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SEISMIC AND CASK DROP EXCITATION EVALUATION OF THE TOWER SHIELDING REACTOR

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ABSTRACT

During the current shutdown of the Tower Shielding Reactor II (TSR-II), analyses were performed to determine the effect of nearby cask drops on the structural and mechanical integrity of the reactor. This evaluation was then extended to include the effects of earthquakes. Several analytic models were developed to simulate the effects of earthquake and cask drop excitation. A coupled soil-structure model was developed. As a result of the analyses, several hardware modifications and enhancements were implemented to ensure reactor integrity during future operations.

INTRODUCTION

The Tower Shielding Reactor facility was built in 1954 and is now used as a low power radiation source for radiation shielding experiments. In the past, the TSR site was also used as a test facility for dropping spent fuel casks weighing up to 50,000 pounds.

After the TSR-II was shut down in 1987 following technical concerns at the High Flux Isotope Reactor, independent review teams recommended that several assessments be performed before restart. The first of these was to determine the effects of past cask drops at the TSR facility on the structural and mechanical integrity of the TSR-II. The second was to evaluate the response of the reactor to a seismic event. EQE was requested to perform both of these evaluations. Several analytic models were developed to simulate the effects of cask drop and earthquake excitation. The analyses were performed in the time domain. The cask drop analysis utilized accelerometer data from 5,000- and 12,900-pound cask drops. The seismic analysis used an acceleration time history matched to a 0.15g Newark-Hall response spectrum.

PLANT DESCRIPTION

The TSR facility is located at the Oak Ridge National Laboratory in Oak Ridge, Tennessee. It is a pressurized, light water moderated and cooled reactor operating at a maximum of 1 MWt. The core is spherical in shape and consists of curved uranium-aluminum fuel plates with safety control plates inside the fuel annulus. The reactor vessel sits inside of a concrete shielding structure (Big Beam Shield) consisting of 5 feet of concrete on three sides and a movable neutron beam shutter on the fourth side (Figure 1).

ANALYTIC MODELS

The reactor vessel is composed of two major structural elements: the reactor pressure vessel and the reactor internals. The pressure vessel is basically a cylindrical aluminum tank with a hemispherical bottom and a circular cover plate (head). The tank is approximately 8 feet long and 3/4 inch thick; its inside diameter at the hemispherical (lower) end is 37 inches, and 40 inches at the upper end. The reactor vessel is supported in the vertical direction only at the bottom

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surface of the flanged connection to the vessel head.

While the reactor internals are considerably more complex than the pressure vessel, the two major structural components consist of the central cylinder assembly and the ionization chamber/lead shield (lead shield). The central cylinder is a 17-inch diameter (inside) tube suspended from the reactor head and co-linear with the vertical axis of the vessel. It travels the full length of the reactor and supports the reactor core fuel elements. The central cylinder also provides the majority of the lateral load resistance for the reactor internals. Four tabs around the bottom edge of the central cylinder fit between lugs fastened to the 3/4-inch thick hemispherical aluminum shell surrounding the lower fuel elements with a small gap. If the bottom of the central cylinder displaces laterally and closes this gap, the lugs provide support for the cylinder, changing its behavior from a free to a propped cantilever.

The control support tube assembly is located within the central cylinder and supports the control mechanism and the upper fuel elements. The lead shield fits within the central cylinder and is also suspended from the reactor head. There is a 1/8-inch gap between the lead shield and the central cylinder, allowing independent structural response as long as this gap is not closed. Figure 2 shows a simplified view of the reactor illustrating the gaps between the central cylinder and reactor vessel, as well as between the central cylinder and lead shield.

COUPLED SOIL STRUCTURE MODEL

A coupled soil structure model was developed for the seismic evaluation. The earthquake motions are broad banded dynamic excitation, and coupled soil structure response is an important contributor to overall system performance. The beam shield structure was modeled to predict the frequency of vibration for the combined soil and shield structure. The soil structure interaction (SSI) problem was solved in the frequency domain by the substructure approach using the CLASSI computer code. The key elements of this method were: specification of the free-field ground motion, representation of the foundation impedance, and representation of the dynamic characteristics of the structures. These elements were combined in the SSI analysis to calculate the response of the coupled soil-structure system. The free-field motion was represented by an orthogonal triad of acceleration time histories at the ground surface. The foundation impedances were represented by frequency-dependent, complex-valued matrices; the impedance matrix for a single rigid foundation was a 6 x 6 matrix relating six force components to six displacements. The structures were represented by their fixed-base eigen-systems and modal damping factors, and pseudo-static modes and foundation coupling stiffness matrices. These structural input data were obtained from analyses using finite element programs. The SSI response calculations were performed using Fourier analysis techniques.

REACTOR MODEL

The shield structure model utilizes a shear beam representation of the structure. The reactor vessel is coupled with the shield model at the reactor support sleeve. The reactor vessel model includes the reactor internals composed of the two major substructures, the internals central cylinder, and the ionization chamber guide assembly and lead shield.

The model includes a 3-dimensional representation of the reactor vessel and the central cylinder as two cantilever beams coupled at the reactor vessel head, which is connected at the support sleeve to the shield structure. The vessel head is assumed to be a rigid coupling member. The guide tube-lead shield assembly model includes the vertical support members and the asymmetric affects of the guide tube attachment of the lead shield. Node locations are chosen to coincide with locations of mechanical connections, critical stress locations, or where displacements are deemed important for determination of gap closures. The single finite element model (Figure 3) developed to represent the major structural components of the TSR-II: the shield structure and foundation, the reactor vessel, the central cylinder, and the lead shield is shown.

The half-space stiffness matrix at the base of the model was calculated using a rigid foundation mat with a size of 15 by 20 feet and represented the soil stiffness properties in translation, vertical and rocking directions. This matrix was developed for cases which envelope the shallow clay soil site conditions. Limited soil boring data indicate a predominantly medium clay material underlying the shield beam structure. Values of soil shear wave velocities of 600, 900, 1350, and 3500 fps were selected which envelope a range from medium clay to rock-like soil stiffness. Time history analyses of the coupled soil, support structure, and reactor vessel model were run for each soil property value.

Nonlinear dynamic effects of the response, interaction, and possible coupling forces between two reactor internal structures were recognized. These are the response of the central lead shield structure within the small (1/8 inch) annular space formed by the internal central cylinder (Figure 2). When a structural component vibrates in a viscous fluid, fluid-structure interaction effects gives rise to a fluid force which can be characterized as an added mass and damping contribution to the dynamic response of the component.

Analytic and correlated test studies have been performed by several investigators of this effect. These effects were quantified to determine the added effective mass and damping effects. The calculated added mass and damping effects on the lead shield were 81 times the nominal mass and 12% of critical, respectively. This model is called the "uncoupled" internals model. A second "coupled" model was also utilized which assumed the lead shield and central cylinder interaction results in completely coupled response.

CASK DROP

Two drop tests of 30-foot height were performed and measurements of the response of the TSR-II were made. The casks differed in weight (5,000 and 12,900 pounds) and provided information on the TSR-II response as a function of load level. The top head of the vessel was instrumented with two 3-component accelerometers. The time history recordings were processed as follows:

(1) The two vertical records are averaged time-step by time-step to obtain the time history of vertical acceleration.

(2) The two vertical records are subtracted time-step by time-step and the resultant scaled by the reciprocal of the distance between the instruments to obtain the rocking time history.

CASK DROP ANALYSES

The dynamic response of the TSR-II was predicted using the processed acceleration time histories as input motion at the top of the reactor model without the beam shield structure portion of the model. The structural system was analyzed with the computer code SSIN, which uses the mode-superposition method of dynamic analysis in the time domain, and assumes a linear multiple degree of freedom model.

Using the time histories from the 12,900-pound (12.9K) drop, the model was run using the coupled and uncoupled model described above. Displacements and velocity time histories at the critical clearances between reactor internal structures were obtained.

The central cylinder responds to the input motions as a cantilever with a fundamental frequency of 20.7 Hz, and its maximum tip displacement just exceeds the clearance to the bottom guides. Energy transfer upon impact with the bottom guides is negligible, since the tip velocity is approaching zero. The lead shield responds to the input motion as a cantilever, with a maximum displacement much less than 1/8 inch, insufficient to cause impact with the central cylinder. Physically, the internal behavior can be thought of as the central cylinder rattling between the bottom guides at a frequency near 21 Hz and the lead shield oscillating independently around 3 Hz.

The analyses of both the lead shield and central cylinder were extrapolated to a 50K drop test by assuming a linear increase in the amplitude of the input acceleration time histories.

SEISMIC ANALYSES

Response time history analyses were performed for the combined soil, beam shield structure, reactor-coupled lead shield and central cylinder model. Response parameters versus time were calculated for each node of the model. The response of this coupled soil and structure system envelope the effect of assumptions on soil shear wave velocity by computation of response for soil shear wave velocities of 600, 900, 1350, and 3500 fps. As the soil stiffness increases, the coupled soil-structure frequency varies from 7 Hz to 15 Hz. For the 3500 fps case, rock-like soil conditions, no significant soil-structure response frequency was exhibited (Figure 4).

The reactor internals, the central cylinder, and lead shield respond to the input motions as a cantilever. The envelope displacement response of the uncoupled internals model indicated no impact of the central cylinder with its bottom stops. The displacement response of the lead shield was 1.8 inches, however, much greater than the 1/8-inch clearance to the central cylinder and therefore impact would occur. With impact, the response of the system cannot be characterized as linear elastic and harmonic, but is nonlinear, forced dynamic response.

NONLINEAR RESPONSE STUDY

A one degree of freedom model of the lead shield was developed and its response to the time history of motions at the reactor vessel head over the range of soil parameters was solved. The solution was performed using a direct step wise integration procedure of the equations of motion developed by N. C. Nigam and P. C. Jennings of the California Institute of Technology.

A computer code was used to perform the Nigam-Jennings procedure. A modification was made to check for each time step "t" that the clearance between the shield and central cylinder is less than 1/8 inch. When contact was made, the velocity V of the lead shield was set to -V and the direct solution was continued. This solution represents forced dynamic motion, impact, and fully elastic rebound of the lead shield off of the central cylinder.

Acceptable values of impact velocity were developed using energy balance techniques. The nonlinear gap conditions were approximated by using an energy balance approach at the point and time of impact (gap closure) to distribute loads to the structural elements. This method used the velocity at closure to define the kinetic energy of the system, and equates this to the strain energy of the resisting members. The equivalent static loads were then calculated. Allowable component member stresses were computed using simplified analytical techniques to distribute the forces resulting from the dynamic analysis.

RESULTS

The acceptable values for both cask drop excitation and seismic were found to be controlled by the strength of the central cylinder screw joint. Thirty-two stainless steel screws connect the upper and lower halves of the central cylinder. The lower portion of the central cylinder is fabricated of 6061 T6 aluminum alloy and the upper section is 5052 aluminum.

The conclusion reached was that given the 1/8-inch gap, impact of the lead shield and central cylinder may exceed design allowables of the central cylinder joint for the 0.15g evaluation earthquake (Figure 5). Impact velocities of the central cylinder against its bottom stops due to cask drop excitation are shown in Figure 6.

CONCLUSIONS AND RECOMMENDATIONS

For cask drop loads, the reactor vessel, internal structure, support components, and connections were found to be within design stress allowables except for two components. The central cylinder joint screws and the bottom plate weld on the fission chamber well were both predicted to exceed the design allowable value. As a result, cask drops were suspended pending further assessments. In addition, an assessment of the potential weld failure concluded that there was no impact on safe operation of the TSR-II.

From the seismic analysis, it was concluded that seismic excitation would not prevent the safety-control plates from functioning and terminating reactor operation on demand. However, the central cylinder joint screws were found to exceed the design allowable value. As a result, spacers were installed between the central cylinder and lead shield to reduce the gap and impact velocities to acceptable values. Tensile tests were also performed on the screws to establish allowable values. Completion of these actions allowed the design allowable value to be met.

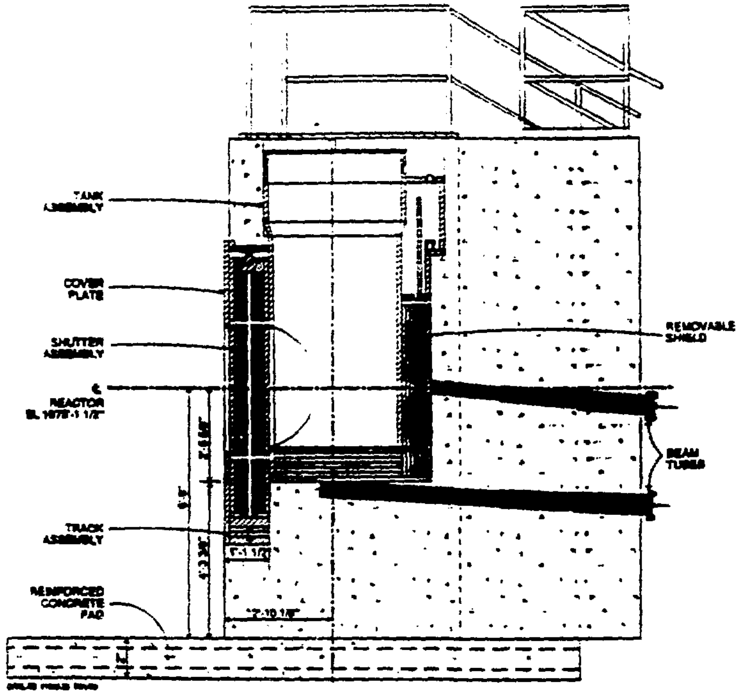


Figure 1: Section Through Beam Shield Looking South

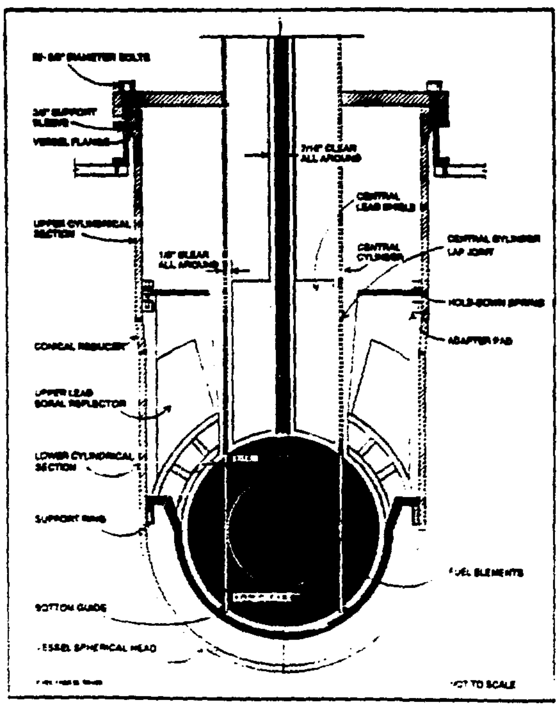


Figure 2: TSR-II Reactor Schematic View

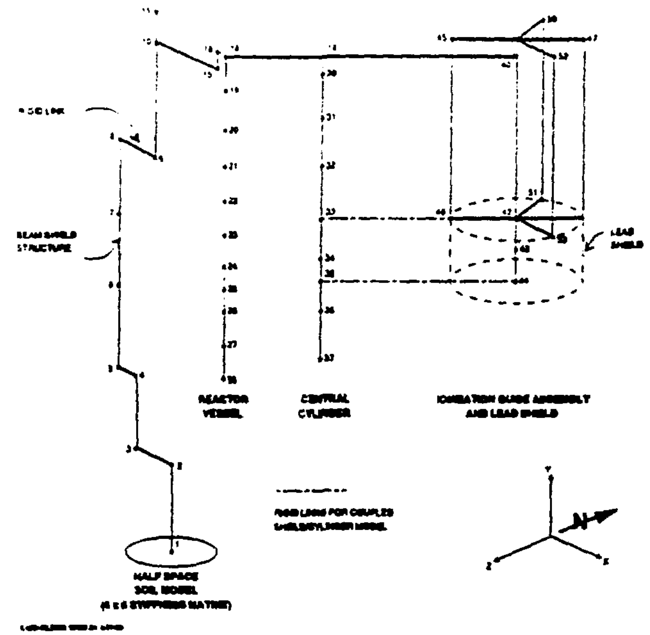


Figure 3: Coupled Soil Structure Reactor Model

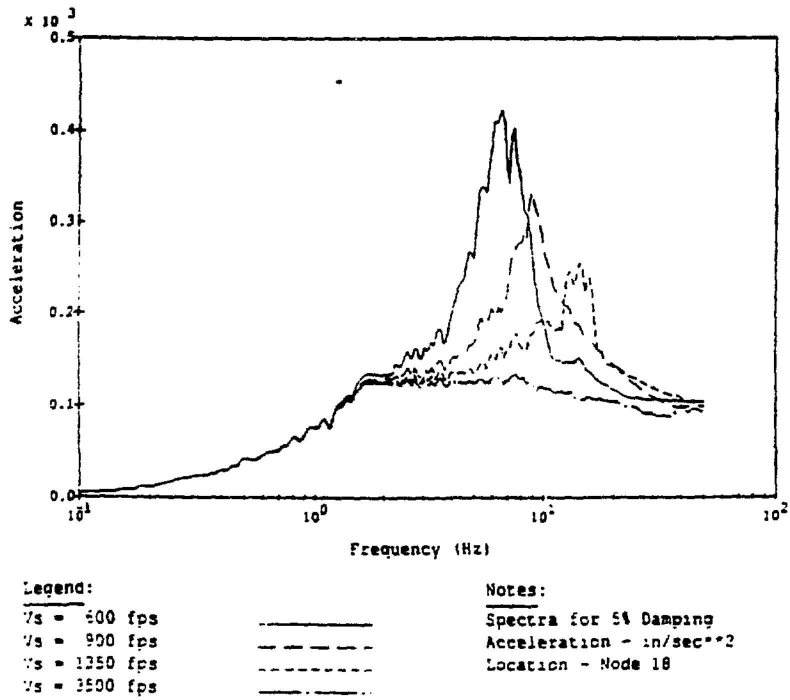


Figure 4: Acceleration Time History Response Spectra of the Reactor Vessel Head for Varied Soil Properties

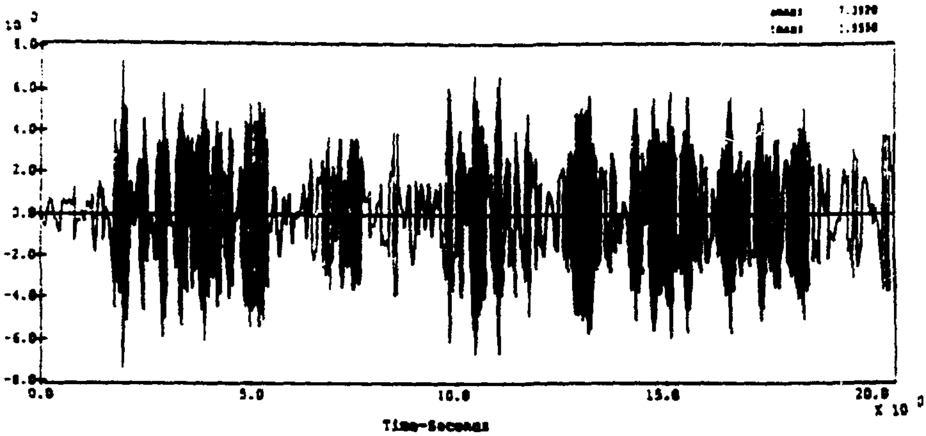
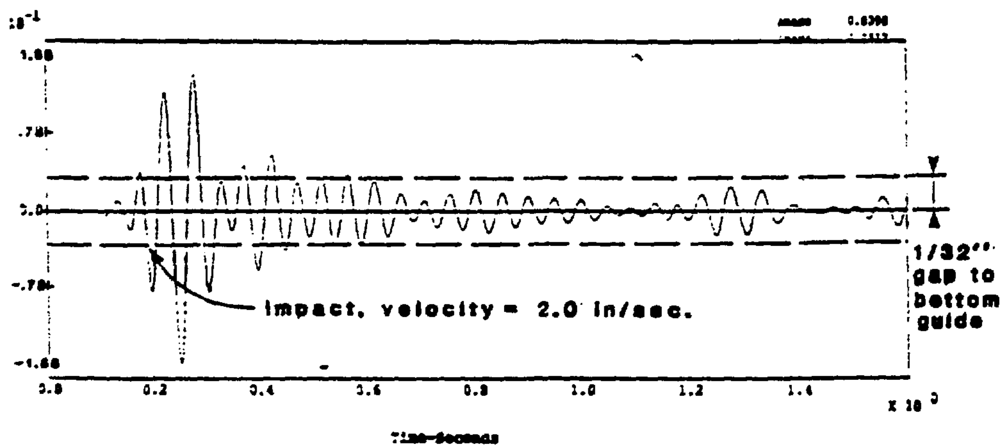


Figure 5: Velocity Time History for Nonlinear Forced Dynamic Excitation



isplacement Response Time History Scaled for 50K Drop, X-Direction, Central Cylinder Assembly