



Structural Analysis Research Needs for Advanced Reactors

Syed A. Ali, Herman L. Graves, III

Office of Nuclear Regulatory Research
United States Nuclear Regulatory Commission, Washington, DC 20555-0001, U.S.A.

ABSTRACT

Historically, the USNRC has been committed to the use of U.S. industry consensus codes and standards for the structural analysis, design, construction, and licensing of commercial nuclear power facilities. The existing industry codes and standards are based on the current class of light water reactors (LWRs) and as such may not adequately address analysis, design, construction, and licensing issues of the advanced light water cooled reactors (ALWRs) such as AP-1000 and International Reactor Innovative and Secure (IRIS) and other types of High Temperature Gas Cooled Reactors (HTGRs) such as Pebble Bed Modular Reactor (PBMR) and Gas Turbine Modular Helium Reactor (GTMHR). As part of its commitment to participate in the development of industry standards, the USNRC plans to conduct research that will involve the review and study of the new and unique features of design basis documentation of the ALWRs and HTGRs.

KEY WORDS: nuclear power plants, high temperature concrete, soil-structure interaction, advance reactors, codes and standards, structural engineering, research needs, gas cooled, seismic analysis, inservice inspection, Nuclear Regulatory Commission.

INTRODUCTION

Historically, the NRC has been committed to the use of U.S. industry consensus standards for the structural analysis, design, construction, and licensing of commercial nuclear power facilities. The existing industry standards are based on the current class of light water reactors (LWRs) and as such may not adequately address analysis, design, construction, and licensing issues of the advanced light water cooled reactors (ALWRs) such as AP-1000 and International Reactor Innovative and Secure (IRIS) and other types of High Temperature Gas Cooled Reactors (HTGRs) such as Pebble Bed Modular Reactor (PBMR) and Gas Turbine Modular Helium Reactor (GTMHR).

The NRC research effort will evaluate the containment, aging, inspection, material aspects, and challenge of external events for the PBMR, GTMHR, AP-1000, and IRIS reactor designs. Based on the findings of the proposed research plan, the staff will be able to determine the need to maintain current deterministic LWR requirements for containments, structures, systems and components or recommend that performance based and/or risk-informed criteria be used to evaluate the acceptability of proposed advanced reactor designs.

In the proposed PBMR reactor vessel internal structure design, the ceramic reflector structure consists of graphite blocks with holes for control rods. Therefore, it is necessary to retain alignment through vertically arranged blocks that are supported vertically by a dowel system, and circumferentially by a radial keying system. For the AP-1000, fuel tubes are taller than conventional designs and the seismic margin is controlled by fuel design. Research is needed on these tall structures since they are subject to nonlinear response during horizontal and vertical earthquakes.

Current soil-structure interaction computer codes are based on structures founded at or near the ground surface. Research is needed to evaluate the responses of new reactors that may be deeply or completely buried in-ground.

In the new HTGRs, concrete structures may be subjected to sustained high temperature. Research is needed to accumulate and expand existing data on effects of high temperatures on properties of concrete. This data is available in various U.S. and international journals, transactions, and proceedings as well as in earlier research by Brookhaven National Laboratory [1], Sandia National Laboratory, and Oak Ridge National Laboratory.

In the mid 1990's, the use of structural modules was proposed for advanced nuclear power plants: 1) Westinghouse's Advanced Pressurized Water Reactor AP-600; 2) General Electric's Advanced Boiling Water Reactor ABWR; and 3) Combustion Engineering System 80+. The objective in utilizing modular construction is to reduce the construction schedule, reduce construction costs, and improve the quality of construction. During the 1995-1997 time frame, NRC conducted research, which evaluated the proposed use of modular construction for safety-related structures in the advanced nuclear power plant designs. The research program included a review of current modular construction technology, development of preliminary licensing review criteria for modular construction, and initial validation of currently available analytical techniques applied to concrete-filled steel structural modules proposed for the AP-600.

The program findings were documented in NUREG/CR-6486, "Assessment of Modular Construction for Safety-Related Structures at Advanced Nuclear Power Plants,"[2]. The key findings of this research were the need for evaluation criteria and the need for verified design/analysis methodology for unique types of modules, such as the concrete-filled steel plate modules.

Because of new reactors' commitment to risk-informed processes, it is anticipated that existing inservice inspection (ISI) requirements for containment structure and structural components will be replaced or augmented by risk-informed ISI (RI-ISI) programs. Independent research is needed to work with the industry to develop methodologies for RI-ISI of containment and associated components such as liners, bellows, and prestressing hardware.

PURPOSE

The purpose of this research activity is to develop the criteria for the structural and seismic evaluation of the new features of advanced reactor designs. The advanced reactor designs that deviate from current practice need to be reviewed to ensure that a level of safety equivalent to that of currently operating LWRs is provided, and that uncertainties in the design and performance are taken into account. For those unique features or areas that are not similar to existing operating nuclear reactors, the USNRC staff will need to conduct research to provide the technical basis for regulatory decision-making. Research is also needed to improve NRC's knowledge and understanding of new phenomena for which analytic methods and analyses are not currently available to the staff. The areas in which research may be conducted include: (1) nonlinear seismic analysis of reactor vessel and core support structures, (2) seismic soil-structure interaction analysis of deeply embedded or buried structures, (3) effects of high temperature on properties of concrete, (4) issues related to modular construction, and (5) risk-informed inservice inspection (RI-ISI) methodologies for containment and associated structures.

OBJECTIVE

The USNRC staff's research effort will evaluate the containment, aging, inspection, material aspects, and challenge of external events for the HTGRs, AP-1000, and IRIS reactor designs. Based on the findings of the proposed research, the staff will be able to determine the need to maintain current deterministic LWR requirements for containments, structures, systems and components or make recommendations related to the use of performance based and/or risk-informed criteria to evaluate the acceptability of proposed advanced reactor designs.

STRUCTURAL ANALYSIS RESEARCH CONSIDERATIONS

Nonlinear Seismic Analysis Of Reactor Vessel And Core Support Structures

The NRC research is aimed at developing an independent capability to evaluate the seismic integrity of the unique and new design features of advanced reactors. Research performed by research and development organizations and regulators will be reviewed for applicability and to determine gaps where additional research is needed. Analytical and experimental research may be conducted to develop seismic and structural analysis models of reactor vessel internals and core support structures and perform seismic analyses for horizontal and vertical earthquakes. The assumptions and limitations of existing finite element analysis codes will be evaluated for applicability to the nonlinear configurations

such as the PBMR reactor components consisting of nonductile graphite core reflectors and supports. There is special need to perform experimental verification of the seismic response of the first-of-a-kind design of PBMR internals.

Research may be conducted on the nonlinear static and dynamic structural analysis of advanced reactors with long fuel tubes and core support structures whose seismic margin might be controlled by the fuel design. For the PBMR reactor, fuel pebbles will be piled into a considerably tall configuration resulting in nonlinear responses during horizontal and vertical components of earthquakes. Research may be conducted to perform linear and nonlinear elastic and plastic stress analyses due to the dead weight and seismic events taking into account contact stresses between the spherical pebbles of the tall piles of fuel pebbles.

Soil Structure Interaction Analysis Of Deeply Embedded Or Buried Structures

For two of the new reactor designs, the entire reactor building and a significant portion of the steam generator building will be partially or completely embedded below grade. For the analysis of seismic events, the soil-structure interaction (SSI) effects and passive earth pressures for these types of deeply embedded structures will have a significant influence on the analytically predicted seismic response. Research experience in the area of seismic analysis and design of tunnels and buried piping will be utilized to the extent applicable.

Current seismic SSI analysis computer codes used in the nuclear industry have been developed for and applied to coupled soil-structure models where the structures are founded at or near the ground surface with shallow embedments. These computer codes have been developed to determine the seismic responses such as amplified response spectra, forces, and moments, that are required for the detailed analysis and design of structures, equipment and piping, taking into account the interaction between the soil and the structure during seismic events. These computer codes will need to be modified for applicability to deeply embedded structures. It is likely that kinematic (vertical and horizontal motion of the structure) interaction effects are more important for deeply embedded structures during seismic events than for conventional plants. It is also likely that dynamic and passive earth pressures on deeply embedded structures will be more important and may require better definitions than are now available.

This research will focus on developing independent and state-of-the-art analytical and experimental capability to determine the coupled seismic SSI responses for deeply or completely buried structures during horizontal and vertical earthquakes. The research will also include shake table studies for the experimental verification of analytical results.

High Temperature Concrete

This research effort will be to investigate the change in concrete properties when it is subjected to sustained high temperatures. In the current American Concrete Institute (ACI) Code [3], the temperature limits specified for concrete are 65.5° C for long term, 93° C for short term, and 149° C for local effects.

The operating temperatures of the primary reactor vessels for some of the advanced reactors designs being considered are greater than those for currently licensed nuclear power reactors. Therefore, depending on the effectiveness of the reactor vessel insulation and cooling system, the concrete reactor building could experience a high temperature environment. Elevated temperatures can reduce the strength and stiffness of concrete due to de-watering effects as well as cause degradations such as cracking and spalling.

This research will include data accumulation and expansion of existing databases. Significant information regarding high temperature effects is available in the literature, including journals, conference transactions, and proceedings. Lessons learned from facilities where concrete was found to be subjected to high temperatures for long durations will also be investigated and utilized.

Modular Construction

Modular construction has not been used in the U.S. for nuclear power plants but some techniques have been used in Japan. It has been proposed by the PBMR, GTMHR, AP-1000 and the IRIS designers to use modular techniques in structural elements inside the containment which must survive seismic loading events. Technical issues relate to the strength and ductility of the module, of the joints and connections as well as appropriate damping values for seismic analyses. Presently, U. S. codes and standards guidance is lacking or non-existent for the design of concrete-filled steel plate wall and foundation modules, and for the design of the connection of the concrete-filled module to a concrete-filled

steel plated foundation module.

This research effort will focus on developing evaluation criteria that will facilitate review of reactors that use modular construction. The NRC staff plans to use the results of earlier research described in NUREG/CR-6486. Calculation methods will be verified based in part on available test data on structural modules such as concrete-filled steel modules. Recommendations on the acceptability of industry codes, ACI 349, "Nuclear Safety Related Concrete Structures," and AISC, N690, "Nuclear Facilities-Steel Safety Related Structures-Design Fabrication and Erection" [4], and required code changes may be made. Regulatory guidance may be established or revised as necessary to reflect the state of the knowledge.

With respect to international agreements, the Japanese nuclear industry has made use of modular construction techniques and has traditionally invested a great deal of resources in testing to demonstrate the design's capabilities. To make use of this research and establish cooperative research efforts it is necessary to establish what research has been completed and what efforts may be underway. In 1997 the NRC staff published NUREG/CR-6486, which discusses some of the Japanese test results and efforts at that time. One of the recommendations of NUREG/CR-6486 was that a "cooperative program be developed to share information...which would provide valuable data useful in verifying the safe application of structural modules in nuclear power plants within the United States."

Risk-Informed Inservice Inspection (Containment And Associated Structures)

Because of new reactors' commitment to risk-informed processes, it is anticipated that existing inservice inspection (ISI) requirements for containment structure and structural components will be replaced or augmented by risk-informed inservice inspection (RI-ISI) programs. Research will be conducted to develop RI-ISI methodologies for ISI of containment and associated components such as liners, bellows, and prestressing hardware. Recent experience with the application of RI-ISI methodologies to ISI of piping has indicated that inspection resources need to be focused on risk-significant areas and that inspection methods should be tailored to the potential degradation mechanisms. Existing inspection requirements have been found to be excessive and not focused on locations where cracks and leaks have been discovered.

American Society of Mechanical Engineers (ASME) has formulated a Task Group to develop methodologies for RI-ISI of containments. The staff will actively participate in this Code activity while independently developing the methodologies for RI-ISI of containments. Research for this item will include compiling data on degradation mechanisms for structures, developing appropriate inspection strategies for these degradation mechanisms, and defining risk categories based on potential degradation mechanisms and consequences of failure. ISI parameters such as the amount of inspection and frequency of inspection will be based on the risk categorization of the structural component. It is expected that the RI-ISI approach will result in focusing inspections on risk-significant areas while reducing unnecessary regulatory burden.

CURRENT RESEARCH ACTIVITY

Currently, we have initiated a program to investigate the applicability of existing seismic soil-structure interaction (SSI) computer codes to deeply embedded or buried (DEB) structures and to recommend any necessary modifications to the SSI computer codes. For two of the new reactor designs submitted to the NRC for preliminary review [PBMR, HTGR], the entire reactor building and a significant portion of the steam generator building will be partially or completely embedded below grade. For the analysis of seismic events, the SSI effects and passive earth pressures for these types of deeply embedded structures may have a significant influence on the predicted seismic response. Research performed by other research and development organizations and regulators will also be reviewed for applicability and to determine gaps where additional research is needed. Research experience in the area of seismic analysis and design of tunnels and buried piping will be utilized to the extent applicable in our current effort.

Efforts to date include the review of existing standards, tests, and practices that have been used in the design and analysis of DEB structures. The computer codes, especially the program entitled "A System for the Analysis of Soil-Structure Interaction" [5], will be reviewed pertaining to its applicability to the SSI analyses for DEB structures.

Current efforts also include an evaluation of NRC seismic analysis guidelines as outlined in the Standard Review Plan (SRP) in light of proposed advanced reactor design features. Based on this limited review of the existing technologies for SSI analyses, gaps that exist in knowledge and potential issues that may require better understanding have been

identified. The approach for addressing these issues in subsequent work is outlined below:

- 1) A retrospective look at the literature with respect to both analytical and experimental treatment of the seismic response analyses of DEB structures;
- 2) Review of the relevant design codes, standards, and regulatory guidelines to determine their applicability and limitations in the seismic design and analyses for DEB structures;
- 3) Discussion of existing recorded data identified as a result of a search of the open literature and the relevance of the data to DEB structures (includes both actual field measurements of past earthquake events, including free-field and structural response, and data from simulation tests);
- 4) Development of benchmark models for the SSI analyses of DEB NPP structures;
- 5) Review of computer codes with respect to their potential application to the seismic analyses for DEB NPP structures;
- 6) Finally, potential issues identified as a result of the review of the open literature with respect to SSI effects for DEB structures.

It is expected that the findings and recommendations from this current effort will be used either to confirm the applicability of existing criteria or to develop new acceptance criteria, if necessary, for guidance to NRC staff for seismic evaluations of DEB NPP structures.

CONCLUSION

The research that needs to be done for structural analysis, design, construction, and licensing issues of the advanced reactors has been identified by considering the gaps in the current knowledge and lessons learned from licensing operating reactors. In addition this evaluation of structural research needs has attempted to factor in the work being performed internationally. Subject to availability of resources NRC research staff will continue to explore cooperative agreements and technical exchanges to supplement its knowledge base.

DISCLAIMER

The contents of this paper are based on the authors' knowledge and their work for the Office of Nuclear Regulatory Research. However, the paper is an independent product of the authors and does not necessarily reflect the views or regulatory position of the NRC.

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