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THE FUGEN PROJECT CONSTRUCTION AND STARTUP

Shiro SHIMA

Michio AKEBI

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Power Reactor & Nuclear Fuel Development Corporation, Japan

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Development Corporation

Shiro SHIMA
Michio AKEBI

ABSTRACT

On March 20, 1978, FUGEN reached minimum criticality with 22 fuel assemblies. The plant is scheduled to go into commercial operation in April 1979. This paper describes the course of progress at the site during the construction and test periods, including the installation and/or erection of important plant components, the functional tests of systems, heavy-water filling, fuel loading, and the approach to minimum criticality. The schedule for startup tests is also introduced.

INTRODUCTION

The 165-MW(e) FUGEN nuclear power plant (Fig. 1) is a prototype featuring a heavy-water-moderated boiling light-water-cooled pressure tube reactor, developed as Japan's FUGEN Project by the Power Reactor and Nuclear Fuel Development Corporation. Construction began at Tsuruga on December 1, 1970 and minimum criticality was reached on March 20, 1978. Some major delays occurred in the overall program due to some unexpected events, including the oil crisis and a problem of stress corrosion cracking and the need for design modifications. Over the last two years, plans have proceeded smoothly according to the revised schedule. All plant components, except water reservoirs and some large storage tanks, were fabricated and tested in the factories of the manufacturers, and no time was lost in waiting for delivery.

The project background, design features, and supporting research and development work have been reported.[1–5]

CONSTRUCTION

Table I shows the construction program of key components and systems.

Construction of Reactor Building and Installation of Major Components

After general preparation of the site and the construction of access roads had been completed, excavation began in September 1971 and was completed by February 1972 (Fig. 2), followed by work on the concrete foundation for the reactor building. In August that year erection of the reactor containment vessel was started, and because weather conditions during that winter were not severe, good progress was made (Fig. 3). Pneumatic pressure and leakage tests were carried out successfully in June 1973.

Construction of the reactor building began after the reactor containment vessel had been completed. From October 1973, there was a delay of six months in construction of the reactor building due to the oil crisis, which led to a shortage of cement and workers, and an extraordinary increase in the prices of materials.

Toward the end of November 1974, the calandria tank and the radiation shields were delivered to the site by sea. Around the beginning of December, when civil engineering work on the reactor building inside the reactor containment vessel was virtually completed, installation of the reactor components began, along with the base radiation shield.

A 180-ton capacity crane was provided temporarily for the installation of these heavy components, such as the calandria tank (150 tons), the radiation shields (top: 145 tons, bottom: 148 tons, sides: 82.5 tons x 4 blocks). These components were placed in position between December 1974 and March 1975 (Fig. 4), and the welding of sleeves to the top and bottom radiation shields continued until October 1975.

The calandria tubes were then joined to the top and bottom tube-sheets of the calandria tank by a rolled-joint method, for which specially developed rolling instruments were used. Pressure and leakage tests on all calandria tubes were carried out in February 1976 to establish the integrity of the rolled joints.

Each batch of pressure tube assemblies, which had been fully manufactured and tested in the factory (Fig. 5), was delivered to the site, inserted into the calandria tubes, welded to the associated feeder and riser pipes, using, in part, autocontrolled welding equipment, and was pressure tested hydraulically. The first batch was inserted in March 1976, and the hydraulic pressure test of the final (eighth) batch was finished in March 1977.

The first of the two steam drums was delivered in May 1975 and the second in July (Fig. 6). Two years later, the internal components of the steam drums were installed after the hydraulic pressure test of the primary cooling circuits had been completed. Four recirculation pumps had been run for more than 200 h under reactor coolant conditions in the factory.

The refueling machine had been under test for about two years at the manufacturer's test stand, under reactor coolant conditions, before being delivered to the site, and its assembly on the site began in December 1975 (Fig. 7).

Installation of the steam turbine began in July 1975 and was finished in the Autumn of 1976 (Fig. 8). To prevent formation of rust, hot air was fed through the turbine and associated equipment.

In June 1975, a 77-kV line was hooked up to the FUGEN station to supply power for construction, and in July two 275-kV lines were connected to provide power for functional tests of the systems already installed.

All important construction and installation was completed by May 1977, and the hydraulic pressure test of the entire primary cooling circuits was carried out satisfactorily on June 20-21.

Questions That Arose During Construction

1. Consideration of Stress Corrosion Cracking: During the construction period the problem of stress corrosion cracking (SCC) of austenitic stainless-steel piping arose, mostly in BWR systems. As materials and operating conditions of the primary coolant circuit of FUGEN are very similar to those of BWRs, an investigation was undertaken to determine the possibility of SCC in the FUGEN system, based on available information at that stage. Although it was concluded that the occurrence of SCC in the FUGEN system would be very unlikely, it was decided to take some countermeasures against the possibility of SCC in the feeder and riser pipes, because it would be difficult to repair or replace them due to the complex piping arrangements.

Water-cooled welding was considered to be the best method. This process had been developed by the manufacturer (Hitachi Ltd.) for FUGEN as well as for a BWR. But although this decision was made, it was found that all riser and feeder pipes had already been welded into unit segments at the factory, so the following two measures were adopted: (a) solution heat treatment for shop welds, and (b) water-cooled welding for site welds. In both cases, welds that would be subject to high operating stresses were selected for application of these measures.

All available information indicated that the conditions likely to initiate SCC were:

a. existence of high tensile stresses
b. sensitization of material
c. corrosive environment.

The measures taken aimed to eliminate the first two of these conditions.

The solution heat treatment effectively reduced the amount of sensitization of the heat-affected zone of the weld. High-frequency induction heaters were used to carry out the treatment.

Water-cooled welding was a very effective means of providing compressive residual stresses over all inside surfaces of welds and heat-affected zones. On the site, this welding was done by cooling water being fed through the pipe.

2. Stress Relief of Pressure Tubes: Just before the machining of pressure tube assembly components began at the factory, failure of the Canadian reactor pressure tubes was reported. Investigations revealed that the cause of failure was delayed hydrogen cracking, and the major factor in initiating the cracks was high residual tensile stresses in the tube wall, but that hydride cracking would not occur if the stress threshold were not exceeded.

A preliminary measurement of residual stresses was carried out, using a rolled-joint model of a FUGEN pressure tube assembly. This revealed that the stress level of the pressure tube wall was about 20 kg/cm^2 in the vicinity of the lower rolled joint. From January to August 1976, the rolling operation of the joints of FUGEN pressure tubes progressed at the factory, under highest quality control. Detailed measurements of residual stresses were then made, using some of the spare pressure tube assemblies. It was revealed that high residual tensile stresses of 50 kg/mm^2 developed in the pressure tube wall adjacent to the lower rolled joint, and that residual stress in the vicinity of the upper rolled joint was about 20 kg/mm^2. As a result, in December 1976 during the course of installation of pressure tube assemblies at the site, it was decided to investigate delayed hydrogen cracking experimentally, and to develop in situ stress relief equipment as soon as possible.

In September 1977, it was decided to adopt in situ stress relief measures to reduce residual stresses to low values to ensure the integrity of pressure tubes, even though accumulated experimental data had demonstrated that cracking was unlikely to occur in the FUGEN reactor. From January 10 to February 3, 1978 stress relief was carried out in situ in the vicinity of all lower rolled joints, using four sets of stress-relief equipment that had been developed to heat the pressure tube sufficiently without affecting the strength and leak tightness of the rolled joints.

FUNCTIONAL TESTS

General

Following completion of each plant system, the whole system was tested as a unit to check both function and performance against design specifications. Most tests were carried out between June 1977 and February 1978. The functional tests included interlock tests, alarm tests, running tests, and tests to the system proper. Some special tests are set out below:

1. The flow rate of individual fuel channels was determined by measuring the pressure drop between the inlet header and the drain pipe of the related feeder tube. The measured value was within ±5% of the calculated value.

2. To run the recirculation pumps of the primary cooling circuit at high speed (pump speed is to be raised from a low of 450 rpm to a high of 900 rpm at about 30% reactor heat output), it was necessary to provide additional flow resistance in the circuit, equivalent to the pressure drops due to the fuel assembly and two-phase flow. This was done by using temporary piping fitted with an orifice to provide flow resistance.

3. In addition to running tests of the emergency core cooling systems using the test lines, water injection into the steam drum and/or the inlet header was carried out, with measurements of flow rate, discharge pressure, closing and opening time of main valves, etc.

4. To determine the rare-gas holdup time, radioactive krypton gas (^{85}Kr) was injected into the charcoal bed. The measured holdup time was 56 h, compared to the design value of 40 h. These data made it possible to predict the holdup time of xenon to be 44 days, compared to the design value of 27 days.

5. The auto-pickup test (cutting off the external power supply to the station) proved that the emergency diesel generators (6000 kVA x 2 sets) started automatically within 10 s, and sequential loads were as designed.

6. To decide the X-Y position (location) of individual pressure tubes, the refueling machine visited every pressure tube and measured the position, and the data were fed into the control computer of the refueling machine. Refueling operations were rehearsed, using dummy fuels to demonstrate correct functioning both by remote manual and computer control operations. Fuel transfer operations, using the dummy fuel, were also carried out. Great efforts were necessary to ensure performance reliability of the refueling machine.

7. The final leak rate test of the reactor containment vessel was carried out from December 19 through 24, 1977, using the absolute pressure method. The reactor containment vessel was pressurized up to 0.85 kg/cm^2, the maximum pressure predicted in case of a loss of coolant accident, and kept thus for at least 24 h. Measurements were taken by temperature sensors (46 points), humidity (26 points), and pressure (1 point), which had been provided inside the vessel. The measured leak rate was 0.018 ± 0.008%/day against the allowable design value of 0.37%/day.

Heavy-Water Filling

The heavy-water circuits, including the calandria tank and the helium gas circuits, were throughly cleaned in June 1977 and tested with light water during July to September that year. Checking the heavy-water flow distribution, fast and slow dump tests, handling tests of ion-exchange resin in the cleanup system, scram tests of control rods, estimation of required volume of heavy water, etc., were also carried out.

After completion of these tests, the light water was drained off and the circuits were blown with instrumentation air (the cleanest and driest air available) until no mist was detected in the blown-off air. Large components, such as the calandria tank, the heavy-water storage tanks, and the dump tank were dried out with cloths.

The circuits were evacuated by vacuum pumps and heated from outside, in the following manner:

1. heating of the radiation shield by steam from the house boiler for the calandria tank

2. heating of the surrounding atmosphere by blowing hot air into the areas where the tanks and the pumps are installed

3. using ribbon heaters locally for valves.

The drying operation took about six weeks. Termination of the drying operation was determined from data on temperature changes, vacuum increase, and the dewpoint decrease of the circuits.

Before the storage tanks were filled with heavy water, a small amount of heavy water was injected into the calandria tank, into the heavy-water circulation pumps, and other places where it was suspected that light water may still remain. The heavy water was then drained off and degradation was checked. This showed only a very small difference of purity between the injected and drained-off heavy water, proving the effectiveness of the drying procedure.

From November 28 through December 7, 1977, 160 tons of heavy water (about 700 drums) was poured into the two storage tanks, using specially designed filling equipment which was able to transfer ten drums of heavy water at one time. Helium leak detection was also carried out for the entire heavy-water circuit to confirm integrity against heavy-water leakage.

The heavy water was then transferred to the circuits and functional tests with the heavy water were carried out until the beginning of February 1978. After the heavy water had been circulated through the system, sampling checks of the heavy water were carried out, and no degradation was observed. (The purity of the heavy water in the circuit was 99.81 mol%.)

Vibration Tests of Piping and Components

During the performance of functional tests, vibration tests were carried out on the pipework of important circuits to confirm the integrity of the pipe work against severe earthquakes and to test the aseismic design of the reactor.

Pipework components selected for the tests were:

1. Riser tube (3 in.)
2. Ring headers of reactor containment vessel spray system (3 and 4 in.)
3. Control rod guide tube (105 mm)
4. High-pressure injection pipe of ECCS (5 in.)
5. Piping of helium circulation circuit (6 in.)
6. Reactor feedwater pipe (10 in.)
7. Downcomer (14 in.)
8. Main steam pipe (16 in.)

Measurements were taken on natural frequency, the damping coefficient, and the mode of vibration, by means of wire cutting and, in some cases, forced vibration.

The results showed that (a) measured natural frequencies were in good agreement with the predictions, and were two to five times compared with the predominant frequency (3.3 Hz) of the reactor building, and that (b) the damping coefficients were more than twice the value (0.5%) used in the seismic analysis.

Vibration tests were also carried out to confirm the anti-earthquake properties of the reactor building and the important components, such as the control rod and its drive mechanism, the refueling machine, control boards and their associated components, the emergency battery, etc.

STARTUP TESTS

Fuel Loading and Approach to Minimum Criticality

All functional tests, the final check of the entire plant, and some remaining modification work had been completed by March 10, 1978.

The heavy-water level in the calandria tank was raised and kept at normal operating level by circulating the heavy water through the circuit. Boron was not injected into the heavy-water moderator at this stage. The primary coolant circuit was filled with light water to the normal water level of the steam drums.

Before fuel loading, a retractable californium neutron source (0.3 Ci) was assembled in the spent-fuel storage pond and loaded into a pressure tube, using the normal fueling procedures of the fuel transfer and refueling machines. Four channels of fuel-loading neutron counter, which had been interstitially provided in the reactor core, were then checked.

96 assemblies of mixed-oxide fuel, fabricated at the Tokai Works of PNC, were temporarily stored in the rack of the refueling pond located in the reactor building.

Fuel loading began on March 15. The central control rod (M) had been withdrawn 40% and all other control rods had been fully withdrawn. The refueling machine was charged with three fuel assemblies at a time, moved to the designated pressure tube, and each fuel assembly loaded into its fuel channel. The M rod was then fully withdrawn and subcriticality was confirmed. These procedures were repeated in the approach to minimum criticality.

Criticality was achieved on March 20, 1978 with 22 fuel assemblies in the core and with the M rod withdrawn 56.3%. The calculated quantity of fuel at the attainment of minimum criticality was 20 ± 3 assemblies. Figure 9 shows the configuration of the reactor core at that stage.

Schedule for Startup Tests

Startup tests of the FUGEN plant comprise the following tests and measurements: (a) reactor physics, (b) plant dynamics, (c) performance of major equipments and systems, and (d) water chemistry and radiation.

The tests that follow are to be carried out during the period March 1978 to March 1979, at the stages of (a) cold zero energy, (b) nuclear heating, and (c) power raising.

At the time of writing, the schedule is:

1. Full core loading of 224 fuel assemblies will be completed by the end of April.

2. Nuclear heating will start the beginning of June.

3. The turbo-generator will be synchronized by the beginning of July.

4. Full power generation will be achieved by the end of October.

5. The plant will go into commercial operation in April 1979.

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1. S. SAWAI et al., "Advanced Reactor Development in Japan," Trans. Am. Nucl. Soc., 29, 329 (1978).
2. S. SHIMA and M. AKEBI, "Engineering Design Features of FUGEN," Nuclex 72, Basel, Switzerland (Oct. 1972); PNC N340 72-13.
3. S. SHIMA and S. SAWAI, "The FUGEN Project," CNA Am. Conf., Toronto, Canada (July 1973); PNC N341 73-15.
4. S. SAWAI, "Some Specific Design Features of FUGEN," Trans. Am. Nucl. Soc., 23, 61 (1976); PNC N341 76-08.
5. S. SAWAI, "Outline of FUGEN and Its R&D," PNC N341 76-27 (Nov. 1976).

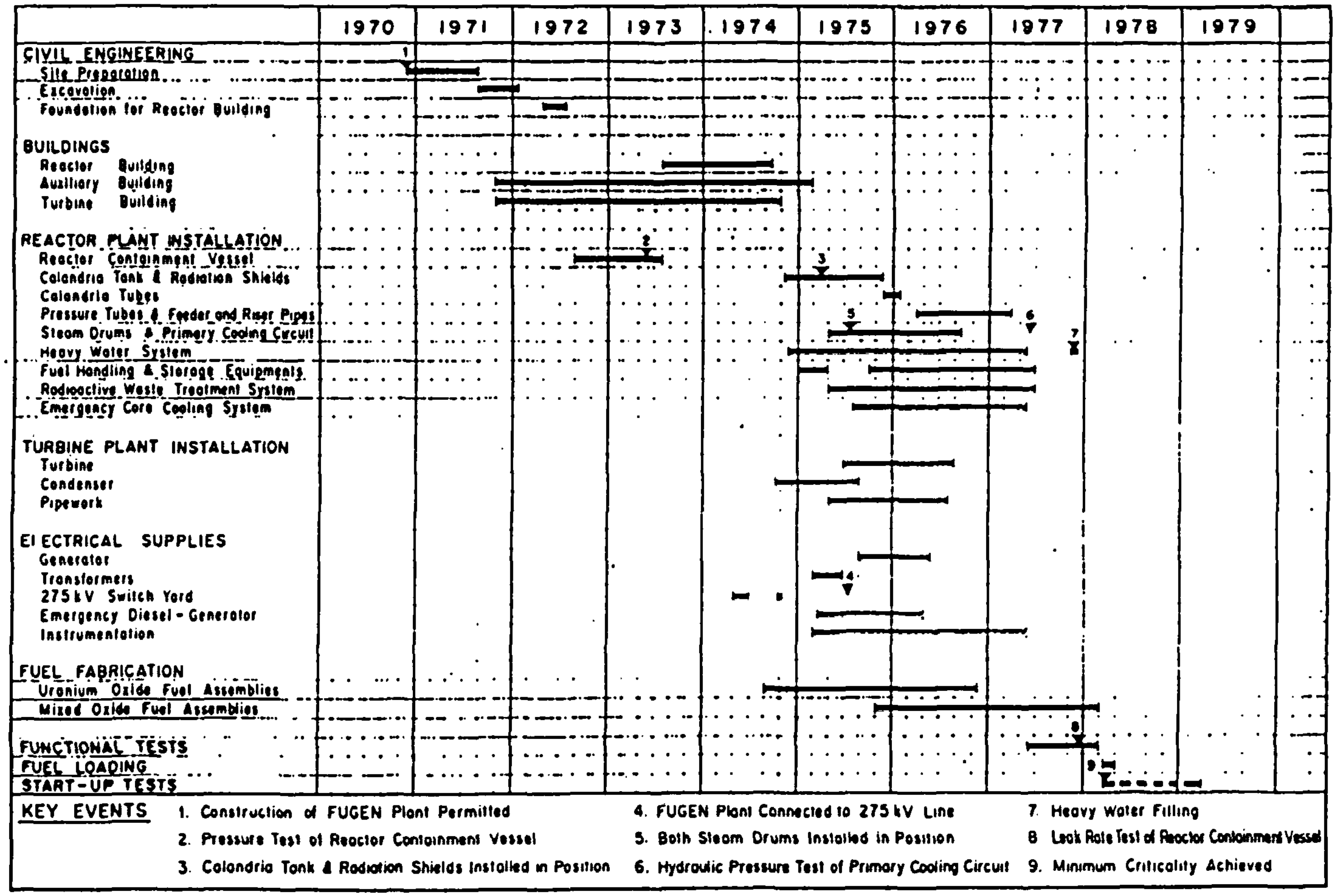

TABLE 1

Construction Program of Key Components and Systems

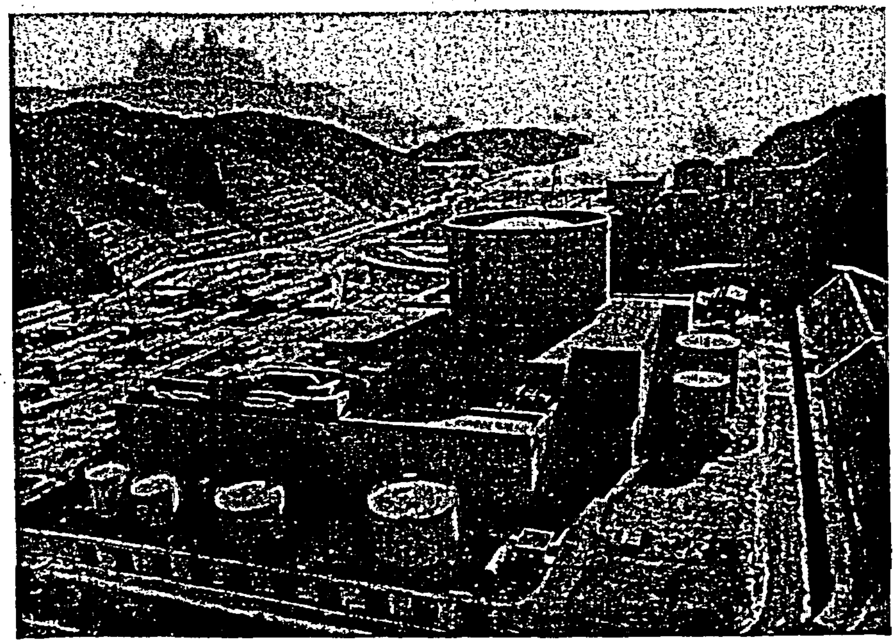

Fig. 1. General View of FUGEN Plant.

Fig. 2. Excavation.

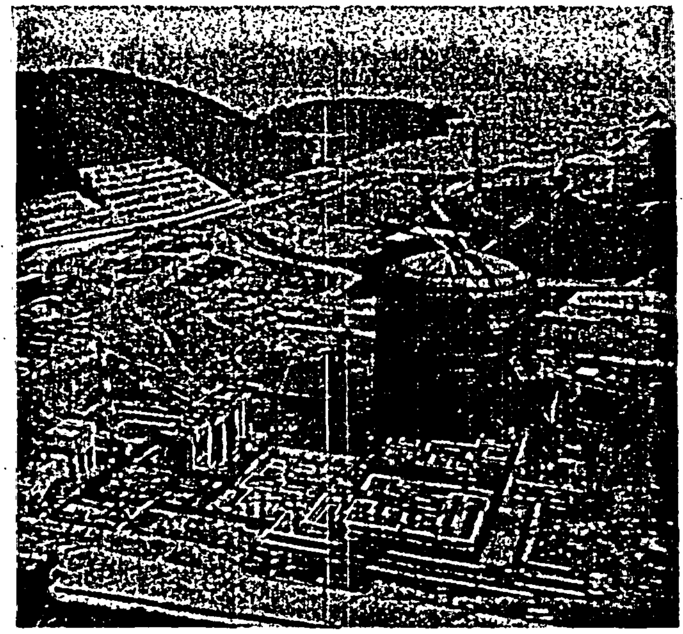

Fig. 3. Completion of Reactor Containment Vessel.

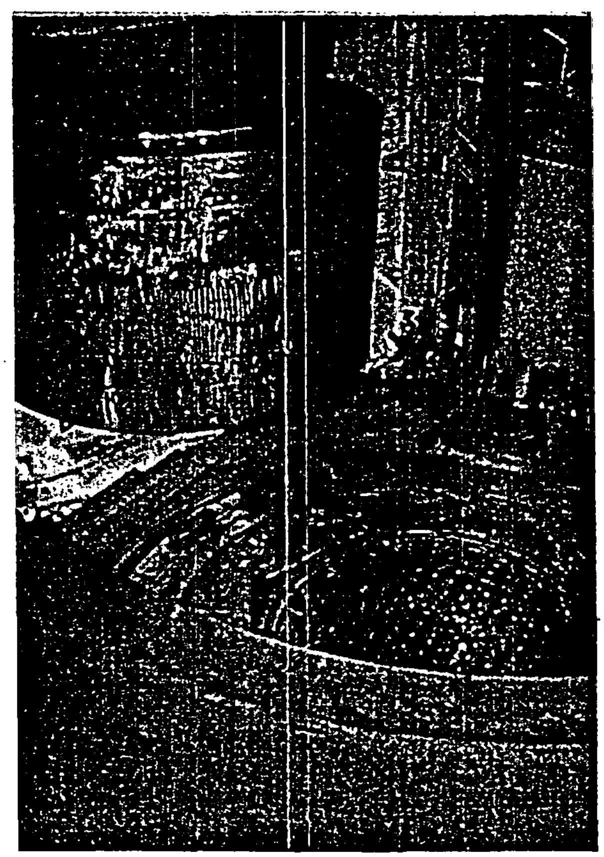

Fig. 4. Installation of Calandria Tank.

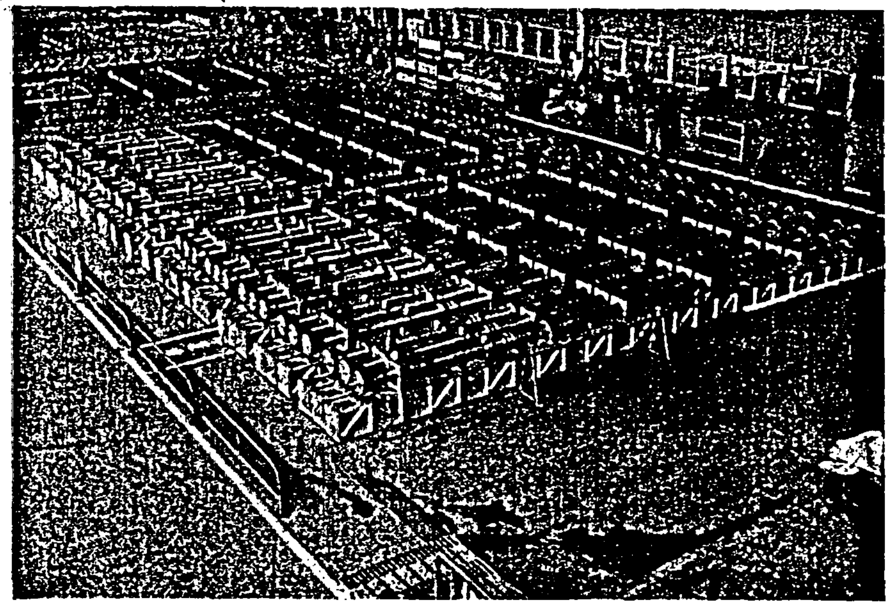

Fig. 5. Pressure Tube Assemblies in the Factory.

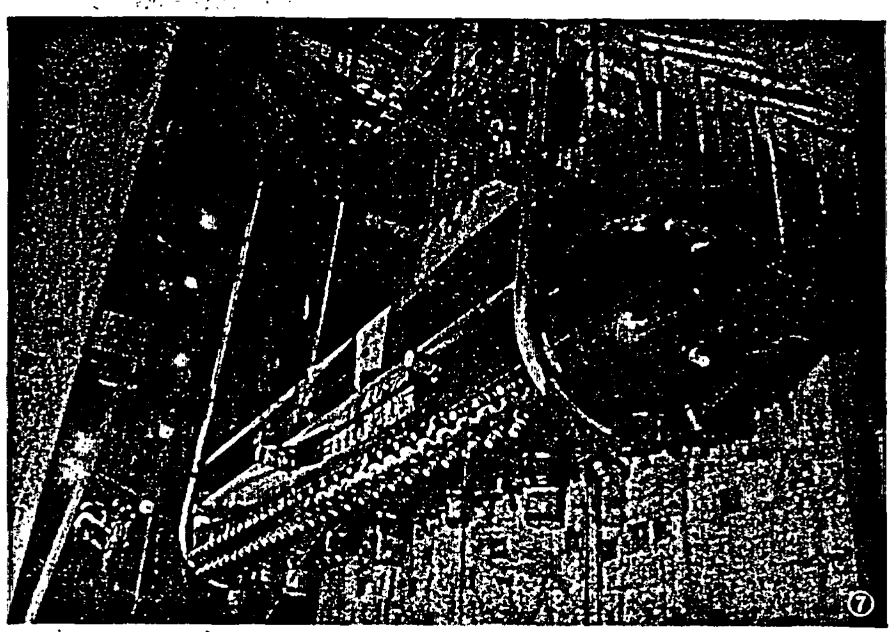

Fig. 6. Installation of Steam Drum.

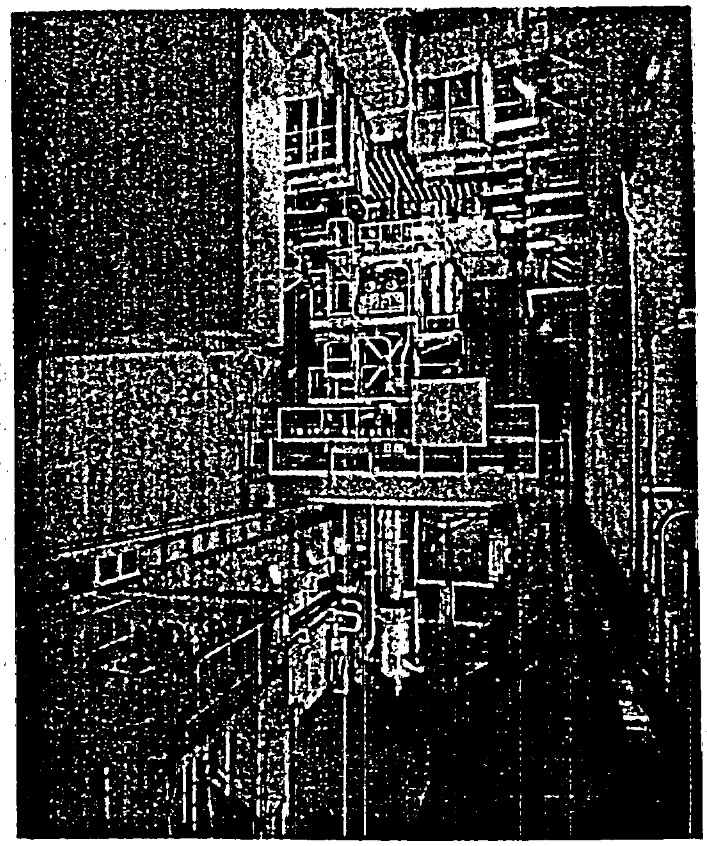

Fig. 7. Refueling Machine.

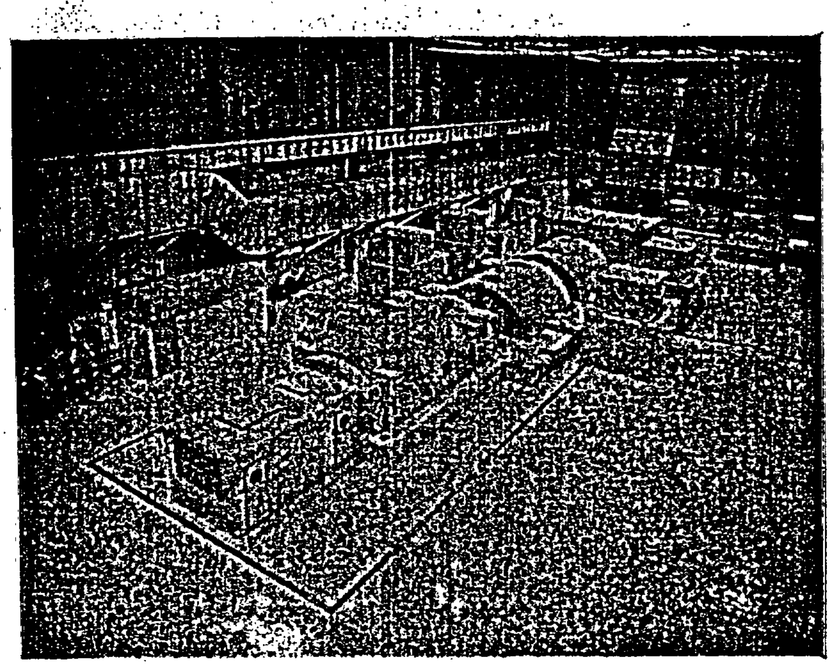

Fig. 8. Turbogenerator.

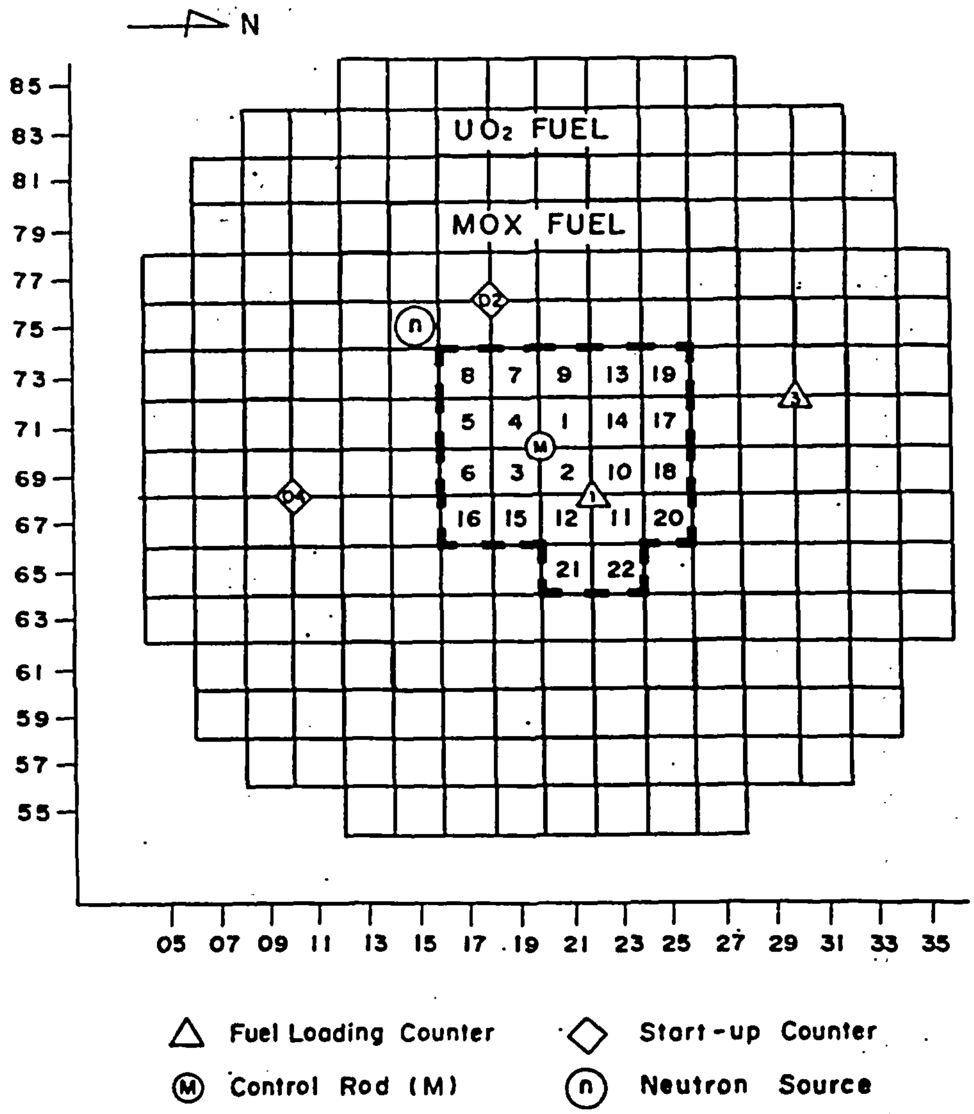

Fig. 9. Configuration of reactor core at minimum criticality.