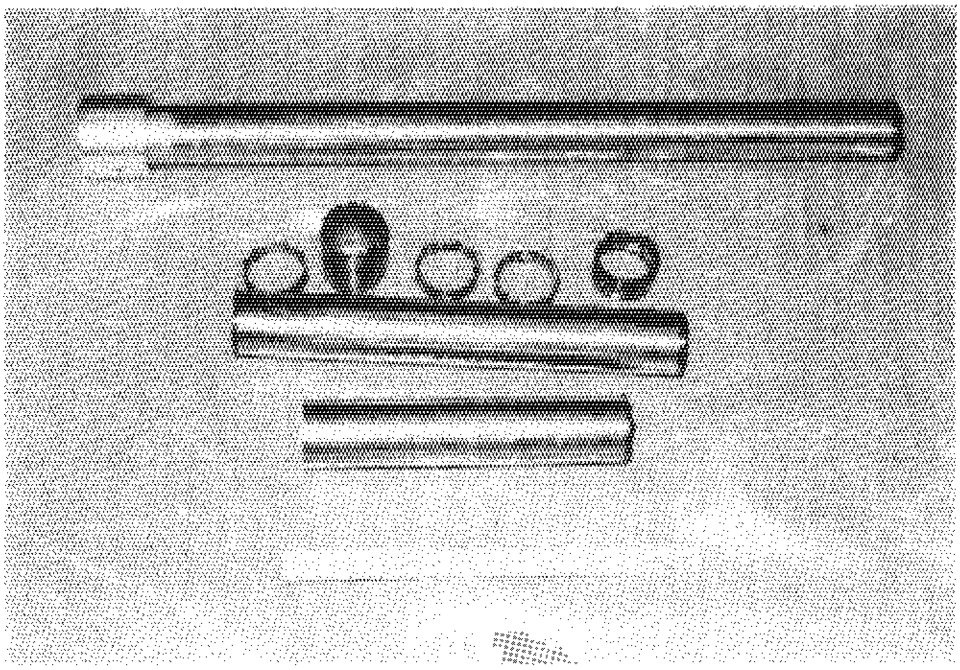

Fig.5-2 Works Cut in the Mock-up Test

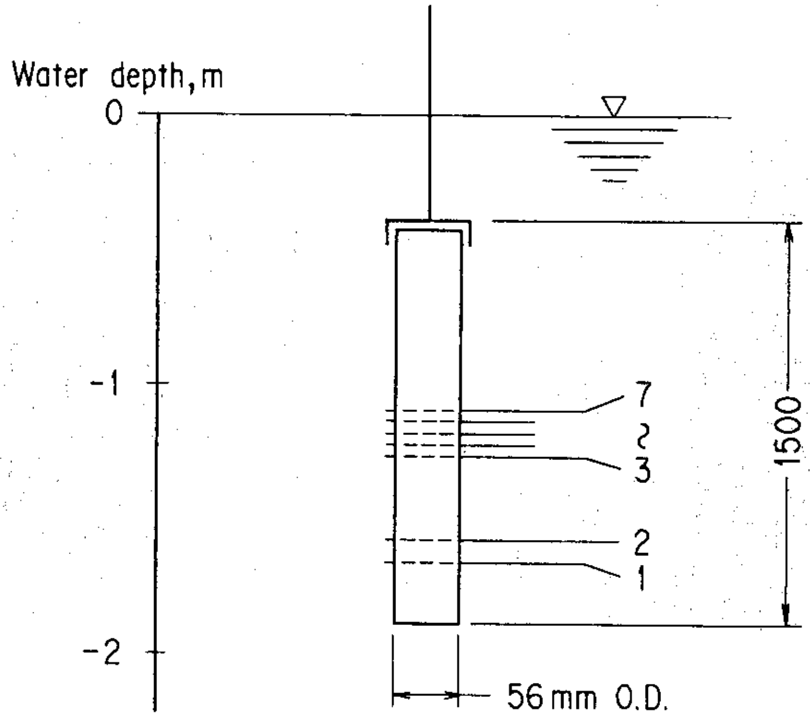

Fig.5-3 Cutting Positions in Mock-up Work

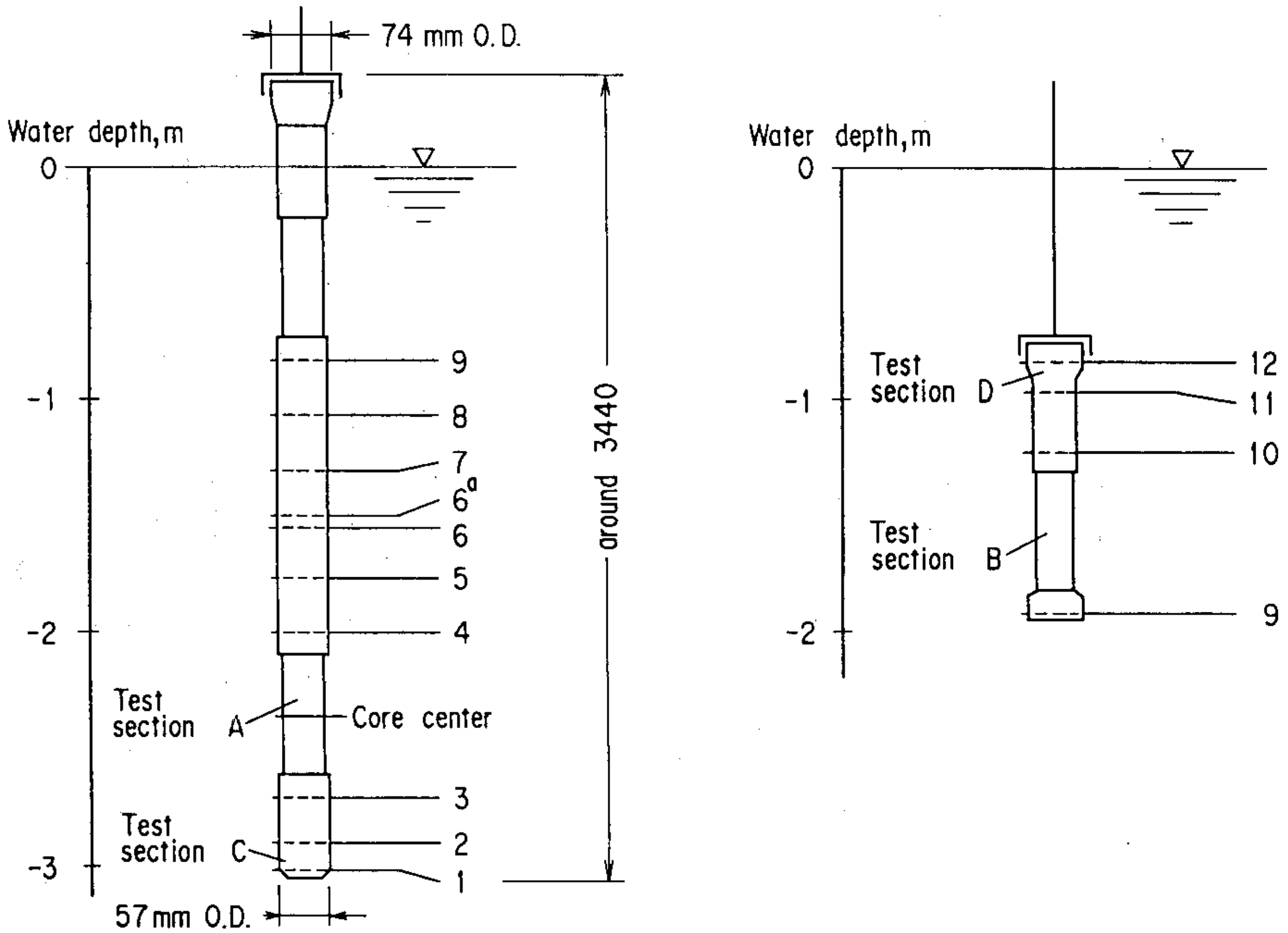

Fig.5-4 Cutting Locations for the Lower Half of the Inner Tube

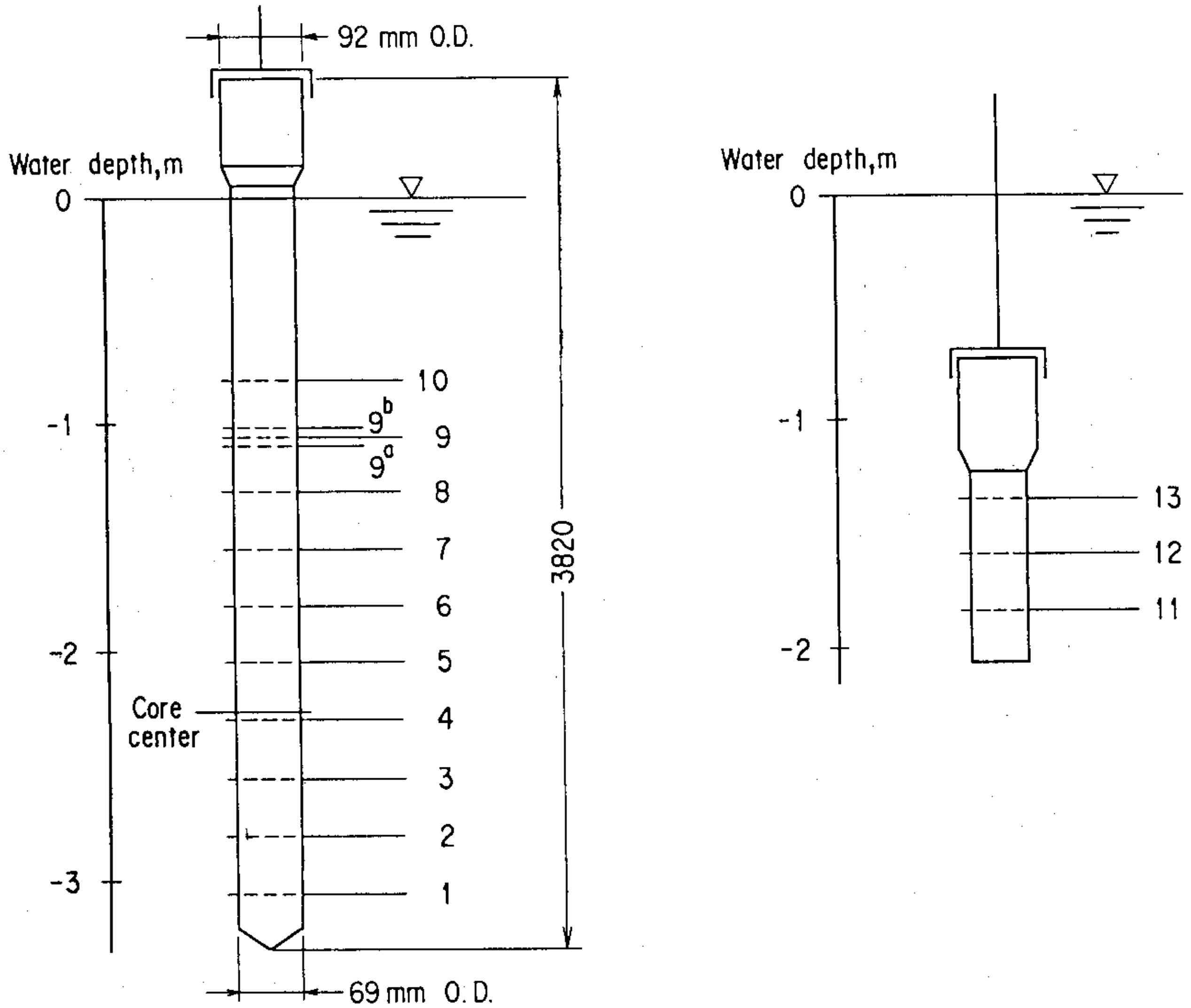

Fig.5-5 Cutting Positions in the Lower Half of the Outer Tube

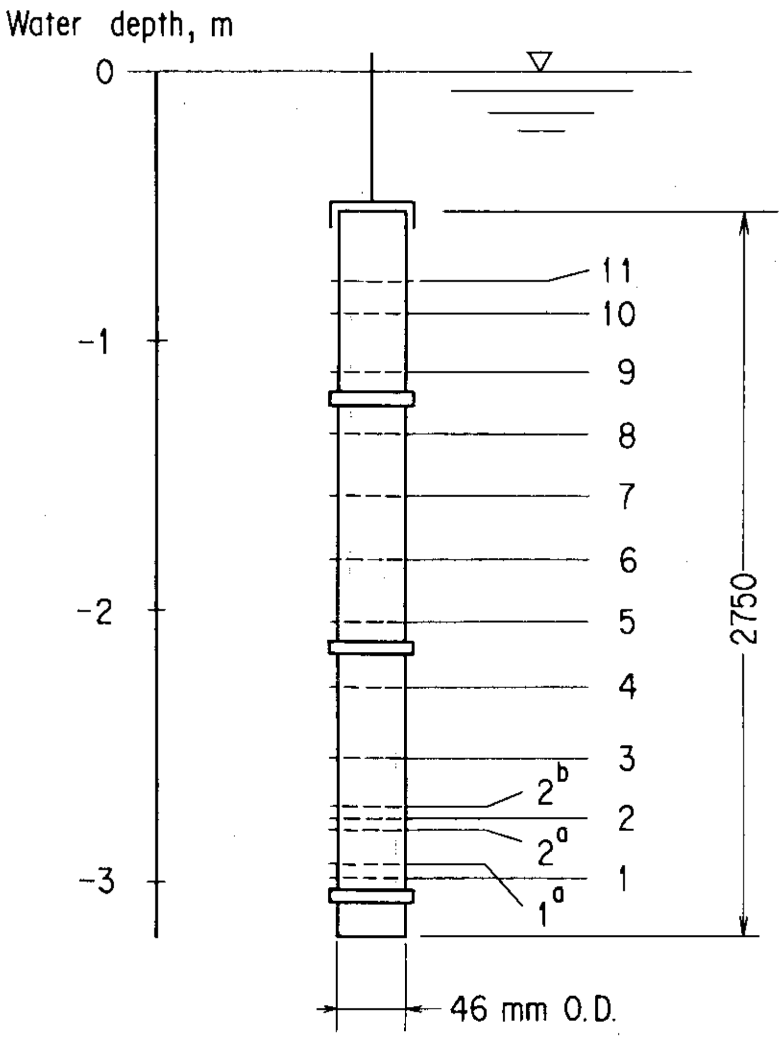

Fig.5-6 Cutting Locations in the Upper Half of the Partition Tube

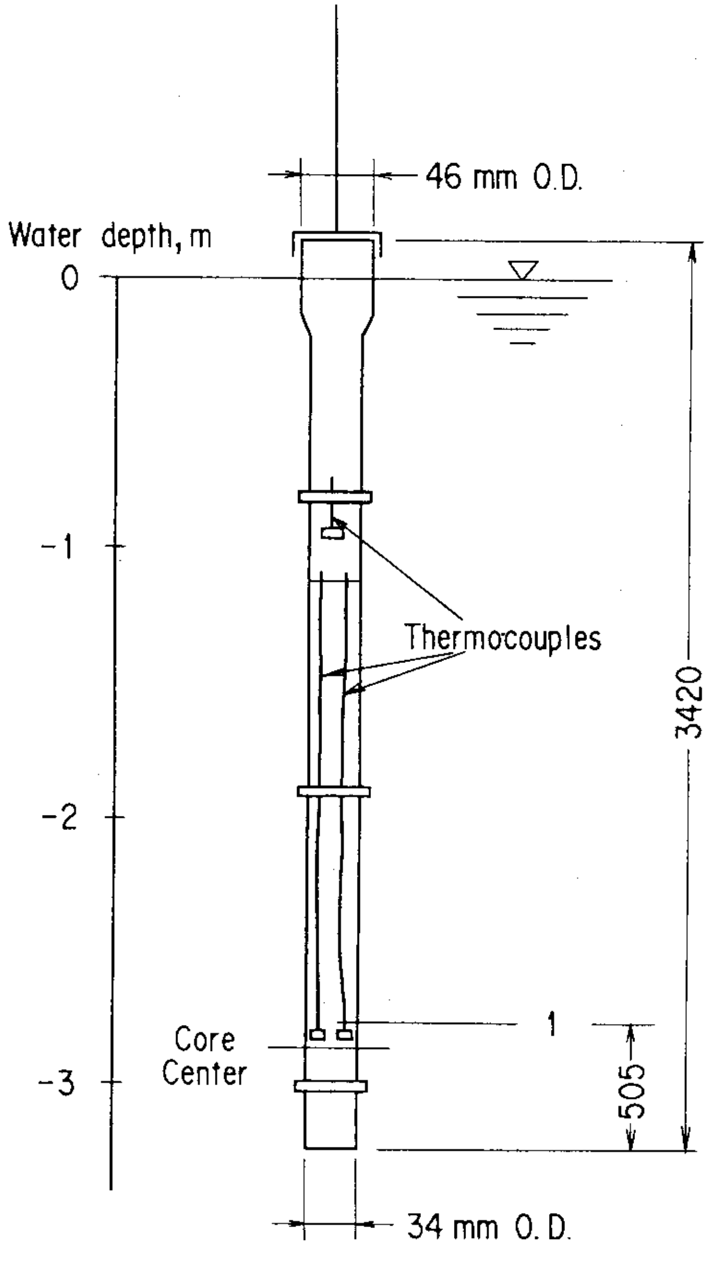

Fig.5-7 Cutting Layout for the Lower Half of the Partition Tube

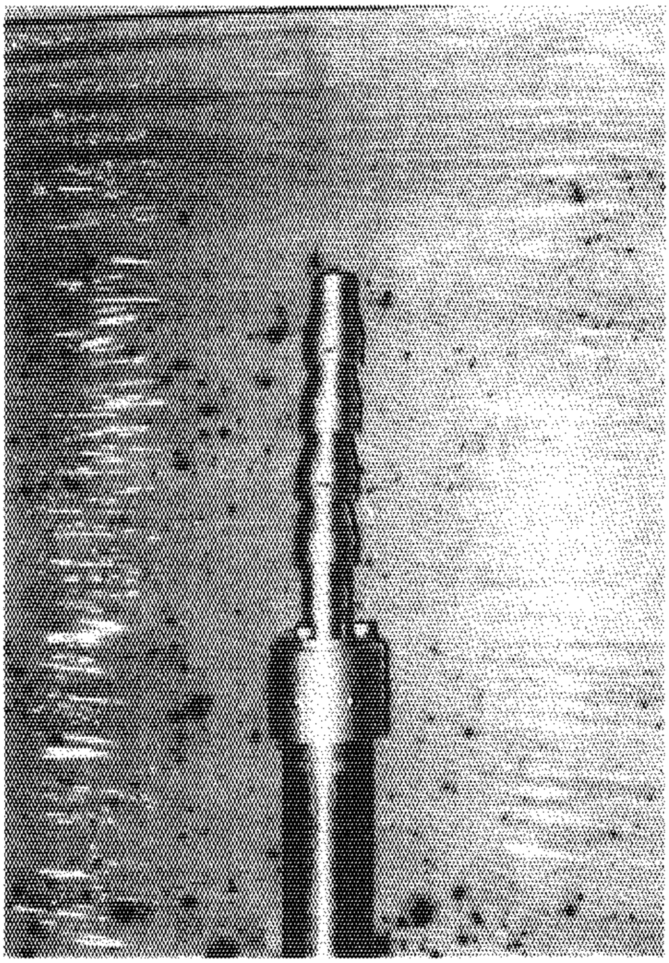

Fig.5-8 Work Suspension Device