ASEISMIC DESIGN FOR JAPAN EXPERIMENTAL FAST REACTOR (JOYO)

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ABSTRACT

This paper explains the aseismic design of Japan Experimental Fast Reactor (50 MWt) called "JEFR" or Japanese nickname "JOYO" which is being constructed at Oarai site in Ibaragi Prefecture, along the shore of the Pacific Ocean.

Even though the aseismic design of JOYO is being progressed now in detail, fundamental design requirements were fixed and some interesting design activities have been continued. This paper introduces those matters, including decision of the design earthquake, idea of plant lay-out, explanation of dynamic analyses of main items, design modification of safety rods, recipe for making flood response spectra, problem of sodium coolant piping and experiment of graphite shielding structure.

1. INTRODUCTION

PNC (Power Reactor and Nuclear Fuel Development Corporation) has intended to experience and solve various problems of technology, through the design, construction and operation of LMFBR (Liquid Metal Fast Breader Reactor) in Japan, which aims to develop prototype fast reactor and large scale commercial fast power reactors in the future. In the nature of the case, the first reactor plants involve structural and mechanical problems which have never been appeared in the designs and constructions of light water reactor plants under construction in Japan, and moreover, most of those peculiar questions relate with the aseismic design.

As is well known, Japan is located in a zone of high seismicity in the world, and very severe inquiry has been made of the aseismic design for every nuclear facility to avoid public disaster due to probable earthquakes. On the other hand, PNC is one of new quasi-governmental organizations and its staff has little experience in the aseismic design. Therefore, JAPC (The Japan Atomic Power Co.) has been entrusted, as a consultant, to assist PNC relating to all of the aseismic design of JOYO with the contract since two years before.

Basic philosophy and method of the aseismic design for JOYO are almost the same with those for large scale commercial light water reactor plants in Japan. "Technical Guidelines for Aseismic Design of Nuclear Power Plants (written in Japanese)", published by Japan Electric

Association in April, 1970, and was edited by a special committee, explains the above philosophy and method, and a member of the committee will introduce this Technical Guidelines at the Conference. Therefore, this paper does not touch upon such general philosophy, criteria and method regarding the aseismic design of nuclear facilities, and it refers only to special topics on the aseismic design appeared in the project of JOYO.

2. DESIGN EARTHQUAKE

2.1. Special Site Condition

In the case of nuclear power plants which are being constructed or planned in Japan, sound rock layers for bearing heavy reactor building sufficiently to withstand strong earthquakes are searched in the course of site selections. In the case of JOYO, even though it does not generate electric power, its size and weight, structural complexity, construction cost and safety requirements are comparable with those of commercial nuclear power plants, and a subsoil profile of JOYO's site shows very deep sand layers up to 162 m below the ground surface. However, since the bottom of reactor building foundation was located 32 m deep from the ground surface, this project presented us with a new problem how the design earthquake be selected considering an effect of very thick sand stratum between the bottom of building and the base rock.

2.2. Maximum Acceleration at Base Rock

First of all, an evaluation of the expected value of the maximum acceleration as the design earthquake at the base rock in Oarai area was made as in the case of other nuclear power plants. Magnitudes, focuses and epicentral distances of 13 earthquakes that occurred in the past 1100 years were investigated, and using these data and also referring to the materials prepared by Kanai [1] and Seed [2], the values of accelerations for the maximum earthquake at the base rock were estimated. Kanai's formula gave the maximum constant velocity 3.2 cm/sec, and this value can be converted into the acceleration 100 gals as the maximum probable figure, and Seed's figure represented less than 50 gals. On the other hand, Kawasumi [3] presented a seismic probability map assuming that the whole land of Japan is covered by a standard uniform soil condition. This map shows 200 gals on the ground surface at Oarai area, and it is said that this value could be reduced to one half to one third, and therefore, 70 - 100 gals acceleration at the base rock would be an expectant value. While, an actual observation of natural small earthquakes in a period of about one year was carried out at the site, and its records indicated the above reduction factor being one quarter to one fifth.

Therefore, we concluded from the above information that as the maximum acceleration of the design earthquake, 100 gals or 3.2 cm/sec in velocity could be selected at the base rock (162 m below the ground surface) in a conservative sense.

2.3. Observation of Small Earthquakes

JAERI (Japan Atomic Energy Research Institute) carried out interesting observations of natural small earthquakes by installing seismographs in and on the ground. Many instrumentations were arranged (a) around JPDR (Japan Power Demonstration Reactor) which is borne by shale and (b) around JMTR (Japan Material Test Reactor) which is borne by sand stratum. The former is located at Tokai 19 km North of Oarai and the latter is some 400 m away from JOYO at Oarai. These observations presented useful data in comparison with each other, and the conclusions on Oarai site are as follows:

(1) Deep sand stratum of 22 m below the ground surface can be regarded as a vibratory base as well as the base rock of shale, because both records represented a constant velocity spectrum of ground movements as shown in Fig. 1.

(2) Predominant periods of the ground are 0.15, 0.5 and 1.1 sec on the surface, and 0.5 and 1.1 sec at the elevation of 22 m below the surface as shown in Fig. 2. Those periods mean that 0.15 sec is the natural period of the over burden and 1.1 sec and 0.5 sec can be regarded as the natural periods of whole sand strata corresponding to the first and second mode vibrations, respectively.

Therefore, -22 m layer can be chosen as the vibratory base instead of -165 m layer, but to perform conservative calculation the latter elevation was defined as the vibratory base.

2.4. Amplification of Sand Stratum

In order to evaluate the amount of amplification of ground movement due to the existence of deep sand strata, a theoretical calculation and actual observation were carried out.

In the theoretical calculation by means of the theory for multilayer reflections, the following matters were considered:

(1) Kanai's report [4] was referred to,

(2) The base rock located -165 m below the surface was regarded as the vibratory base,

(3) Input vibration at the vibratory base was sinusoidal motions having parametric various frequencies to make a frequency response sectrum,

(4) Coefficient of viscosity was calculated referring to the formula in the paper by Kanai [5] and using density and coefficient of rigidity of each stratum,

(5) Case A or to account the amplification effect from the vibratory base towards the bottom of an equivalent building, which has 0.2 sec natural period and was located -22 m below the surface at its bottom, three subsoil strata were taken, and Case B or to account that towards the open surface, seven strata were taken, and

(6) Required physical numbers of all strata were given from soil information obtained at the site.

The conclusions of the calculations were shown in Fig. 3 and its summary is as follows:

(1) For Case B, 5.6 times amplification was evaluated at 1.1 - 1.2 sec. and 7 times amplification at 0.3 - 0.4 sec.

(2) For Case A, 4.8 times amplification was evaluated at 1.1 - 1.2 sec. and contrary to the above, only 1.6 times amplification at 0.3 sec.

The above tendency appeared in the experimental records. Fourier velocity spectra of four recorded earthquakes at elevations of -0.18 m (on the surface) and -22.18 m (underground) were averaged and plotted in Fig. 2. The amplifications for longer periods were approximately the same, but for shorter periods larger amplification occurred just on the surface.

Referring to the above theoretical calculation and experimental evidence, in order to decide the value of the maximum acceleration to apply the bottom of the reactor building foundation, we made such judgement, that a selection of 1.5 times amplification factor to multiply the value of 100 gals at the base rock for shorter periods was adequate, and that the acceleration acting at the bottom of the reactor building should be small for longer periods, because the acceleration at the base rock reduced owing to a velocity constant tendency, though an amplification factor being large as shown in Fig. 3.

2.5. Selection of Earthquake Waves

As apparent from the previous investigations, two different tendencies should be taken into consideration for selecting the design earthquake waves, the one has the spectral peak at a range of 0.3 - 0.4 sec periods and the other peak at 1.0 - 1.1 sec. Locking for many records obtained by Strong Motion Accelograms and after examining them, the following two waves were selected and their values of the maximum accelerations were decided respectively to normalize them for the purpose of designing JOYO:

El Centro NS, 1940, Maximum Acceleration = 150 gals

Akita Record EW, 1964 (obtained at Niigata Earthquake on building of Akita Prefectural Government), Maximum Acceleration = 100 gals

By the way, Fig. 4 represents the response spectra for 5% of critical damping of the above two design earthquakes.

3. PLANT LAYOUT

An original conceptual layout of buildings indicated that the reactor building together with the containment vessel was one individual structure, and several other buildings, in which many A class facilities were supported, were arranged around the reactor building. However, the bottom of the reactor building foundation is located at -32 m below the ground surface since an elevation of the operating floor has to be coincided with the ground surface for convenience of transporting the spent fuel cask car. In such a layout, not only the reactor building but other buildings should be A class, and many trenches and cable tunnels should be arranged between the reactor building and others on loose back fill, and it would be difficult to make accurate aseismic designs for many buildings, trenches and tunnels.

Therefore, in order to avoid the above risky and troublesome designs, one large rigid and strong building consisting of the reactor building at the center and auxiliary building having monolithic basement was proposed as shown in Figs. 5A and 5B. The intention of designing such a large building was to house every A and B class facility in it, except the main secondary sodium cooling system and its large air coolers.

4. DYNAMIC ANALYSES OF MAIN ITEMS

4.1. Models for Response Calculations

For different purposes of the response analyses, two analytical models were selected. The first model consisted of the reactor building, containment vessel and auxiliary building, as shown in Fig. 6A, to obtain the response accelerations, moments, shearing forces, etc. for those structures, and the second model consisted of the reactor building, auxiliary building, reactor vessel and vessel internals as shown in Fig. 6B, to obtain the response accelerations, moments, deformations, stresses, etc. for the vessel internals. Owing to a limitation of computer capacity for working out time history calculations, the containment vessel was omitted in the latter model.

4.2. Spring Constants of Soil

As mentioned in 2.5., two earthquakes or El Centro and Akita waves were selected for the design, however, Akita wave does not affect the above two models, because a range of natural periods of the first mode of the both models is 0.25 - 0.35 sec and an amplification factor due to Akita wave in this range is very low. Therefore, just only El Centro wave is meaningful for the response calculation of the above two models. It is said that plural input waves should be applied to the response analysis for the design, however, we found out such other appropriate scheme that setting a certain range for spring constants of soil which produce rocking and swaying vibration modes can generate some amplifications in a broad range instead of selecting plural input waves.

There are several references presented by Tajimi [6], Timoshenko et al. [7], Toriumi [8] etc. to account the spring constants, but those formulas gave different results, namely, it can be said that working out the spring constants is an uncertain problem, therefore setting a certain range for the spring constant is an advisable technique.

The calculated numbers of Kθ and Ks obtained from the above formulas and averages of these numbers were regarded as corresponding to the case of the hardest soil condition, and one half of the above averaged numbers were regarded as corresponding to the other case of the softest soil condition. Duplicate response calculations applying to El Centro Earthquake wave for both soil conditions were performed, and the designs of all A class items have been required to satisfy the both cases.

4.3. Calculated Results

Calculated results of the response analyses were shown in Fig. 6A for the first model and in Fig. 6B for the second model. With respect to the first model, the dynamic response analysis gave an insignificant result for the design of the buildings and containment vessel, compared with the distribution of respondent acceleration and the static requirement which was defined as the seismic coefficient represented by the step-wise full lines in Fig. 6A. However, many computed outputs for the first model were used as inputs for calculating Floor Response Curves which will be explained in 6. With respect to the second model, the calculated results were valuable for the hardware designs of the reactor vessel and its internals.

4.4. Application of Finite Element Method

In the above analyses it was assumed that the input earthquake excitation took place at the bottom of the main building foundation, even though the building hid deeply into the ground and thick soil surrounded the side-walls of the building. A member of ACRS (Advisory Committee of Reactor Safety) asked that it should be clarified what effect due to input excitation taking place along the side walls, especially near the ground surface, might exist for the response of the main building. This question belonged to an academic problem, and we could not reply straightforwardly, however, we performed dynamic response calculation by means of the finite element method referring to the paper by Tsushima et al. [9], for the main building model surrounded by a large amount of soil as shown in Fig. 7. In order to investigate the effect pointed out on the above, two comparable models were selected assuming the two dimentional problem. In the first model the side wall of the building touched the soil, and in the second model certain clearance between the side wall and soil was ideally prepared. The input excitation was El Centro Earthquake normalizing 100 gals acting along the bottom line of the soil model, and physical numbers obtained from soil data were used for [illegible] soil strata.

Looking at the figures of calculated result, for instance regarding the maximum acceleration shown in Fig. 7, much difference appeared between two models in the upper portion of the soil, but in the portion of the building any appreciable deference did not appear, and rather less amplification at the building roof of the first model than the second model was observed. Then the method and results of the usual dynamic analyses mentioned in the above 4.1 through 4.3 were accepted.

5. FUEL ASSEMBLIES AND CONTROL RODS

5.1. Capability of Scramming

The most important problem in the aseismic design of JOYO was whether or not the safety rods can be inserted into the core when a destructive earthquake excites the reactor building. Dynamic behaviors of key items (see Figs. 8A and 8B) relating to this problem will be as follows:

(1) The reactor vessel moves together with the concrete structure,

(2) The core barrel and core cover structure, which are vertical cantilevers, move independently and some relative displacement between the top of barrel and the bottom of cover structure occur in sodium coolant, and

(3) The hexagonal fuel and blanket assemblies lean on the core barrel owing to the existence of clearances between the assemblies, and this amount of deformations is critical.

5.2. Design Modification

In the original design, there were no pads along the outer surface of hexagonal assemblies considering bowing deformation, charging and discharging, and an accumulation of 3.2 mm clearance between each assembly intimated much deformation of the assembly columns. In order to estimate the amount of the above deformation, numerous theoretical calculations were worked out but it turned out a failure since it was a non-linear problem accompanying a chattering vibration.

Therefore, a design conception was reconsidered such that the dimension of every hardware should be appropriate to assure the scramming even if the maximum relative deformation, which can be defined from a possible geometrical relation and not from an analyses, takes place. According to this design conception the following three design modifications were performed:

(1) 3.2 mm clearances between all assemblies were reduced to 1.2 mm by means of new provision, namely additions of 6 pads at the top of assemblies along the hexagonal outside edges,

(2) In the original design 6 control rods were identical, but in the current design the clearances between the rods and their lower guide tubes are 1 mm for 2 control rods and 5 mm for 4 safety rods to give more assured insertion of the safety rods than the control rods, and

(3) 94 mm inside diameter of the upper guide tubes was enlarged to 144 mm giving head to an anticipated large relative deformation.

6. FLOOR RESPONSE SPECTRA

For the designs of vital items, the time history response analyses were made as mentioned in 4.3., however, for the designs of such equipment as piping, etc. classified as As and A classes, a simple and convenient analytical method using the floor response spectra now being generalized in Japan is also applied. In the case of JOYO, two earthquake waves having an isolate characteristic were selected and the range for the spring constants of soil was considered as mentioned in 2.5 and 4.2 respectively. Therefore, a special treatment should be carried out for making the floor response spectra.

As an example, the floor response spectra for the 4th floor which correspond to an elevation suspending the reactor vessel and for 1% of critical damping are shown in Fig. 9. Computer calculation drew the curves A for the hardest soil and B for the softest, and the third C was the artificial design curve. In making the curve C the followings were taken into consideration:

(1) Hill *I* covers the elastic vibration mode of the reactor building which appears in the curve B,

(2) *II* covers the rocking vibration mode which is affected mainly by changing the spring constants of soil,

(3) *III* was drawn judging from the response due to the Akita wave,

(4) The left foot corresponds to the maximum response acceleration of the building at the same elevation, and

(5) The right foot corresponds to the maximum response displacement of the building due to El Centro wave.

7. SODIUM COOLANT PIPING

LMFBR piping design needs a peculiar deliberation owing to its high temperature, thin pipe thickness, double-walled primary system and aseismic supports. First of all, a winding piping arrangement was made to reduce thermal expansion stress as low as possible for the main primary cooling system as shown in Fig. 10, and a trial of the response calculation as the aseismic design is being worked out by fixing or replacing the seismic supports, or hydraulic snubbers. The final winding and locations of supports will be decided by comparing the stresses due to the thermal expansion, thermal shock, seismic vibration, pressure and weight, and this study is now being carried out. An experiment to evaluate a rigidity of the double-walled pipes was made, and a development of new type hydraulic snubber including irradiation and deterioration tests has been performed. As the applicable code USAS B.31.7.0., Nuclear Power Piping and its Case Interpretations were referred to in the design of the piping systems.

8. GRAPHITE SHIELDING STRUCTURE

In order to protect the concrete shielding structure, the graphite shielding structure will be piled up between the reactor vessel and the safety vessel as shown in Fig. 8A. An original conception of the graphite structure was a group of column-type stacks, but this conception was abandoned because no design of an adequate restraint withstanding the earthquakes could be found. Contrary to the original conception, a new proposal was the pile up of sideways graphite blocks connected with the safety vessel by means of outermost hole drilled into each block and vertical steel rod inserted into the hole. A certain clearance between the reactor vessel and graphite structure will be kept not to allow any contamination to the vessel. However, the design of the graphite structure has not yet been finalized, and its model test using a vibration table will be carried out in May, 1971, to evaluate stress distribution, factor of impact, size of key, etc., and Fig. 11 represents the portions of the reduced model.

9. CONCLUSION

Construction work of the containment vessel is being carried out and engineering detail design of many components are also proceeding now. Some outcomes which have been solved or concluded up to this date in the preparation and design stages are mentioned before. We have a responsibility for finalizing the design and construction of JOYO, and we do not know what new bothersome problems in the aseismic design may arise in future, but we should find appropriate solutions on all such cases to the best of our knowledge.

10. ACKNOWLEDGEMENT

Thanks are due to the Power Reactor and Nuclear Fuel Development Corporation for giving us participation in the project and for permitting our presentation of the paper in the conference.

Appreciation is expressed to engineers and research members of the contractor and venders for their assistances and cooperations in the analyses and calculations and to Mr. T. Uchida for his kindful submittal of useful data for earthquake observations at Tokai and Oarai performed by Japan Atomic Energy Research Institute.

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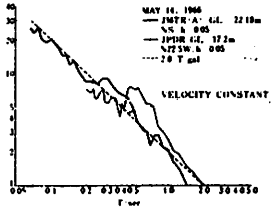

Fig. 1. Response acceleration spectra of earthquake waves observed simultaneously around JMTR and JPDR.

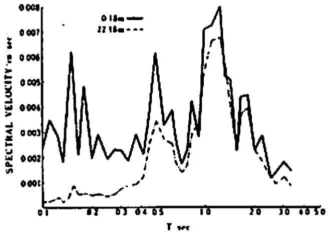

Fig. 2. Fourier velocity spectra of observed earthquake waves.

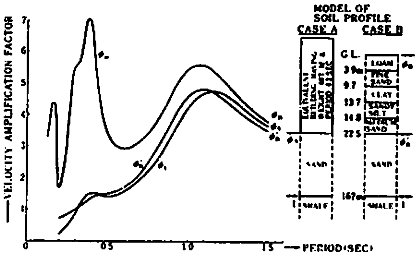

Fig. 3. Theoritical velocity amplification spectra of ground strata.

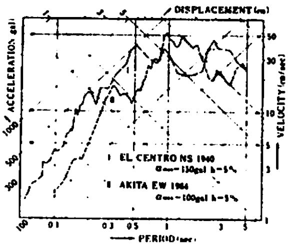

Fig. 4. Response spectra of design earthquake waves.

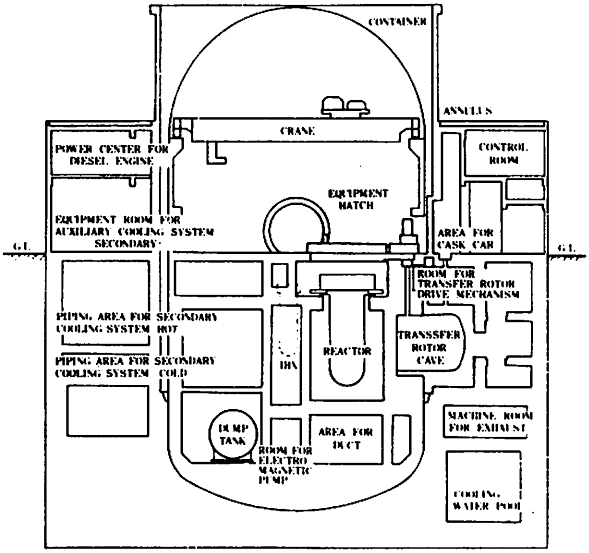

Fig. 5A. Vertical section of main building.

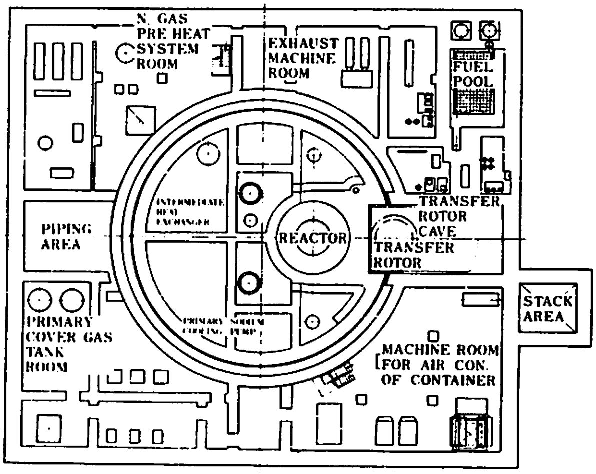

Fig. 5B. Plan of main building at GL.-3.4m.

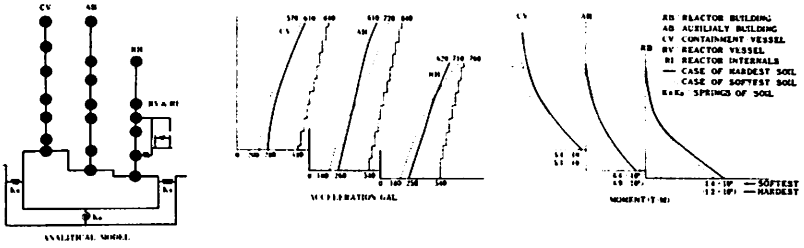

Fig. 6A. Results of earthquake response analysis for the first model, or for buildings and containment vessel.

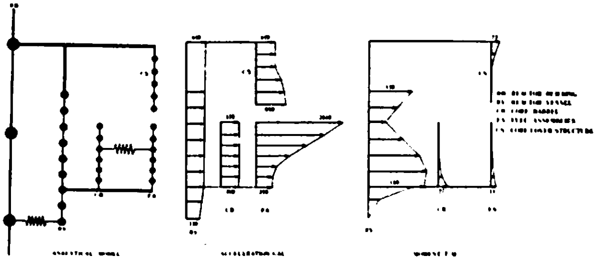

Fig. 6B. Results of earthquake response analysis for the second model, or for reactor vessel and its internals.

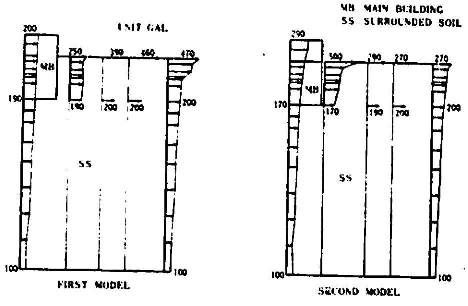

Fig. 7. Responded acceleration for two models of building and surrounded soil by means of finite element method.

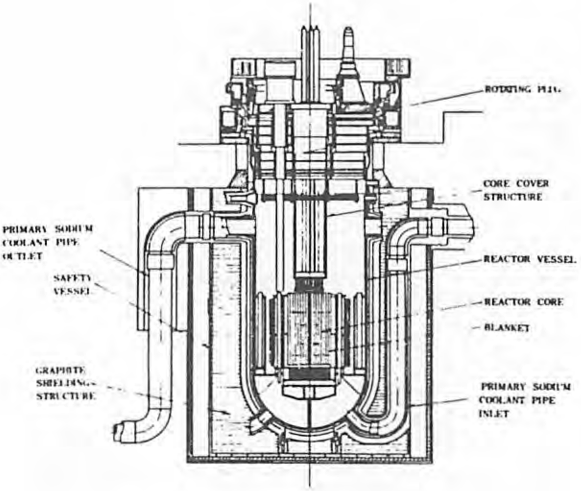

Fig. 8A. Vertical section of reactor structure.

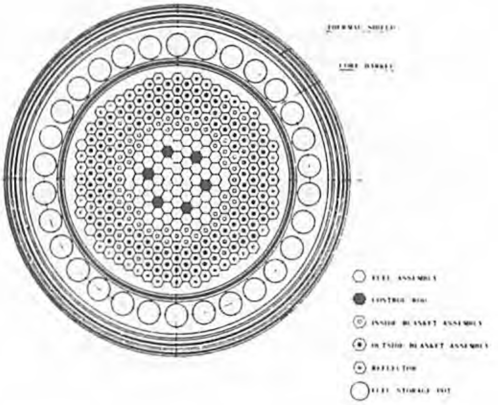

Fig. 8B. Plan of reactor.

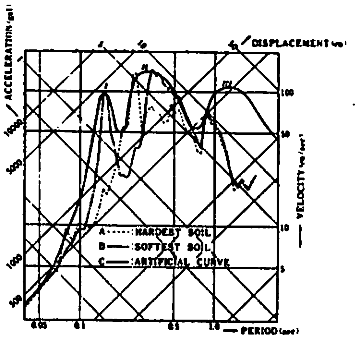

Fig. 9. Typical floor response spectra for reactor building.

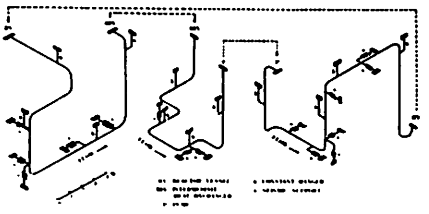

Fig. 10. Analytical model of primary sodium coolant pipe.

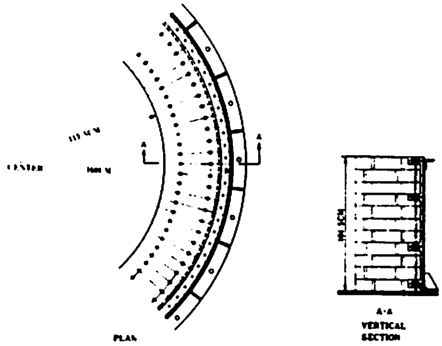

Fig. 11. Model of graphite structure for vibration test.

DISCUSSION

Q C. B. SMITH, U. S. A.

In the vibration tests of graphite shielding:

a) How was the experimental structure tested ?

b) Did your measurements include observations of "impact" between individual graphite blocks ?

c) In your opinion is "impact" likely to be a significant factor after the graphite has undergone radiation damage ?

A K. AKINO, Japan

a) It is the largest shaking table in the world, its owner is Desaster Prevention Center, Japan Government, at Tsukuba in Ibarägi Prefecture. The maximum loading capacity is 500 metric tons, and its control is carried out by displacement of either sinusoidal or random vibrations.

b) We provided accelerometers and U-gauges or pick-up to observe relative displacement of each block. Those records indicate "impact", for instance, 10 g in acceleration.

c) Now, the other group is performing irradiation tests of the graphite material. After receiving our and their data, we should have discussion about that point you asked.