# Effects of Core Barrel on Vessel Seismic Loadings

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Reliability of reactor systems under seismic events is a major concern for the safety of the nuclear power plants. This paper deals with the effects of the core barrel on the seismic response of reactor tanks. The main emphases are the effects of core barrel on the free-surface wave height and the fluid coupling effects between the core barrel and primary tank. This study represents an initial step to investigate the effects of in-tank components, structures on the seismically-induced hydrodynamic behavior of the reactor tanks.

To simplify the analysis, the tank used in the study is simulated by a two-dimensional model. Two parametric studies were carried out, in which the wall flexibility and location of core barrel were used as parameter, respectively.

The most important conclusions obtained from the study are as follows:

1. The presence of core barrel reduces the sloshing frequency which in turn may increase or decrease the maximum wave height, depending on the response spectrum of the base motion. The effective fluid depth can be approximately taken as the fluid depth above the core barrel.

2. The fluid pressures between the tank wall and barrel appear to be uniform. They can be significantly amplified when the tank or core barrel becomes more flexible.

3. The fluid in the tank can be approximately divided into three zones. The fluid below the top of core barrel can be considered as "strong coupling zone", where the coupling interaction between the tank and core barrel is very significant. As the distance between tank and core barrel becomes smaller, the coupling interaction is more pronounced. The second zone, "medium coupling zone", is the fluid around the top of core barrel. Due to the edge effect, the coupling interaction is less significant than that in the strong coupling zone. The third zone is the fluid located far away from the core barrel. The zone can be considered as "weak coupling zone", where the coupling effects are almost negligible.

The results obtained from this study provide very useful information on the seismic response of the fluid-tank systems with the in-tank components. They can be used for future reactor designs.

## 1. Introduction

The nature of the hydrodynamic loading likely to be experienced by an LMFBR vessel during a seismic event depends on the confinement of the fluid imposed by the surrounding reactor components or structures. Generally, fluid within the reactor vessel can be classed into three groups according to the confinement conditions.

In the first group, the fluid is strongly confined by the surrounding structures. For example, the fluid in cold pool region of pool-type reactor or inlet plenum of loop-type reactor is strongly confined by the vessel bottom and core support structure. For all practical purposes, this fluid can be treated as completely confined for no relative movement exists between the fluid and the surrounding structures under seismic excitations. The hydrodynamics is entirely due to the fluid inertial effect which can be modeled by a rigid mass attached to the surrounding structures.

In the second group, the fluid is found in various annulii between concentric cylinders, such as fluid between the thermal liner and reactor vessel and fluid between the core barrel and reactor vessel. Hydrodynamic phenomena in this group include both the fluid inertial effect and the fluid coupling effect [1-5]. The latter is caused by the relative motion of the cylinders, since motion of one has an effect on the other.

The third group is the fluid in the hot pool of pool-type reactor or outlet plenum of loop-type reactor which is confined by the thermal liner and thermal baffle. This group of fluid is characterized by having a large fluid volume, large free surface, and, in some cases, by the presence of many deck-mounted components projecting down into the pool. Due to the presence of large free surface, portions of the fluid will participate the seismically-induced sloshing motion, characterized by a low-frequency oscillation with standing waves on the free surface moving up and down [6-10].

This paper deals with the effects of the core barrel on the seismic response of reactor tank. The main emphases are the effects of core barrel on the free-surface wave height and the fluid coupling effects between the core barrel and primary tank. To simplify the analysis, the reactor tank and core barrel are simulated by a two-dimensional model. Two parametric studies were carried out, in which the wall flexibility and location of core barrel were used as parameters, respectively. The results obtained from this study provide very useful information on the seismic response of the fluid-tank systems with the in-tank components. They can be used for future reactor design. In the paper, the mathematical model of the reactor tank and core barrel is first described. Then, the results of the parametric study on the wall flexibility and location of core barrel are discussed. Finally, the conclusions are given.

## 2. Parametric Study on Tank Wall Flexibility

The two dimensional finite element model is shown in Fig. 1 in which the reactor tank and core barrel are simulated by the plane strain cantilevered beams. The reactor coolant in the tank is treated by the continuum fluid element. The dimension of the tank is 14.63 m (48') x 21.94 m (72') (width x height). The fluid depth is 18.28 m (60'). The dimension of the core barrel is 4.87 m (16') x 10.97 m (36') (width x height). The height of core barrel is 60% of fluid depth. The flexibility of the tank wall and the location of the core barrel were used as parameters in the analysis.

In the flexibility study, five cases were investigated. They are:

1. Rigid tank with no core barrel.
2. Rigid tank with a rigid core barrel.
3. Rigid tank with a flexible core barrel.
4. Flexible tank with a rigid core barrel.
5. Flexible tank with a flexible core barrel.

If the tank wall and core barrel are flexible, five different wall thicknesses, 2.54 m (100"), 1.27 m (50"), 0.762 m (30"), 0.381 m (15"), and 0.254 m (10"), were used. Therefore, a total of 17 computer runs were made in the wall-flexibility parametric study. It should be mentioned that cantilever beams have very small stiffness value. In order to simulate the stiffness of the cylindrical core barrel properly, the thickness of the cantilever beam becomes extraordinarily thick. The above thicknesses of cantilever beams correspond to cylindrical core barrels having frequencies of 10.5, 5.3, 2.75, 0.8, and 0.6 Hz, which are within the range of frequencies of core barrels in LMFBR design.

The 10 s duration 0.5 g modified El Centro acceleration time history was applied at the tank base. The fluid-structure interaction time-history analysis was carried out using the linear option of the FLUSTR1 code. The results of rigid tank with a flexible core barrel, flexible tank with a rigid core barrel and flexible tank with a flexible core barrel are discussed below.

## 2.1 Rigid Tank with a Flexible Core Barrel

The computed maximum sloshing wave height of the free surface, and the maximum fluid pressure at various locations on the tank wall and core barrel for the rigid tank with a flexible core barrel are depicted in Fig. 2. For comparison purposes, the results of rigid tank with no core barrel and rigid tank with a rigid core barrel are also given. The pressure distribution is antisymmetric with respect to the center line of the tank.

As can be seen from Fig. 2, the maximum wave height for the cases of rigid tank with rigid or flexible core barrel is about 111 cm (44"). This indicates that the flexibility of core barrel has an insignificant effect on the free surface wave height. However, the wave height for a rigid tank without core barrel is only 94 cm (37"). This indicates that the presence of a core barrel in a tank system can change the sloshing frequency of the tank. Figure 3 shows the free surface sloshing plots of the rigid tank for the cases with and without a core barrel. The observed sloshing frequencies for the tank with and without a core barrel are 0.215 Hz and 0.222 Hz, respectively. The theoretical sloshing frequencies [6,7] of the tank system without a core barrel are given below as a function of the fluid depth:

| Fluid depth cm (in.) | Sloshing frequency (Hz) |
|---|---|
| 1828 (720) | 0.232 |
| 1270 (500) | 0.231 |
| 762 (300) | 0.223 |
| 508 (200) | 0.207 |
| 254 (100) | 0.164 |

Using the above table, the equivalent fluid depth for a tank with a core barrel and a frequency of 0.215 Hz is about 600 cm (236"), which is almost equal to the depth of fluid about the core barrel. Thus, the presence of the core barrel in a reactor tank system will reduce the effective fluid depth for sloshing motion. The sloshing frequency is also reduced accordingly. In most cases, the depth of the fluid above the core barrel can be considered as the effective fluid depth of the tank. Because the maximum free surface wave height is affected by the spectrum of the ground acceleration, the decrease of sloshing frequency may increase or decrease the maximum wave height, depending on the correlation between the sloshing frequency and the response spectrum of the input base acceleration.

The fluid inside of the core barrel can be assumed to move with the core barrel during seismic disturbances. For the case of a rigid core barrel, the maximum pressures of the fluid elements at the base, midheight and top of the core barrel are 0.0089 MPa (1.3 psi). Since the fluid pressure is defined at the center of the fluid element, the pressure exerted on the core barrel wall is 1.73 psi (1.3 x 4/3 = 1.73). It is equal to $1/2\ \rho\ \ddot{x}\ \ell$ ($1/2\ \rho\ \ddot{x}\ \ell = 1/2 \times 0.0000934 \times 193 \times 192 = 1.73$ psi), the fluid inertial pressure. The pressures in fluid elements between tank and core barrel are more complicated than those inside the core barrel. The maximum pressures exerted on the tank wall and rigid core barrel are 0.0207 MPa and 0.0055 MPa (3 psi and 0.8 psi), respectively. The pressure on the outer surface of core barrel is smaller than that on the inner surface of the core barrel (0.0055 MPa vs. 0.0089 MPa).

For the cases of flexible core barrel, the fluid pressures are found to be much larger than those of rigid core barrel cases. For 30" core barrel case, it has a maximum fluid pressure of 0.094 MPa (13.6 psi). The pressure inside the core barrel is not amplified too much comparing to that of the rigid barrel case. However, the pressures in the fluid elements between the core barrel and tank wall are significantly amplified. It is also noted that the pressures exerted on the outer surface of the core barrel are almost identical to those on the inner surface of the tank wall. The observed vibrational frequency for the 30" core barrel case is 2.75 Hz, which is very close to the maximum amplification region of the response spectrum of the input motion (2.5 Hz).

### 2.2 Flexible Tank with a Rigid Core Barrel

The maximum wave height and maximum pressures of the flexible tank with a rigid core barrel are shown in Fig. 4. As can be seen, the maximum wave height increases as the tank wall becomes more flexible. This is due to the superposition of the tank wall vibration on the sloshing wave height. This phenomenon has been discussed in detail in the flexibility study of the tank system without core barrel [11,12].

The characteristics of pressure distribution between the tank wall and core barrel are similar to those of the rigid tank with flexible core barrel. The pressures exerted on the inner surface of tank wall are identical and in phase with those exerted on the outer surface of core barrel. For 50" tank wall, it has a maximum fluid pressure of 0.1655 MPa (24 psi), and the observed vibrational frequency is about 2 Hz. The pressures exerted on the inner face of the rigid core barrel remain constant at 0.00896 MPa (1.3 psi).

### 2.3 Flexible Tank with a Flexible Core Barrel

The maximum wave height and maximum pressures of the flexible tank with flexible core barrel are shown in Fig. 5. As can be seen, the maximum fluid pressure, 0.29 MPa (42 psi), occurs in the case of 30"-thickness tank wall and core barrel. This pressure is about fourteen times larger than the maximum pressure 0.0207 MPa (3 psi) in the rigid tank and rigid core barrel case and three times larger than the maximum pressure 0.094 MPa (13.6 psi) in the rigid tank and flexible core barrel case and two times larger than the maximum pressure (24 psi) in the flexible tank and rigid core barrel case. Again, it is found that the pressures in the fluid elements between the tank wall and core barrel are nearly uniform. The fluid pressures inside the core barrel are relatively small compared to the pressures between tank and core barrel. The previous parametric study of the 2-D flexible tanks without in-tank components [11,12] indicated the maximum pressure exerted on the tank wall is 0.11 MPa (16 psi). Hence, the maximum hydrodynamic pressure experienced in the flexible tank with core barrel can be significantly higher than the maximum pressure experienced in the tank without core barrel due to the fluid coupling effect.

The maximum sloshing wave height of those cases is 223 cm (88"). Again, this is due to the superposition of tank wall vibrations on the sloshing motion.

## 3. Parametric Study on Location of Core Barrel

In this study, the wall thickness of the tank and core barrel was fixed to be 1.27 m (50"). Four computer runs were made, in which the distances between the tank and core barrel were 6.90 m (20'), 4.87 m (16'), 3.65 m (12'), and 2.43 m (8'), respectively. The finite element meshes are shown in Fig. 6. The maximum fluid pressures and wave height are depicted on Fig. 7. As can be seen, the wave height does not vary too much among these cases. The case of the smallest distance (8') between the tank and core barrel has the maximum fluid pressure 0.427 MPa (62 psi). The fluid in the tank can be approximately divided into three zones. The fluid below the top of core barrel can be considered as "strong coupling zone", where the coupling interaction between the tank and core barrel is very significant. As the distance between tank and core barrel becomes smaller, the coupling interaction is more pronounced. The second zone, "medium coupling zone", is the fluid around the top of core barrel. Due to the edge effect, the coupling interaction is less significant than that in the strong coupling zone. The third zone is the fluid located far away from the core barrel. This zone can be considered as "weak coupling zone", where the coupling effects are almost negligible. As can be seen from Fig. 7, the presence of core barrel has very little influence on the pressures exerted on the tank wall at the weak coupling zone.

## 4. Conclusions

This study represents an initial step to investigate the effects of in-tank components on the hydrodynamic response of reactor tanks. The most significant findings are as follows:

1. The presence of core barrel reduces the sloshing frequency which in turn may increase or decrease the maximum wave height, depending on the response spectrum of the base motion. The effective fluid depth can be approximately taken as the fluid depth above the core barrel.

2. The flexibility of core barrel has an insignificant effect on the sloshing wave height.

3. The coolant inside the core barrel moves along with the core barrel during seismic events. The pressures inside the barrel are relatively low compared to the pressures outside the barrel.

4. The fluid pressures between the tank wall and barrel appear to be uniform. They can be significantly amplified when the tank or core barrel becomes more flexible.

5. The fluid can be approximately divided into "strong", "medium", and "weak" coupling zones. In the first two zones, when the distance between the tank and barrel becomes smaller, the fluid coupling effect is more pronounced.

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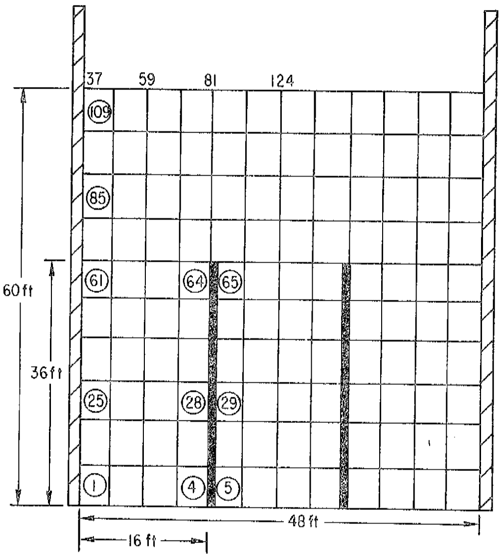
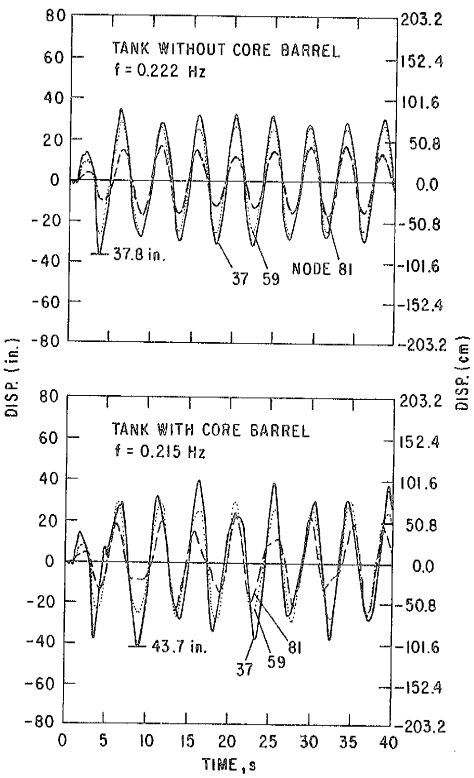
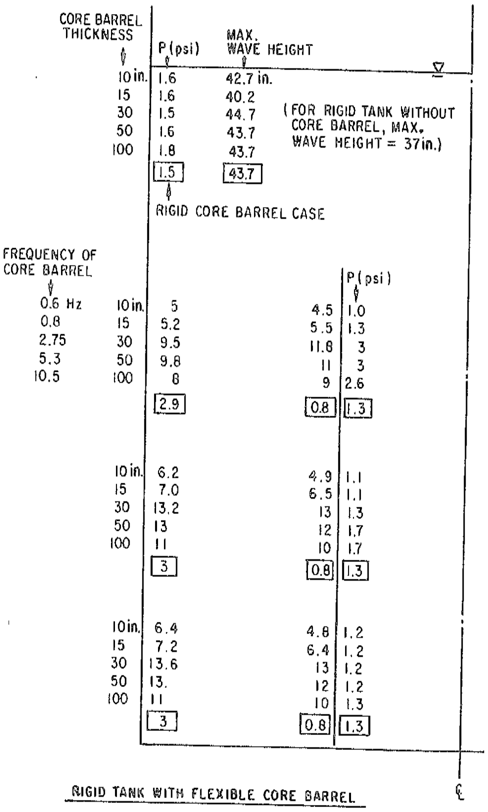


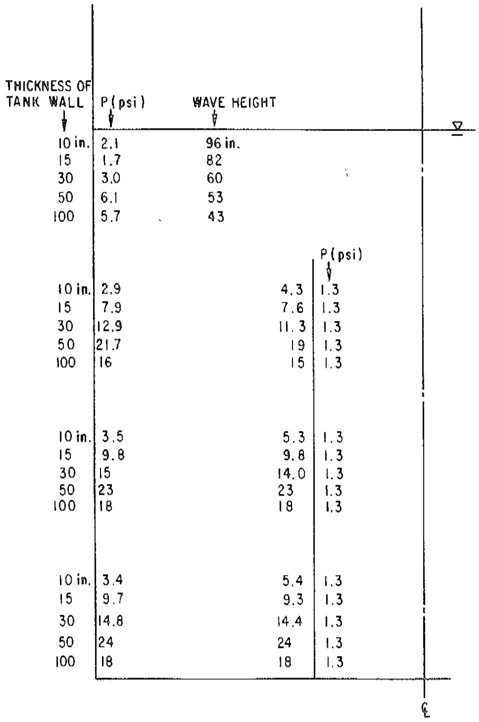
1. Finite Element Model of 2-D Tank with Core Barrel (Flexibility Study)



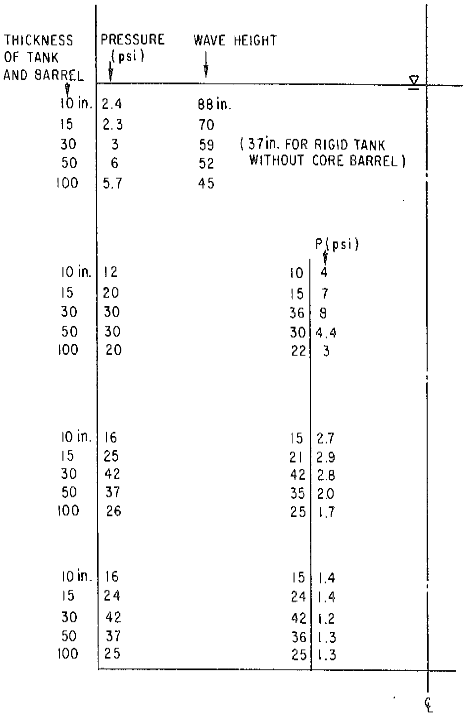
3. Plot of Sloshing Motion (40 s) of a 2-D Tank with and without Core Barrel



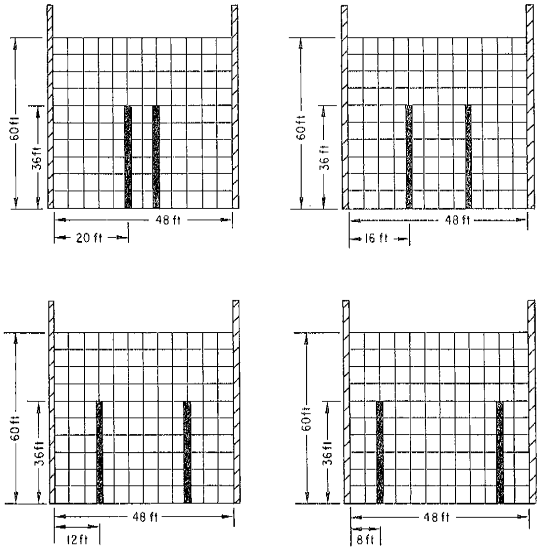
2. Maximum Wave Height and Maximum Pressures of Rigid Tank with a Flexible Core Barrel



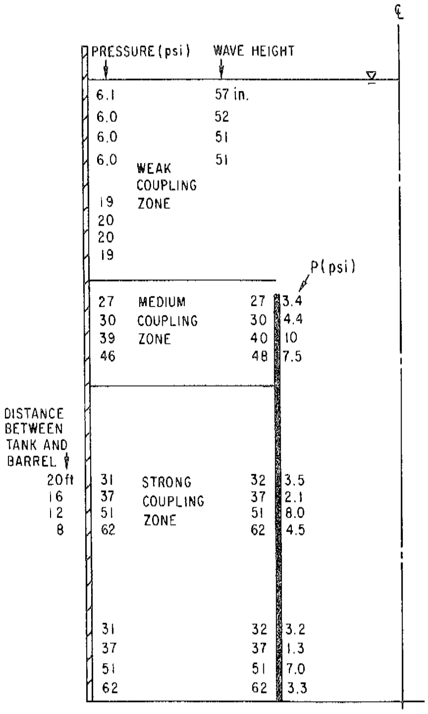
4. Maximum Wave Height and Maximum Pressures of a Flexible Tank with a Rigid Core Barrel



5. Maximum Wave Height and Maximum Pressures of a Flexible Tank with a Flexible Core Barrel



6. 2-D Tank Model with Various Locations of the Core Barrel



7. Maximum Wave Height and Maximum Pressures of the Tank with Various Locations of the Core Barrel