1. INTRODUCTION

The Specialists' Meeting on "Gas-Cooled Reactor Seismic Design Problems and Solutions" was held at General Atomic Company in San Diego, California, USA, 30 August-1 September, 1982. The meeting was sponsored by the IAEA on the recommendation of the International Working Group on Gas-Cooled Reactors and hosted by General Atomic Company. It was attended by 24 participants from the Federal Republic of Germany, Japan, the United Kingdom of Great Britain and Northern Ireland, and the United States of America. The objective of the meeting was to provide a forum for the exchange and discussion of technical information on the seismic behavior of gas-cooled reactors, including descriptions of seismic analysis and testing.

The meeting was opened by Mr. J. Larrimore on behalf of General Atomic Company and by Mr. J. Kupitz on behalf of the IAEA. The technical part of the meeting was subdivided into three sessions. A total of eleven papers was presented by the participants on behalf of their organizations during the meeting, and an opportunity for open discussion of the papers followed each presentation. The programme of the meeting and the list of participants are given in Chapters 4 and 5 of this report.

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2. SESSION SUMMARIES

2A. Summary of Session 1: Seismic Response Analysis and Dynamic Testing, Part A

Chairman: A. J. Neylan

Three papers were presented in Session I. Two related to seismic analysis and testing of the HTGR core; one related to the HTGR steam generator.

The papers on the HTGR core summarized to a large extent the extensive 10-year period. The objective of this task has been to develop seismic core analysis methods for the HTGR and verify these with model testing. The effort was spearheaded by General Atomic in support of the 3000 MW(t) and 2000 MW(t) reference designs for the Fulton and Delmarva nuclear power stations and independent regulatory (NRC) review was performed by National Laboratories, BNL and LANL. A similar development program was also undertaken in Japan for the VHTR as reported in a paper by Mr. K. Tamura in the second part of Session I.

Overall, it can be concluded that the seismic behavior of the HTGR core is well understood. This is largely based on the agreement between the experimental results obtained from the above-mentioned programs. One- and two-dimensional analytical methods incorporating the nonlinear and discontinuous modeling of rigid body core block motions have also been developed successfully. Good correlation between analysis and test results has been achieved within realistic criteria allowing for experimental errors.

The first core related paper, presented by R. C. Dove, focussed on model scaling laws, material selection and model instrumentation. The theoretical difficulties in developing scale models consistent with similitude theory were discussed. The variation in the response of simplified models and the effect of materials of construction in terms of maximum strains in the distorted model system were shown by test. The effect of Coulomb damping was demonstrated by using friction pads at the model element interfaces. The paper concluded:

1. Scale models of block cores can give valid predictions of seismic excitation.
2. Small-scale models may be used.
3. Sinusoidal testing is useful but may constitute severe overtesting.
4. Parametric studies are possible with scale models and, hence, may prove useful during preliminary design studies.

The second paper, presented by H. Shatoff, reported on developments of computer methods for HTGR core seismic design. Specifically, the use of an array processor in conjunction with a main frame Univac computer was presented. The author showed that routine running of large computer programs such as the core seismic codes is now possible. Running costs have been reduced by 50-fold and time, three-fold. Because of this development, three-dimensional analysis of the HTGR core is also within reach.

The analysis of the 1/5 scale HTGR core model was compared to test results for sine-sweep motion. Correlation of frequency characteristics between test analysis was very good (within 10%). Boundary spring load magnitudes also correlated reasonably well.

The third paper, presented by R. Schleicher, covered the seismic design and testing of the current HTGR steam generator. The problems of providing sufficient rigidity in support structures, such that natural resonance frequencies are above the design response spectra thresholds for high amplification factors, were expounded. The problem was compounded by the need to provide relative thermal expansion between the high temperature structures and heat exchanger bundle. The load paths from seismic excitation are, therefore, complex. The need to confirm the same (i.e., transmittal of load from the steam generator tubes and tube support plates to the shroud via tangential loading) and the amount of damping in the steam generator structures will be confirmed by tests currently in progress.

2B. Summary of Session 1: Seismic Response Analysis and Dynamic Testing, Part B

Chairman: K. A. Kleine-Tebbe

This session concerned the seismic response analysis and experimental dynamic testing of very different topics.

First, J. B. Steedman reported about a procedure in which digital signal processing, modal testing and finite element techniques can be used in equipment qualification and acceptance testing. The illustrative example of the use of these techniques involves the seismic (earthquake) qualification of a large Heating, Ventilating and Air Conditioning (HVAC) Control Panel.

This method should demonstrate how a seismic qualification can be made by combined analysis and "soft" testing techniques.

The presentation of K. A. Kleine-Tebbe considered the seismic response of the core cavern of a pebble bed HTR. The safety and integrity of the Prototype THTR-300 could be demonstrated using a simplified calculational model.

In view of present day licensing practices and the higher ground accelerations to be assumed, the need for experimental testing occurs. The experiments with scaled down models of the pebble bed system inducting the side reflector shall be carried out on the new high performance seismic test facility SAMSON and should verify the analytical models in very highly damped systems. The results of the seismic tests with the KLAK-system have been presented.

The report of K. Tamura concerned the large seismic test program, which was initiated in 1975 to study the dynamic response of the experimental VHTR core arrangement to seismic excitation.

Many data on the response characteristics of columns and the effect of the side support stiffness on the core vibration characteristics were derived from the basic tests with different core section models. The test results are as follows:

-- soft side support reduces the reaction forces

-- hard side support reduces the block deflection

-- preloading on side support spring is useful for reduction of reaction force and block deflection.

Some computer codes which were developed by using the test results showed a good correlation with the experimental results. Improvement of the codes will be made in order to achieve better correlation with the experiments with a highly nonlinear system.

Finally, K. Peters reported on calculations in which external events--earthquake and aircraft impact--are considered to estimate the response of a modular gas-cooled HTR. The modular concept consists of some (e.g., four) small reactor units in a common reactor building. Each unit is connected to a steam generator by a hot gas duct.

To reduce the loads to the components inside the building, a special building design is proposed in which the components are decoupled from the effects of aircraft impact, while in the case of an earthquake, the advantage of monolithical behavior will still be achieved.

The following extensive discussions concerned mainly the special topics of the presentations.

More generally the different well known methods for seismic qualification of reactor buildings and components using analytical models and computer codes have been discussed. In the case of nonlinear structures with rather high damping, the calculation of seismic response of the reactor parts will be difficult and can lead to a very conservative construction according to pessimistic assumptions for model parameters. The experimental work, which has been done and will be continued, has the goal to improve the analytical codes by fitting the parameters to the experimental results.

2C. Summary of Session II: Seismic Criteria and Methods

Chairman: C. M. Charman

Five scheduled papers and one impromptu presentation spurred by general interest from the audience were presented in Session 2. The first paper was devoted to seismic design criteria selection for the US HTGR. Two papers were devoted to the treatment of soil-structure-interaction problems associated with gas-cooled reactors. Two papers covered seismic evaluation and qualification studies on gas-cooled reactor plants in the UK. The final presentation concerned a study of ground acceleration versus the response of mechanical and electrical equipment taken from records of actual earthquakes.

The first paper, presented by H. Gotschall and P. Yanev, discussed the basis for the establishment of seismic design criteria for the US HTGR reactor plant. The criteria selection is based on the concept of a "standard plant" which is capable of being replicated on a wide range of sites of varying seismic design levels and various soil profiles.

Four general areas were addressed:

1. Design peak acceleration regionalized over the continental US.

2. Geotechnical data and seismic design parameters for existing US plants.

3. Shear wave velocity profile regionalized over the continental US.

4. Review of acceptability of soil-structure-interaction methods for HTGR analysis.

A contour map of the US was presented showing safe shutdown earthquake levels. Sites on the west coast of California were deliberately excluded from the study. These sites would require review on a case-by-case basis. The report concluded that an OBE/SSE design level of .15/.30g will cover 80 to 90% of available sites in the continental US. Soil profiles shear wave velocities ranging from 1000 ft/sec to 8000 ft/sec should be considered in parametric standard plant design studies.

Various methods for soil-structure-interaction were also discussed. These methods have been demonstrated to be based on sound mathematical principles. However, significant attention should be paid to accurate modeling of features such as mat flexibility, variation in soil properties, back fill, etc. The characterization of plant seismic capability at a specific site will probably require a combination of finite element and continuum solution methods to ensure that the results are not method dependent.

The initial soil-structure-interaction paper, presented by J. P. Wolf, covered the theoretical development of a frequency dependent stiffness matrix for a surface foundation on a layered half space. The method is applicable to flexible or rigid foundations of arbitrary shapes. The dynamic stiffness matrix appears in the basic equations of motion for soil-structure-interaction analysis based on the substructure approach.

Over the years there has been considerable controversy over which methods of soil-structure-interaction analysis are correct. The concern is whether or not soil-structure-interaction analyses will lead to the same result if correct modeling techniques are used. The burden is placed on the analyst to ensure consistent modeling.

A number of the results presented compared half-space and two-layer soil conditions for both two- and three-dimensional cases. Comparison of a two-dimensional approximate solution with a three-dimension solution to the disk on the half-space was made. The two-dimensional solutions were shown to overestimate the damping, which could lead to unconservative results. The two-layer soil case sometimes shows a strong dependency on frequency; however, no firm conclusion could be reached regarding the accuracy of the solution. The paper concluded that three-dimensional analysis is now possible and two-dimensional approximation with the resulting uncertainty is unnecessary.

The second soil-structure-interaction paper, presented by T. H. Lee, began with a brief discussion of the history of soil-structure-interaction analysis of nuclear plants from 1967 to the present. Comparative studies were shown covering the effects of through soil coupling on the response of a power plant complex consisting of the HTGR NSSS and control/turbine building. Results were presented comparing the response of various versions of the HTGR plant for surface founded conditions using frequency independent soil springs and solutions using finite element approaches accounting for embedment. The effect of embedment caused a general reduction in the seismic response level of the plant without an appreciable change in the shape of the design spectra.

The results of a simplified inelastic analysis of a plant subjected to a horizontally traveling shear wave were also presented. These results showed the effect of foundation filtering and reduction of motion due to nonlinear soil effects.

The fourth paper, presented by J. Day, reported on the seismic qualification of the Heysham II AGR. The discussion began with a review of the history of the Heysham II AGR reactor. The plant was intended to be a duplicate of the Hinkley Point "B" design with additional seismic requirements. The seismic design level was selected at .25g which corresponds to an event probability of approximately 10^{-4} per year. The seismic specification was taken as a target and not as a rigid requirement and some latitude in interpretation of results was allowed. The overall station modeling with the FLUSH computer code and the strategy for qualification of plant equipment were discussed. A combination of limited testing and linear and nonlinear analysis is employed.

Several areas of the plant were found to require some design changes in order to meet the seismic criteria. Modifications were made to the key system between the core and the gas baffle and the fuel handling machine. The piping system required the addition of approximately 1000 hydraulic snubbers which were designed to fail free. It was established that the oil and seals would be changed every five years. The electrical steel work required modification and is currently being analysed using nonlinear methods.

The final presentation was made by K. Fullard, who reported on the seismic evaluation of early Magnox stations. The presentation covered an evaluation of the seismic capability of the stations at Chapel Cross and Calder. This work was required by the NII to establish what earthquake level the stations could withstand.

The overall plant model was based on a mixed method where an explicit finite difference technique was used for the soil and an implicit technique was used for the superstructure. Low level in-structure testing showed good correlation with the first mode at 4 Hz. No damping data was collected.

The following limits were established for the critical components:

1.	Pressure vessels and supports	.20g
2.	Diagrid (core support)	.40g
3.	Core cooling blockage due to shearing of keys	.90g
4.	Core structure sliding on radial keys	.11g
5.	Ducting	.10g
6.	Steam generator tube bundle	.12g

It was concluded that the plant could withstand a .10g free field motion without concern. This level of earthquake would have a return period of between 1000 to 5000 years at the plant site.

The session concluded with an unscheduled presentation by P. Yanev. After hearing the presentation on the seismic evaluation of the early Magnox stations by K. Fullard, he felt that he had information which might be of interest to the CEGB people and the working group in general.

The presentation focused on the bahavior of power station equipment during actual earthquakes. Data collected for four California earthquakes, ranging in magnitude from 5.5 to 6.6, was presented. The discussion centered on 2600 pieces of equipment in 24 power station units which was subjected to the San Fernando quake of 1971. Of the 2600 components studied only one failure had occurred. This failure was in an air-actuated valve and resulted from an impact with a girder after 4 inches of deflection. No pipe failures occurred in piping greater than 1/2" in diameter and no electrical conduits failed. The power plants experiencing 0.35g and lower ground motion stayed on line generating power. Of four plants experiencing 1.4g and above, two plants lost power and two tripped but stayed on line. The conclusion was reached that if power plant equipment is anchored adequately to survive a static acceleration of .25g it could be expected to survive an earthquake at between .2 to .3g ground motion.

2D. Summary of Session 3: Round Table Discussions

Chairman: K. Fullard

In discussing gas-cooled reactor seismic design problems and solutions it was clear that there is a wide variety of types of gas-cooled reactor and that there had been omissions in those considered--for example, nothing had been said about gas-cooled fast breeder reactors. What were the special factors which make the aseismic design of gas-cooled reactor plant different from other systems? To various extents these included temperature, plant mass and multi-degree of freedom cores.

The specialists found difficulty in restricting their thoughts to the specific topic, and generic issues such as soil-structure-interaction analysis methods, the desirability of non-response spectrum analysis techniques and risk analysis appeared in the discussion. It was pointed out that there is the opportunity for wider discussion of these matters at the Structural Mechanics in Reactor Technology Conferences held every two years.

It was clear that a significant period of time must elapse before the specialists could reassemble to consider further developments on core analysis, modular HTR concepts and other topics relevant to gas-cooled reactors. It was decided that the International Working Group should be recommended to arrange a further specialists' meeting in three years' time.