THE SEISMIC DESIGN OF A NUCLEAR POWER STATION FOR JAPAN

by

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INTRODUCTION

Japan's first natural uranium nuclear power station is to be built at Tokai - Mura as part of the network of the Tokyo - Yokohama area of Honshu, operated by members of the Japan Atomic Power Company. The J.A.P.C. was formed in 1957 by the collaboration of nine power companies, the governmental Electric Power Development Company, and leading industrial concerns. An Enquiry for a single - reactor station based on the Calder Hall type was issued in February 1958 and tenders were submitted in the following July. The letter of Intent on G.E.C. was issued in April 1959 and the Contract signed in Tokyo on the 22nd December, 1959. Preliminary work by the J.A.P.C. on site and excavation for the reactor has already begun. Concreting of the reactor structure will begin at the end of the year and the station is due for completion in 1964.

Possibly the most interesting feature of the station is that it is designed to resist earthquake, it is not surprising, therefore that this station should differ appreciably in many ways from the one being built at Hunterston in Scotland, since from its initial conception all design decisions were made only after giving due consideration to the effect of an earthquake on the particular part of the station being considered. For example, the choice of bottom charge for the reactor in the case of Hunterston was made after a careful study of all the mechanical advantages and disadvantages associated with this system; however, for the Japanese Station it was clear from the beginning that top charge was necessary because of the importance of keeping the centre of gravity of the reactor building and its contents as low as possible to minimise the effects of horizontal accelerations during an earthquake. Again, a noticeable difference between the Japanese reactor and all the British commercial reactors is that the former has a core with a triangular lattice, while the latter have cores with the familiar square lattice. Although perhaps not apparent at first sight, the reason for this change is due entirely to a consideration of the structural stability of the core during an earthquake. Tests have shown that when their nuclear properties are essentially the same, a core with bricks on a triangular lattice has individual bricks which have a higher ultimate strength than the corresponding bricks used in a core with a square lattice.

Basically the station has been designed as a number of self contained units, each of which is capable of withstanding earthquakes far more severe than those likely to occur in Tokai-Mura. Thus the reactor, heat exchangers and the duct system form one unit integral with the biological shield and the superstructure of the reactor

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building, while the turbine hall forms another unit. During normal operation of the station, there is a central pipe and cable bridge giving a relatively flexible connection between these units, however, the reactor building has been provided with all the plant necessary for the complete removal of the heat generated in the reactor core even if all connections with the turbine hall and other buildings and supplies were broken. This provision assumes that the reactor has been automatically shut down and that fission reactions have been stopped so that heat comes only from the radioactive decay of the fission products in the fuel.

In general, all parts of the plant are designed so that their relative displacements during an earthquake do not interfere with the operation of normal controlling devices, such as the insertion of control rods into the core. Nevertheless, to ensure maximum safety, provision is made to meet conditions associated with a catastrophic earthquake having an intensity far in excess of that for which the station is designed, and therefore, far greater than any earthquake ever experienced or ever likely to be experienced in Tokai-Mura. The main essential in any emergency is to stop the fission reactions in the uranium fuel. In case the normal control rods should not be able to do this, an alternative shut down system has been devised for the G.E.C. reactor. This emergency system can be triggered manually, by seismographs, or by special sensing devices that will detect any unsafe misalignment of the core support grid, the core, or the reactor pressure vessel. Shut down is caused by allowing many thousands of small boron-steel balls to fall into a number of special channels in the core. The size of the balls is such that even if the whole reactor were grossly tilted from its vertical position they would still roll in, and even severe disruption of the reactor core would not prevent their entry. Moreover, it is possible to remove the balls from the core after use by means of a magnet grab, or by using the pressure difference of the carbon dioxide gas inside the system. To prevent spurious operation of the system due to circuit faults, the control circuits are triplicated and the simulataneous operation of two is necessary to initiate an emergency shut down.

EARTHQUAKE DESIGN LOADS

As will be appreciated, the additional loads imposed on a structure during an earthquake cannot be predicted accurately; furthermore, the dynamic behaviour of any particular structure depends on such intractable factors as the inherent degree of damping, foundation conditions, and so on. Thus the formulation of design criteria for an earthquake resistant structure is particularly difficult and must be determined from experience and a consideration of structural designs that have been proved safe during past earthquakes.

For some structures, including most of those for the Tokai-Mura nuclear power station, the occurrence of an earthquake can be considered from a design point of view as resulting in additional forces acting vertically and horizontally through the centre of gravity of each component, and proportional to their mass. Thus if W is the weight of a structural component, the temporary horizontal and vertical earthquake loading would be C_HW and C_VW, where C_H and C_V are seismic coefficients given by the building codes of the country concerned.

With regard to the seismic coefficients for the present design, in accordance with a policy of extreme safety, it was specified that.

(1) The reactor building and its foundation mat, except those parts specified under items 2 and 3 below, shall be designed to resist safely a seismic force one and a half times the value specified in the Japanese Building Code.

(2) The biological shielding and principal sub-structures surrounding or supporting the primary circuits shall be designed to resist safely seismic forces three times those specified in the code.

(3) All structures and structural parts inside the biological shielding structure and steam-raising units shall be designed to resist safely horizontal seismic forces as specified in item 2 above, together with vertical seismic forces whose intensity is equal to 50 per cent of the horizontal forces. In this case, the vertical and horizontal forces are considered to act simultaneously.

(4) Seismic coefficients for the gas ducts, joints and supports shall be 2.0 in all horizontal directions.

PARTICULAR EARTHQUAKE DESIGN PROBLEMS.

It is outside the scope of this paper to describe in detail all the problems associated with the design of an earthquake-resistant nuclear power station, for this reason attention is confined mainly to the more interesting structural problems of the reactor core, pressure vessel and gas ducts. However, before considering these particular problems, a brief survey of the general arrangement of reactor building may be of interest.

Referring to figure 1, it will be seen that the whole reactor structure is supported on a cellular reinforced concrete raft, the top face of which is located at ground level, while the bottom face rests on a system of caissons 22 feet below. The caissons have been designed to withstand the horizontal forces due to an earthquake, as well as the normal dead load of the structure. The cellular raft consists of a number of longitudinal and transverse members which mainly carry shear loads, and top and bottom slab members which mainly resist bending. It will be noticed that the cold ducts are partially located inside the cellular raft, an arrangement which leads to a reduction in the overall height of the structure. Furthermore, each cold gas duct is taken from the side of the steam-raising unit remote from the reactor, thus enabling the steam-raising unit to be located much nearer the biological shield, to which it is attached near the top conical head of the vessel by means of an earthquake restraint.

The cellular raft, the biological shield, and the reactor building superstructure up to the roof of the biological shield, form a monolithic unit, while the two box-like structures surrounding the hot gas ducts and supporting the rails for the charge machine have been considered as independent units cantilevered from the top of the biological shield. This is justified on account of their relative flexibility. In accordance with standard Japanese practice for earthquake resistant structures, the service building and other more conventional buildings have a mild steel skeleton embedded in the concrete with an approximate amount of reinforcement. The stack at the top of the reactor building has been designed for normal seismic forces acting in a horizontal direction.

With regard to the structural analysis for the complete reactor building, specified seismic coefficients were used to determine the magnitude of the horizontal shear forces during an earthquake. This shear was then distributed between the various components of the structure in proportion to their stiffnesses, thus ensuring compatibility of displacement in a horizontal direction.

(a) REACTOR CORE

The reactor core consists of a cylindrical stack of graphite bricks supported on a plate girder grillage and contained within a cylindrical steel shell designed to give additional stability to the graphite structure during an earthquake. The core is approximately 12.8 m (44 feet) diameter, 8.15 m (26 feet) high, and, excluding the grillage and stabilising cylinder, weighs over 2,000 tons when fully charged. Except at the boundary of the core, each brick in the moderator and reflector is a hexagonal prism approximately 230 mm (9 inches) across the flats and 940 mm (37 inches) long. There are no tiles ie. thinner layers separating the layers of bricks. As shown in figure 2, keys and keyways are machined on alternate sides of the bricks. Thus, when the core is constructed, there is a complete interlocking of the graphite bricks since the key of one brick is located in the keyway of an adjacent brick (see figure 3).

The central region of the core forming the moderator is approximately 11.2 m (37 feet) in diameter. The bricks in this region are centrally bored, forming a core with a triangular lattice. To maintain complete interlocking of the bricks without reducing locally the structural strength of the core, control rods are located in empty charge channels rather than in specially prepared channels at the intersection point of three bricks. The outermost bricks of the reflector are spigotted to narrow stiffening rings which project from the inside face of the steel earthquake stabilising cylinder which surrounds the core, bricks at the bottom of the core are supported on the steel support plates resting on top of the grillage.

As a result of constructing the core from interlocking bricks, body forces due to an earthquake can be transmitted readily from brick to brick via the keys and hence into the stabilising cylinder and down to the grillage and bottom skirt of the pressure vessel. Furthermore, the geometry of the bricks enables the core to expand symmetrically radially without imposing any type of restraint on the keys. For example, during start up of the reactor, the thermal expansion of the core stabilizing cylinder and grillage is about three times as large as for the core, to which they are attached by means of the spigots described above. The radial keys ensure that every brick is dragged out a small distance radially by the stabilizing cylinder thus forming a gap of approximately 0.58 mm (0.023 inches) between faces of adjacent bricks and resulting in an overall expansion equivalent to that of steel. The core will be constructed with small initial gaps between adjacent brick faces to accommodate any initial Wigner expansion of the bricks.

A full size model of part of the core which demonstrates this effect is shown in figure 4. In the model the radial spokes are attached to a hub which is loosely located over the central brick, while the ends of the spokes are spigotted into the six corner bricks of the hexagonal portion of core. Six steel sliding bars on the boundary of the model ensure that there is no relative rotation of bricks when the gaps in the model are closed, the hub is located so that the radial spokes are eccentric. Thus, a rotation of the hub into a position which reduces the eccentricity of the spokes produces an equivalent radial expansion of the core accompanied by gaps between individual bricks. For demonstration purposes the hub of the model is rotated by means of the wooden handle shown in figure 4.

Another feature of the interlocked core is that individual bricks can expand or contract relative to their own centre of gravity without experiencing restraint from adjacent parts of the core. For example, during the life of the reactor the graphite is subjected to irradiation damage which is approximately proportional to the fast flux distribution. As a result, after prolonged irradiation every brick tends to shrink, but since the irradiation damage across a key and keyway is the same, there is no change in the initial clearance in the keyway. At the same time the radial keys ensure that the bricks shrink towards their own centre of gravity, thus opening gaps between adjacent brick faces. In practice, even in the most highly irradiated part of the core, this gap will be only about 0.254 mm (0.1 inches) after twenty years.

When considering the stability of the core against a horizontal earthquake force, it is useful to consider initially the outermost ring of bricks fixed to the cylinder. The keys between this ring of bricks and the adjacent ring are radial towards the centre of each brick. Hence, each brick in this ring is fixed relative to the outer ring by virtue of the inclination of the keys. Similarly, the third ring of bricks is fixed to the second, and so on to the centre of the core. Thus the degree of fixity between any two bricks depends on the slackness in the keys and keyways, and since this can be controlled by small machining tolerances, it is found that the total slackness in the core is quite small.

In general, it may be observed that whilst the radial keys permit temperature and shrinkage movements of bricks without restraint, they resist non-symmetrical distortion of the core as a whole, except in so far as there is a very limited amount of distortion due to clearances between keys and keyways. At the same time, and this has been demonstrated by a test, it is impossible to jam a key in a keyway either by displacement or rotation of a single brick.

As previously explained, the earthquake loads are transmitted as shear across the keys of individual bricks to the steel stabilising cylinder. Calculations and strength tests on individual bricks show that provided the load is transmitted smoothly through the core there is a large factor of safety on the structural strength of the core even when the horizontal earthquake load is taken as high as 0.8g. Two factors ensure a smooth distribution of boundary reactions of the core. Firstly, the steel stabilising cylinder and core are connected by relatively flexible spigots which prevent load concentrations. Secondly the core consists of thousands of unit bricks which during an earthquake tend to distribute the load more smoothly than the case of a core made up of a small number of large monolithic units, each with a corresponding large number of keys and keyways.

Experimental work on the earthquake stability of the core is being carried out at the Japanese Building Research Station in Tokyo. For this purpose a large vibration table has been installed so that horizontal slices of the core as much as 3.55 m. (14 feet) diameter can be given accelerations greater than those expected to be experienced during an earthquake. For example, at the time of the Kanto District Great Earthquake in 1923, the horizontal acceleration caused in the ground on the hill-side of the City of Tokyo was in the order of 0.1g. Accelerations far in excess of this value can be given to models of the core weighing up to 28 tons by using the above vibration table. Furthermore, the table can be tilted mechanically into a near vertical plane so that static loads equivalent to 0.7g. can be imposed on the graphite bricks and so their behaviour can be studied when under the action of the specified earthquake load.

In general the work being done in Japan is confined mainly to large diameter slices of the core using bricks having an almost full size cross-section and an axial length of 3 inches. Such tests have been designed to study the distribution of the earthquake load in the core, the interaction of loads between the core and the steel stabilising cylinder, as well as the radial expansion of the core during temperature changes.

Additional experimental work on the earthquake behaviour of the reactor core is being done at The General Electric Company's works in England, and for this purpose a reasonably large vibration table has been constructed. This table has been designed to carry three dimensional models of the core about 1.84 m. (6 feet) diameter and 1.92 m. (3 feet) high, and by suitably choosing the springs in the machine it is possible to develop accelerations of 2g with amplitudes of 50.8 mm (2 inches).

For the particular experiments being done at Erith, over 2,500 graphite bricks 76. mm (3 inches) wide and 152 mm (6 inches) long are being used to construct a representative portion of the core. With this model it is proposed to study the distribution of the earthquake forces from one horizontal slice of the core to another, and hence determine the distribution of the load transmitted to the grillage and to the core stabilising cylinder. The vibration table will also be used to consider the degree of damping in the core due to this non-monolithic unit brick construction.

(b) REACTOR PRESSURE VESSEL AND SUPPORTS.

The reactor pressure vessel (see figure 1) is a sphere of fine-grain aluminium-killed steel having a diameter of 18.9 m (62 feet) and a thickness of 83 mm (3¼ inches); its gross weight is about 1,500 tonnes, and it has been designed to withstand an internal pressure of 16.2 kg/cm^2 (230 lb/in^2). The vessel is supported by a cylindrical skirt having a diameter of 12.4 m (40 feet 9 inches) and a thickness of 63.5 mm (2½ inches). During normal operating conditions this skirt supports the combined weight of the pressure vessel, reactor core, grillage, etc. (approximately 4,000 tonnes), while in the event of an earthquake it resists vertical oscillations corresponding to an additional dead load of approximately 1,300 tonnes.

The skirt is extended several feet into the vessel in order to form a support for the plate-girder grillage which carries the reactor core. The actual length of the internal skirt was chosen to be as short as possible, consistent with the condition that its length was sufficient to permit substantial attenuation of applied edge bending and shear stresses.

In addition, there is a further skirt located on the outside of the vessel above the equator, as shown in figure 1. This skirt has a thickness of 25.4 mm (1 inch), and has been designed to transmit a portion of the horizontal earthquake load from the reactor pressure vessel to the biological shield. This is effected by means of two thin steel diaphragms located in horizontal planes at the upper end of the skirt and anchored to the inner face of the biological shield. The diaphragms have sufficient flexibility to permit vertical temperature movements of the top skirt without imposing serious restraining forces on the vessel.

The effect of supporting a spherical pressure vessel and its core on continuous skirt supports, one of which is located inside the vessel and the other directly underneath on the outside, is to induce in the skirt and loaded vessel a system of bending and shear stresses due to the constraining effect of the skirts. The magnitude of these stresses depends on the relative thicknesses of the components joined at the discontinuity as well as the pressure in the vessel, the weight of the core, the temperature variations in the structure in the region of the discontinuity, and the intensity of any particular earthquake.

For the design of the J.A.P.C. reactor pressure vessel, a detailed stress analysis was made for the supporting means, and it was found that by suitably choosing the thickness of the various skirts, the bending stresses induced in the structure could be kept relatively low so that the sum of the membrane and bending stresses in the vessel and skirt at the point of discontinuity were everywhere reasonably less than the yield stress of the material even during a severe earthquake.

Basically, the analysis of the skirt problem reduces to the finding of the unknown bending moments and shear forces induced in the four components of the structure meeting at the discontinuity. This involves the solution of a large number of simultaneous equations which, for the J.A.P.C. pressure vessel, was done to give expressions for the induced stresses in terms of the following dimensional variables.

(1) thickness of vessel

(2) thickness of skirts

(3) diameter of skirts

(4) diameter of sphere

For design purposes this solution was used to find expressions for the stresses induced in the vessel and skirts due to the following systems:

(1) internal pressure in vessel

(2) weight of core

(3) weight of vessel

(4) weight of standpipes and other vessel attachments.

(5) an axial temperature gradient in the bottom skirt.

In addition, the restraining effect of the top skirt was considered when determining the induced stresses due to horizontal earthquake forces.

With regard to the stress analysis for the skirt to shell junction, a method for analysing the induced bending and shear stresses in a symmetrically loaded shell of revolution was developed in 1912 by H. Reissner[1]. This method was generalised and applied to particular cases by E. Meissner[2] who obtained a solution to the basic differential equation in the form of hypergeometrical series. Later an approximate solution to the problem was obtained by J.W. Geckeler[3], who made the simplifying assumption that in the region of the induced moments and shear forces, the shell of revolution can be replaced by an equivalent cylinder. A better approximation, and the one often used in practice, was obtained by Hetenyi[4] in 1938. This approximation is equivalent to assuming that in the region of the vessel where the induced stresses are relatively large, the vessel can be replaced by an equivalent conical section, because the meridional length of such a region is small compared with the radius of curvature of the vessel at the point considered.

Based on the approximate theories of Geckeler and Hetényi, a general analysis for the normal operating stresses at a skirt to shell junction has been done by Hicks[5], and this was used to evaluate the stresses for non-earthquake conditions in the J.A.P.C. reactor vessel.

For a non-symmetrically loaded shell of revolution, various methods of analysis have been proposed by different authors. In all cases a number of assumptions were made in order to reduce the basic differential equations for the shell to forms which considerably simplified the mathematics. Thus, for a cylinder, the basic equations of Flügge[6] are the most accurate, while the equations of Donnell[7] although less accurate are easier to apply to particular problems and can be used to give a closed solution which has been obtained by Hoff[8]. Similarly, for a sphere, basic equations have been obtained by Havers[9], Tsuboi and Akino[10], and others.

For the non-symmetrical earthquake effects on the reactor pressure vessel and skirts, a complete analysis was done by Leckie and Levesley (unpublished) of Cambridge University. Using the equations of Havers for the sphere and Hoff for the skirts, they obtained values for the earthquake stresses induced into the structure at the point of the bottom skirt support. They found that during an earthquake the horizontal shear on the reactor core is carried mainly by the bottom skirt, while the horizontal shear on the pressure vessel due to the top dome standpipes is transmitted almost completely to the biological shield via the top skirt and diaphragms. On the other hand, the horizontal earthquake body forces on the sphere are shared more or less equally between the top and bottom skirts.

It is interesting to note that in the event of no top skirt, the induced earthquake stresses at the bottom skirt to shell junction are increased considerably. This increase can be attributed mainly to the additional overturning moment in the bottom skirt by the standpipes located at the top of the reactor pressure vessel.

It will be appreciated that for a reactor pressure vessel the analysis for the stresses at the junction of the vessel and support skirt involves a great deal of numerical computation, for example; sets of more than thirty simultaneous equations have to be solved to determine the magnitude of the earthquake stresses. For this reason, where possible, experimental work has been done to verify theoretical calculations and to justify the use of particular shell theories. At the works of the General Electric Company, a one sixth scale model of the sphere and support is being used to check earthquake stresses, while a full size mock-up of part of the support skirt is used to determine temperature gradients for the evaluation of thermal stresses. Furthermore, additional experimental work is being done independently in Japan under the direction of Professor Muto for the Japan Atomic Power Company.

(c) MAIN GAS DUCTS.

Consideration of such features as mass flow, frictional losses and the number of steam raising units, led to a final duct diameter of approximately 6 feet. To ensure flexibility for temperature expansions, three hinged bellows are incorporated in each duct system, the bellows being designed to take an axial load without transmitting any appreciable bending moment.

As previously stated, during an earthquake the ducts are considered as under the action of additional loads equivalent to 2g acting horizontally and 1g acting vertically, at the same time, the vibration behaviour of the system must be such as to ensure that there will be no danger of excessive resonance displacements due to forced vibration caused by an earthquake. Since each duct system is co-planar, deflections in directions normal to the plane of ducts have been restricted by introducing a series of sliding supports which merely permit axial and diametral thermal expansions, while vertical and horizontal earthquake deflections in the plane of the system are restricted by a number of viscous dampers each of which is connected to a duct by means of a single lever. The function of the lever is to improve the effectiveness of the damper by increasing its throw for a given deflection of the duct at the point where it is attached to the lever. In general it has been found that the deflections of the duct system are small and correspond to the lower limit of movement normally associated with effective viscous damping. In this respect it is advantageous to have lobster-back bends in the ductwork to increase its overall flexibility.

To illustrate the method of design, reference may be made to the particular case of the hot duct system shown diagramatically in figure 5. As will be seen, the duct is attached to the reactor pressure vessel and the heat exchanger at the points A and C respectively. The hinged bellows are located at B_1, B_2 and B_3, while a valve which isolates the pressure vessel from the heat exchanger has been placed at the point V. The total mass of the bellows and valve is in the same order as the mass of the complete duct system from A to B.

An initial calculation showed that in the event of an earthquake the duct system became seriously over stressed unless supported at a number of intermediate points along its length; furthermore, mainly because of the presence of the bellows, gross displacements where likely to occur due to forced vibrations. For this reason additional horizontal supports were placed at the points H_1 and H_2, and additional vertical supports were placed at Z_1 and Z_2, these latter supports being designed so as not to support any of the dead load of the ducts during normal operating conditions. Since considerable movements occur in the ductwork due to temperature changes in the reactor during normal operating conditions, and because these movements are relatively slow compared with the frequency of vibration of an earthquake, the additional support for the ductwork was supplied by using viscous dampers at the intermediate points mentioned above. As will be appreciated, in the event of an earthquake, the deflections of these supports will depend on the periodicity of the applied loading, the natural frequency of the ductwork, and the viscosity of the dampers themselves. It follows that within practical limits this last factor may be varied to give a high or low resistance to the deflections of the ductwork as required.

With regard to the design of the dampers, particularly with reference to their viscosity, this was done by considering the allowable stress and corresponding deflections in the ductwork during an earthquake. For example, if there is full restraint at H_2, a horizontal earthquake loading will result in certain stresses in the duct system but there will be no deflections of the point H_2. However, if the restraint H_2 is reduced, there will be an accompanying deflection of the ductwork at this point, with the result that additional stresses will be induced in the duct system. This implies that if the maximum stress in the system is initially fixed, then this determines the maximum deflection at H_2 and the viscosity of the damper.

The above example has been simplified considerably to illustrate the essential features of the design calculations. In practice it was necessary to consider the simultaneous deflections of all the damper supports during an earthquake, and to adjust the viscosity of the various dampers to prevent excessive stresses in any part of the system. Furthermore, since the deflections of the restrained duct system are inherently small, it was necessary to consider the additional flexibility due to the lobster back bends and the localised flexibility of the reactor pressure vessel at the point S, the latter being estimated by using reference 11.

Since the effectiveness of the dampers depends on their actual location on the ductwork it was essential to study the vibrational behaviour of the system and see where the deflections became excessive, particularly near the point of resonance. For this purpose models of the ductwork were tested on a small vibration table having a frequency range of two to twenty two cycles per second. The models were made geometrically similar to the prototype in the direction of the axis of each straight component of the duct systems, and, although the models were made from flat brass strips rather than tubes, the correct bending stiffnesses were maintained. Masses were added at the valve and bellows positions to obtain the correct ratio of concentrated to distributed load, while very thin short lengths of spring were used to represent the bellows.

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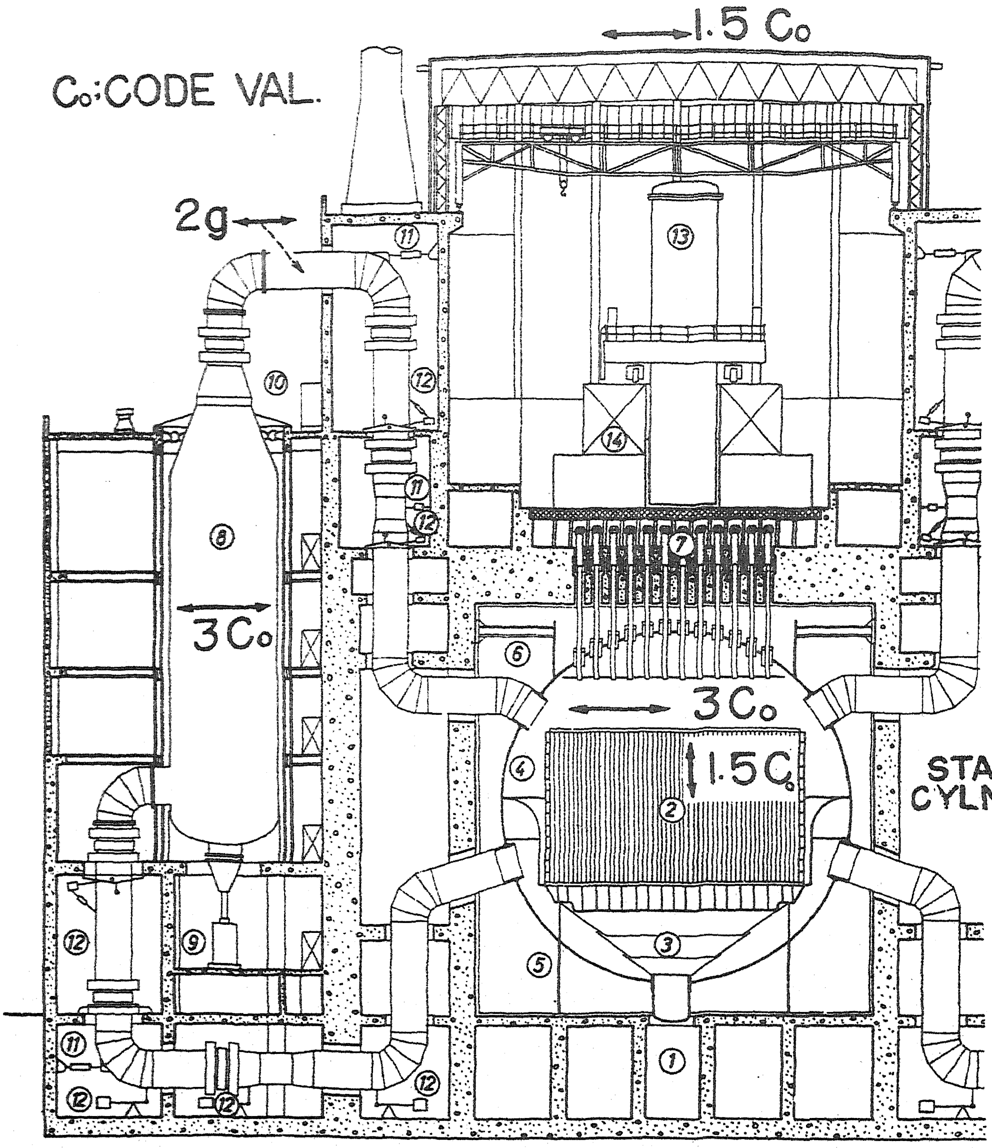

1. Reactor Raft
② Reactor Core
3. Debris Collector Cones
4. Pressure Vessel
5. Reactor Support Skirt.
⑥ Pressure Vessel Earthquake Restraint.
7. Charge/Discharge Standpipes.
8. Steam Raising Unit
9. Gas Circulator Turbine Drive
⑩ S.R.U. Earthquake Restraint
⑪ Duct Earthquake Restraint
12. Duct Counterweight Supports.
13. Charge Machine
14. Charge Machine Bridge.

FIGURE 1.

CROSS SECTION THROUGH REACTOR BUILDING

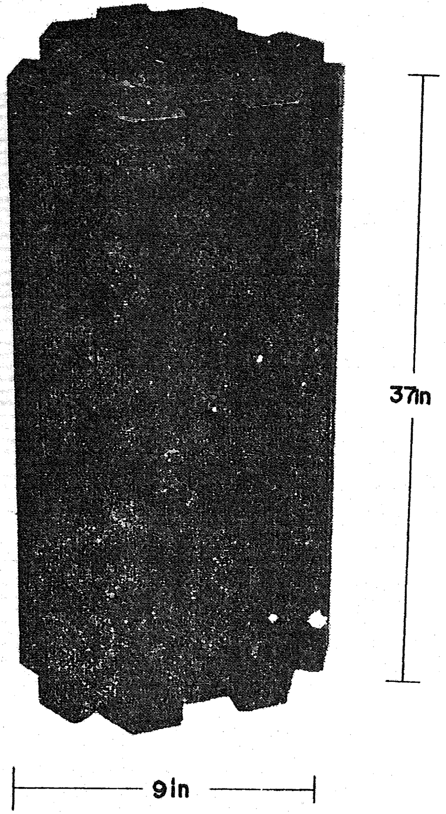

FIGURE 2

MODEL OF HEXAGONAL GRAPHITE BRICK SHOWING KEYS AND KEYWAYS.

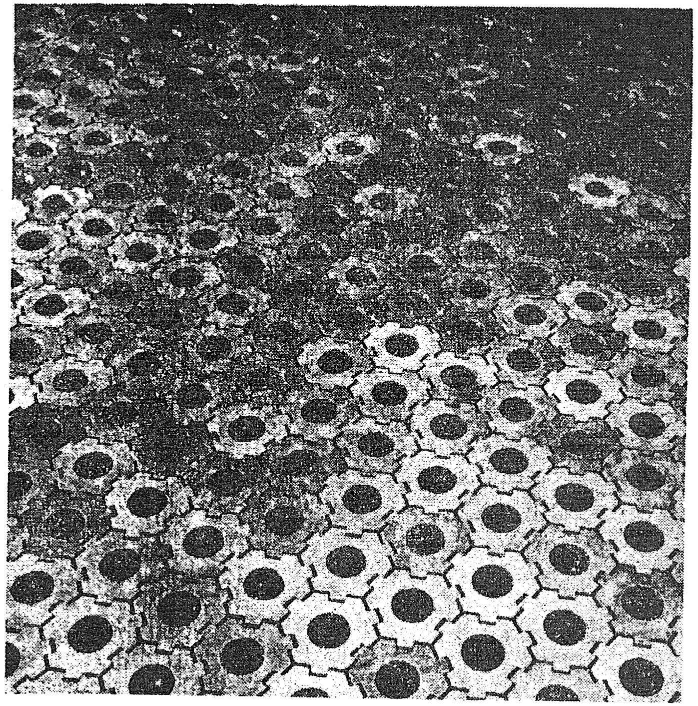

FIGURE 3

SLICE OF A MODEL GRAPHITE CORE SHOWING INTERLOCKING OF BRICKS.

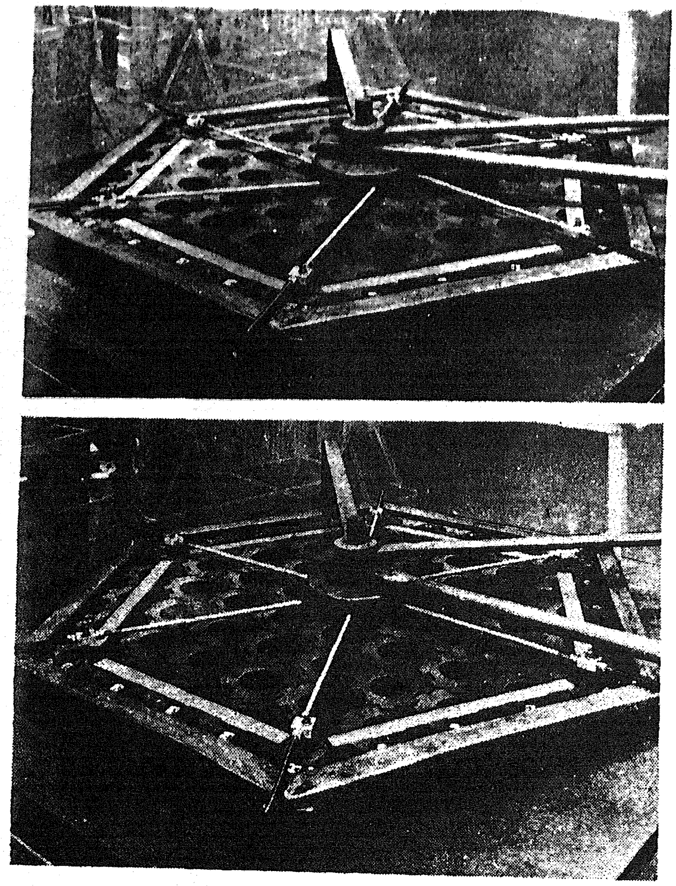

FIGURE 4

MODEL FOR DEMONSTRATING UNRESTRAINED RADIAL EXPANSIONS OF THE CORE.

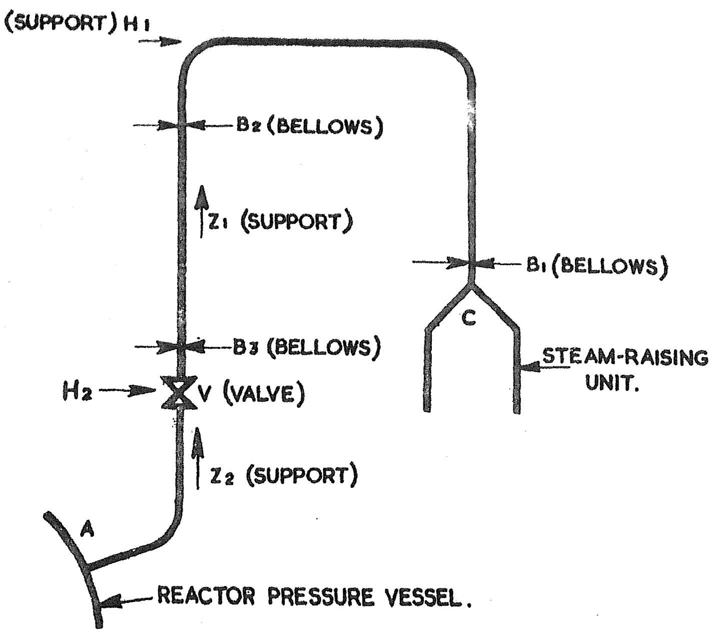

FIGURE 5

DIAGRAM OF HOT DUCT SHOWING POSITIONS OF EARTHQUAKE SUPPORTS.