STRUCTURAL DESIGN OF LARGE VERTICAL SPENT FUEL DRY STORAGE MODULE

W. Ajam[1], A. Khan[1], A. Alizadeh[2], H. Tran[1], and B. Canas Calderon[1]

[1] EACL CANDU
1155, rue Metcalfe
Montréal (Québec)
Canada H3B 2V6

[2] AECL CANDU
2251 Speakman Drive
Mississauga, Ontario
Canada L5K 1B2

ABSTRACT

CANSTOR is the large vertical spent fuel dry storage module developed at AECL CANDU for the storage of irradiated fuel from nuclear power plants. The heat removal concept used is based on convection cooling and has proven to be more effective than conduction through a thickness of concrete. The more effective heat removal results in reduced temperature differentials accross the wall thickness and in lower reinforcement requirements. The structure consists of a concrete base slab, walls and a roof with inlet and outlet openings for cooling air circulation.

This paper describes the analysis and design of the CANSTOR module using the finite element method.

1.0 INTRODUCTION

Nuclear power plants produce highly radioactive waste from the fissioning of the uranium fuel inside the reactor. The irradiated fuel is stored in fuel bundle trays underwater in specially designed and engineered pools. All CANDU stations provide such pool storage space for on-site short-term storage of the fuel. The dry storage concept was developed to supplement the pool storage capacity at nuclear power plants.

The initial dry storage concept developed by AECL CANDU is the stand-alone canister design. In this design the individual fuel bundles are loaded into stainless steel baskets that are seal welded. Each basket contains 60 bundles. Up to nine baskets are stacked in a steel liner shell which is built inside a reinforced concrete canister. These canisters are then stored above ground in installations which are closely monitored.

The CANSTOR design combines a number of stainless steel storage stacks inside a larger reinforced concrete module. The CANSTOR module is required to meet functional requirements within the same boundary parameters as the canister design.

The major boundary parameters are as follows:

- have a 60-bundle dry storage basket capacity;
- be compatible with the existing flask and loading equipment used for the canisters;
- meet requirements for storing fuel that has been cooled for a minimum of 6 years in the pool;
- perform similar shielding and cooling functions as the canister.

The CANSTOR structure is 71' long and 26' 8" wide and has a height of 24'8" including the base slab (see Figures 1 to 3). The cooling of the CANSTOR module is achieved by air convection through the structure instead of relying on heat conduction through the concrete wall. The cooling air enters the module at the bottom, reaches the internal air volume where the steel containment shells are located and then exits the module near the top. Direct air cooling of the containment by convection is significantly more efficient than thermal conduction through concrete.

The thermal load on the concrete is highly critical in the design of CANSTOR. A number of full scale tests were conducted in order to determine the CANSTOR concrete operating temperature. The tests showed that the maximum fuel temperature was measured at the top of the stack of fuel baskets. The maximum temperature reached in this location is about 30°C lower than that of the stand-alone canister design. The lower basket in the stack reached a maximum temperature 55°C lower than that of the stand-alone canister design.

The civil design parameters, with respect to soil properties, meteorological and seismic loads applied to the CANSTOR module are identical to those specified for the standard design of CANDU 3 nuclear power plants.

The scope of the present work is to carry out a seismic and static structural analysis of the CANSTOR module which will form the basis for the structural design of the module.

2.0 ANALYSIS METHOD and LOADS

The analysis of static and seismic loads is carried out using the finite element method and the STARDYNE computer code. The procedure used for the static analysis and the dynamic analysis mainly consists of preparing the separate finite element model for each analysis and calculating and applying the individual loads on the structure.

The loading considered for the CANSTOR module is as follows:

The dead load consisting of the weight of the structure and the fuel storage baskets.

The live load consisting of the crane load and a uniformly distributed load as an alternative to snow.

A thermal load consisting of winter and summer temperature gradients across the thickness of the structure. The gradients result from the differences between the ambient temperature, the concrete pouring temperature (base temperature), the ground temperature and the heat generated by the fuel storage baskets.

Shrinkage and creep loads resulting from time-dependent deformations in the concrete and the temperature and loading history of the structure.

The CANSTOR module is designed to remain intact following a Design Basis Earthquake (DBE). The DBE is defined with a peak ground acceleration of 0.3 g and a peak ground velocity of 365.8 mm/s.

The Design Basis Tornado applied in CANSTOR has the same specific value used in a CANDU 3 plant with a maximum wind speed equal to 420 km/h = 116.7 m/s.

Static and dynamic analyses have been performed for two base restraint conditions. In the first case, the assumption was made that the base structure was free to move along in the x and y (horizontal) directions with respect to the soil foundations, while in the second case, no displacement along the x and y directions was allowed. These two cases were considered since geotechnical conditions vary from site to site and this may have an effect on the design specifications and the restraint conditions for the base structure.

3.0 STATIC ANALYSIS

This section describes the finite element model, and the loads considered for both the fixed and free sliding base. In the sliding base model, there is movement of the base slab due to thermal and shrinkage loads.

3.1 Finite element model

A three-dimensional finite element symmetric quarter model of the CANSTOR was created. The structure is modelled using an eight-node isoparametric solid element with three degrees of freedom per node. The displacement is defined by three translations at each node.

The structural model is represented by 772 cube elements. A fictitious beam element with a small area is superimposed in some locations in order to obtain the edge stresses along the x, y or z directions. The shells in which the baskets are stored are modelled by beam tubes connected between top and bottom slabs.

4.0 DYNAMIC ANALYSIS

The dynamic analysis is performed for both the fixed and sliding bases. Each stage of analysis has three steps related to these boundary conditions. This is due to the fact that the seismic loading acts on the CANSTOR structure in an antisymmetric way. For this reason, the boundary conditions of the quarter model will change when the load acts along the x, y or z direction. The resulting seismic stresses in the CANSTOR module due to the Design Basis Earthquake (DBE) are computed as the square root of the sum of the squares for the three directions of DBE.

4.1 Seismic model

The finite element model used in the STARDYNE dynamic analysis is based on the static model with boundary modifications. The weight of the structure is calculated based on the given density of reinforced concrete and is lumped at selected nodes to provide a good weight distribution. A lumped weight representing the weight of the fuel storage baskets is also applied at the node of the beam tubes.

For the STARDYNE runs, the earthquake load is represented by the ground response spectrum as defined in CSA Standard N289.3- M81. The peak ground acceleration level used is 0.3 g. This earthquake loading is applied at the base of the structure. A damping value of 5% is used for the concrete structure.

4.2 Seismic analysis

The finite element dynamic analysis consists of an eigenvalue extraction based on the Lanczos Modal Extraction method followed by a response spectrum analysis for the evaluation of seismic forces, stresses and displacements.

5.0 TORNADO ANALYSIS

The tornado loads applied to CANSTOR are the same as those used in the CANDU 3 standard product design, with a maximum wind speed equal to 420 km/h. The most severe missile impact is a wooden plank which creates an effect equivalent to a concentrated force of 470 kips applied at a critical point along the height of the wall.

A finite element model for the CANSTOR structure with openings representing the air inlets and outlets is developed to appropriately evaluate the effect of the tornado missile on the CANSTOR. The analysis is carried out for a concentrated horizontal force equal to 470 kips applied at four different locations along the wall. The structure is also analyzed for the same concentrated force applied vertically at the center of a quadrant of the top slab.

6.0 RESULTS

A detailed structural and seismic design of the reinforced concrete structure of the CANSTOR module has been carried out, based on the maximum stresses obtained at various sections of the structure for each of the static and seismic loadings, for fixed and sliding base considerations, respectively.

The following remarks are noted:

- The stresses due to the thermal and shrinkage loads are much greater than the stresses due to other loads and therefore govern the design of the walls and the slabs. This is due to the highly constrained nature of the thick-walled concrete geometry.
- In the case of the base slab assumed to be fixed to the ground, the maximum thermal and shrinkage stresses are as high as 240 ksf in tension and 136 ksf in compression for winter and summer operating conditions respectively.
- The same thermal stresses at the base are reduced by as much as 60% when the base is assumed free to slide with respect to the ground under thermal load. The shrinkage stresses are reduced even more.
- It is expected that through the introduction of a bond breaking membrane the sliding base case is closer to the actual behaviour of the structure. In such a case the sliding stability is achieved by providing central shear keys for the foundations.

7.0 CONCLUSIONS

The CANSTOR module is a feasible and economic method for the surface dry storage of used fuel from nuclear power plants. The convection cooling of the CANSTOR module is effective and leads to a significant reduction in the uniform and differential temperature in the concrete shielding structure. This also results in a considerable cost reduction due to lower reinforcement requirements.

- The module is stable with respect to overturning, sliding and uplift.
- The bearing stresses due to expected loads, including the dead weight of the module, are within the allowable bearing stresses for most foundation materials.

- The dimensions of the concrete elements are adequate for shielding and structural considerations.
- The CANSTOR module is qualified for the Design Basis Earthquake and for the Design Basis Tornado equivalent to those used for the standard CANDU 3 power plants.
- Further refinement of the design is under way to further reduce the impact of thermal loads by introducing more flexibility into the interfaces between the walls and the slabs of the structure.

REFERENCES

1. "Vibrations of soils and foundations", F.E. Richart, J.L. Hall, 1970 by Prentice-Hall, Inc.

2. "ACI Manual of concrete practice 1988", American Concrete Institute.

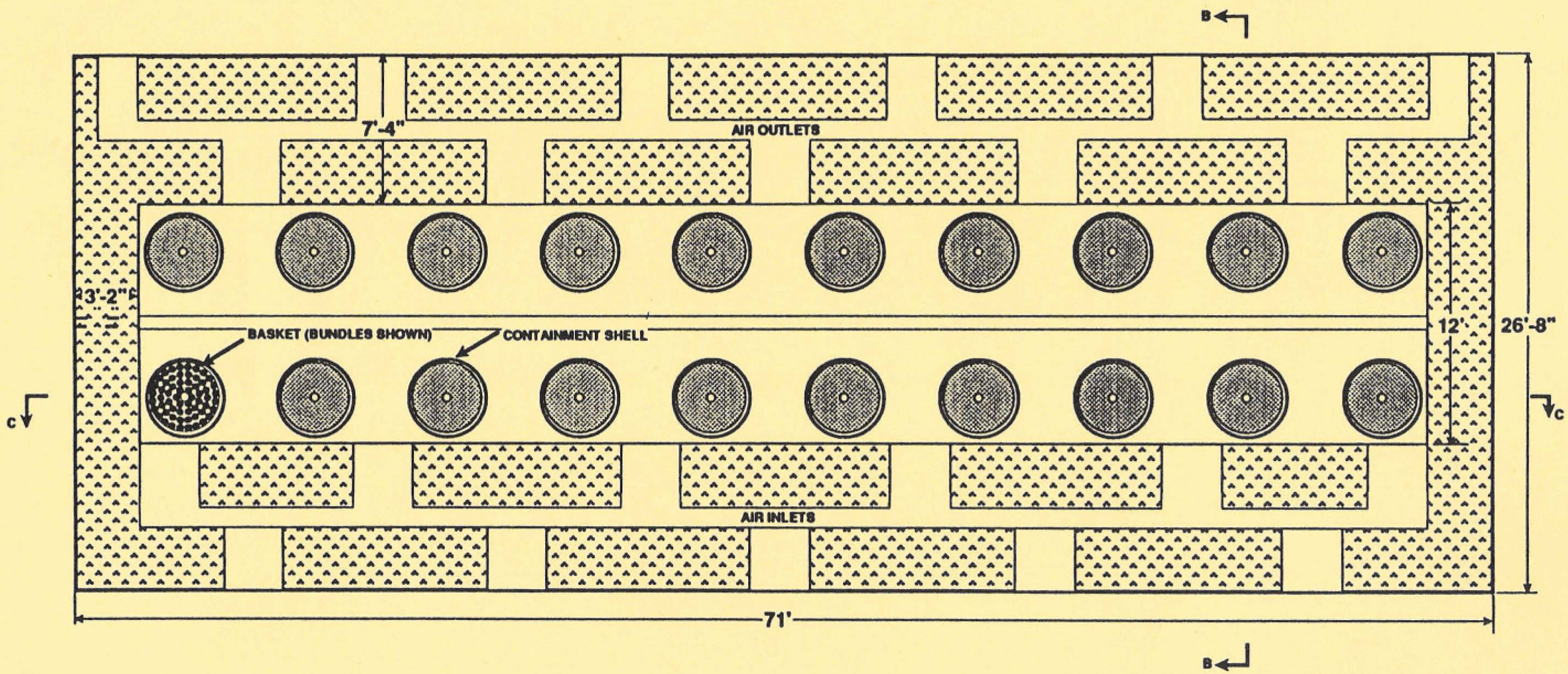

FIGURE 1 - CANSTOR PLAN VIEW

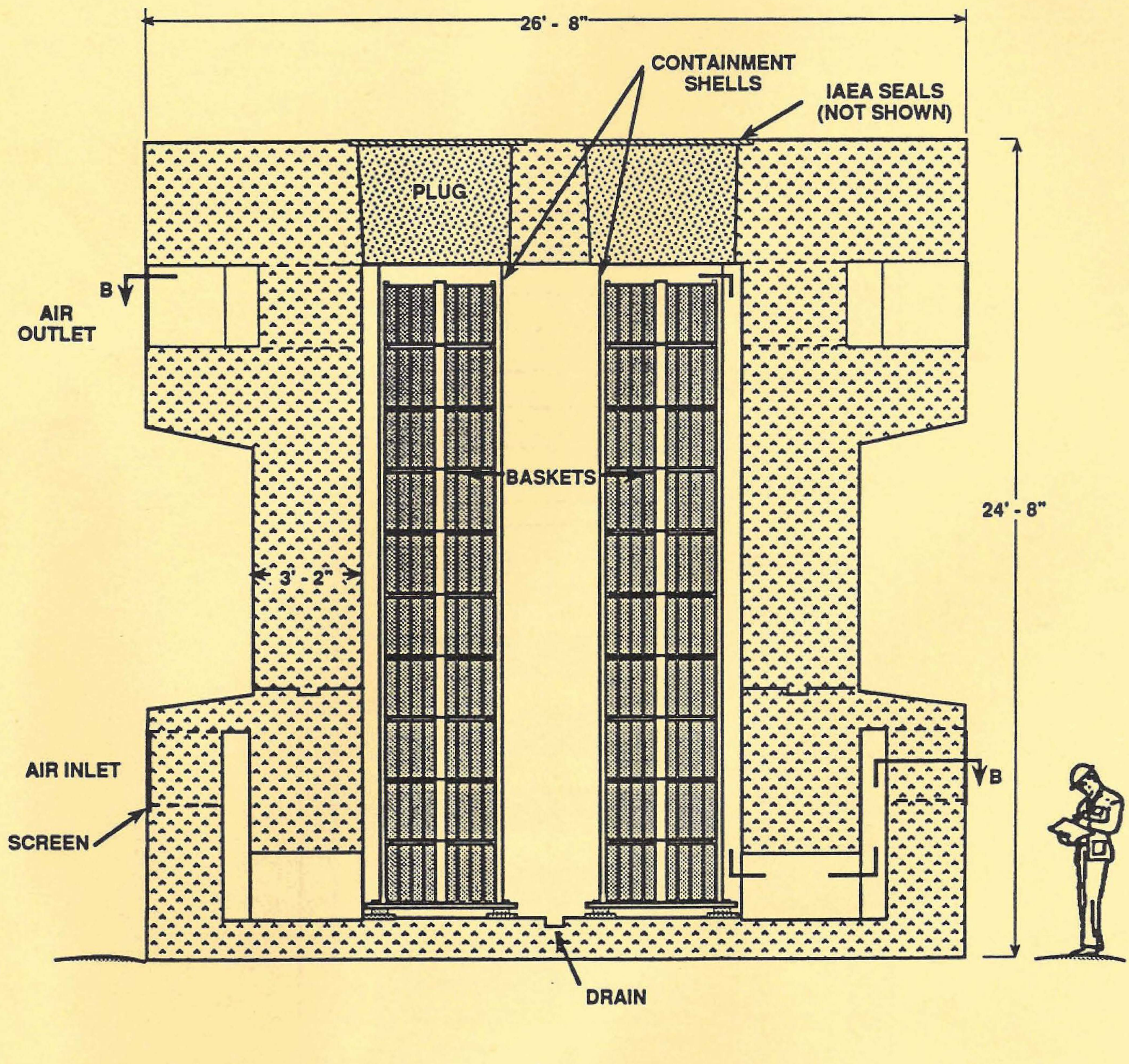

FIGURE 2 - CANSTOR END VIEW

SECTION B-B OF FIGURE 1

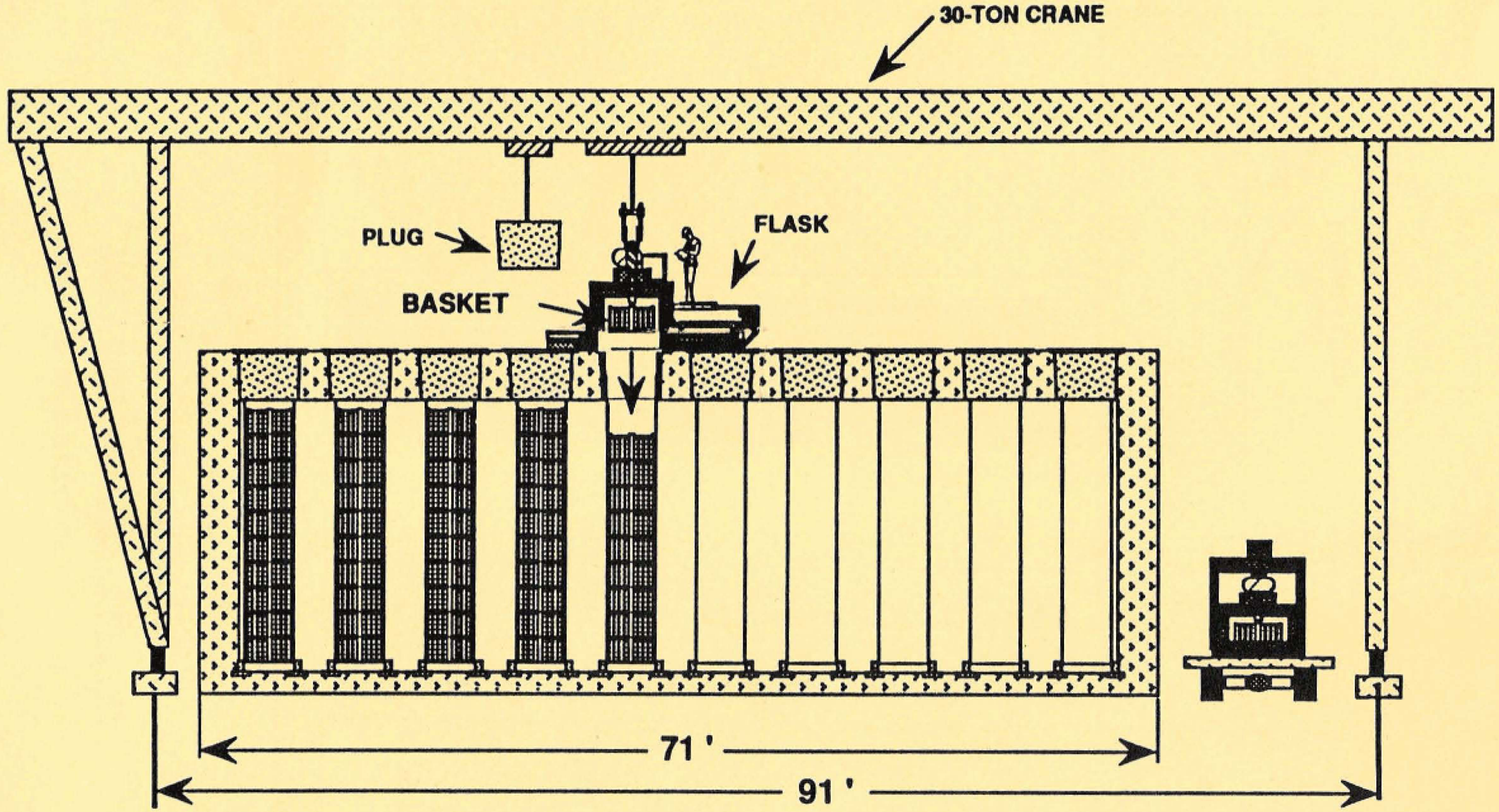

FIGURE 3 - CANSTOR ELEVATION

SECTION C-C OF FIGURE 1