Simulating Thermal Behavior of AECL's Spent Fuel Dry Storage System with CATHENA

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ABSTRACT

This paper documents the comparisons between CATHENA predictions and temperature measurements taken at the Gentilly-2 NPP spent fuel dry storage facility and in a mock-up of a storage basket placed inside a storage cylinder. It also presents CATHENA temperature predictions related to the storage of spent fuel in MACSTOR modules as planned for Ignalina NPP, Lithuania. CATHENA has been chosen because it can simulate many noncondensable gases including air and helium, and because of its great flexibility in the representation of the MACSTOR module geometry.

The results of the simulations show good agreement with the experimental measurements. The two comparisons indicate that CATHENA can be used to simulate heat transfer from the fuel to the external air circuit of the spent fuel dry storage system. For the Ignalina MACSTOR module, containing RBMK fuel having higher heat release than typical CANDU fuel, CATHENA predicts that the maximum fuel temperature is expected to be around 240 °C, giving an acceptable margin below the maximum allowed temperature of 300 °C. In conclusion, this paper shows that the thermalhydraulic code CATHENA can accurately predict the thermal behavior of AECL's air cooled spent fuel dry storage system.

INTRODUCTION

AECL has successfully developed various spent fuel dry storage systems over the last two decades. The first system, concrete silos, is used to store spent fuel at Whiteshell Laboratories, Douglas Point NPP, Chalk River Laboratories, Point Lepreau NPP and Wolsong 1 NPP. Following these successes, AECL developed the more advanced, high performance MACSTOR™ technology. This concept applies to dry storage of

CANDU^{TM} spent fuel under the name CANSTOR^{TM}. The first CANSTOR modules have been build recently at the Gentilly-2 nuclear power station of Hydro-Québec.

Dissipation of the residual heat generated by the spent fuel is a major factor in the design of spent fuel dry storage and one of the key elements for its licensing. Heat dissipation is important to maintain the integrity of the fuel and of the concrete. Several heat transfer analyses have been done on experiments performed at Whiteshell Laboratories based on a mock-up of the MACSTOR concept [1,2]. In the present paper, temperature measurements obtained from an operating CANSTOR module and from a mock-up of the baskets containing the spent fuel are compared to CATHENA predictions. The purpose of this work is to demonstrate that a single flexible code can accurately predict the heat transfer in the dry spent fuel system from the fuel to the outside walls. Details about the design of the CANSTOR module and the heat transfer mechanisms are presented in the next sections.

AECL'S SPENT FUEL DRY STORAGE SYSTEM

The first CANSTOR modules have been built at the Gentilly-2 site (Figure 1). The high thermal performance of the CANSTOR module is achieved by using a continuous passive convection process to cool the fuel storage cylinders inside the concrete vault. The cooling circuit consists of air inlets at the bottom of the module, of the main internal vault where the storage cylinders are located and of the air outlets located in the upper portion of the side walls (see Figure 2). The air is heated around the storage cylinders inside the vault and develops the buoyancy head driving the natural circulation. Cool air enters the module via the air inlets and warm air is released to the atmosphere through the outlets. The air inlets and outlets form a labyrinth to ensure shielding against nuclear radiation and to prevent direct impact of postulated tornado missiles on the storage cylinders. The external side of the air inlets is located well above the ground to prevent their blockage by a flood, accumulation of debris or snow, and the internal side of the inlets is designed to supply the cooling air at the bottom of the storage cylinders. Both inlets and outlets are equipped with protective screens for safety and environmental protection reasons. Each module contains 20 cylinders as shown in Figure 3. Each cylinder contains 10 baskets (Figure 4) and each basket contains 60 CANDU spent fuel bundles (Figure 5). A MACSTOR module is planned to be built at the Ignalina nuclear power station in Lithuania to store RBMK spent fuel assemblies (see Figure 6).

CATHENA THERMALHYDRAULIC COMPUTER CODE

The thermalhydraulic code CATHENA [3] predicts the one-dimensional flowrate of fluids in pipes and the two-dimensional heat transfer in solids. CATHENA simulates the heat transfer by convection, conduction and thermal radiation. It solves the conservation equations for mass, momentum and energy. It is the main thermalhydraulic code used by

AECL for safety analyses of Wolsong 2, 3, 4 and Qinshan. It is also used in many other applications like the safety analysis of the MAPLE research reactor and simulations of experiments performed at Chalk River and Whiteshell. The CATHENA code has been chosen to simulate dry spent fuel storage systems because it models different noncondensable gases, particularly air and helium, and has a great flexibility in the geometrical representation of the modules.

COMPARISON BETWEEN CATHENA AND CANSTOR'S EXPERIMENTAL MEASUREMENTS

A CATHENA model of the air circuit, the walls, the roof and the storage cylinders of the CANSTOR module has been created. Four storage cylinders are modelled to replicate the test configuration. Thermal radiation between the cylinders and the walls is modeled. The heat transfer coefficient between the walls and the outside air is assumed to be 10.0 $W/m^2/°C$. The heat transfer coefficient between the storage cylinders and the inside air was adjusted for one of the instrumented cylinders.

Besides what has already been mentioned, the following assumptions were taken:

- The radiative exchange between the cylinders and the roof is supposed negligible.
- The heat transfer through the CANSTOR bottom slab is neglected.
- In CATHENA, all module components are modelled as cylinders. The walls and the roof of the CANSTOR are thus modelled as cylinders, respecting the internal heat transfer surfaces and the distances between the cylinders and the walls for radiation.
- The vertical conduction in the concrete wall is neglected in the model.
- The energy distribution in the storage cylinders is assumed to be vertically uniform.

A program of in-situ measurements was intituted at Gentilly-2 during the first campaign of spent fuel dry storage in a CANSTOR module [4]. Temperatures of the ambiant air, the air in the outlets and the storage cylinder surfaces were taken. Table 1 shows the results of the CATHENA predictions and their comparison with the on-site measurements. The values shown in the column "measurements" are the median values. The 90-10 interval indicates the variability of the temperature measurements: 10 % of the temperature difference measurements between the air coming into the module and the air going out were lower than 3 °C and 90 % of the measurements were lower than 13 °C. The precision of the instruments (taking the convertors into account) is estimated to be ± 1.5 °C. It can be seen that the fluctuations in the measured temperatures are important and are greater than the instruments' precision. Reference 4 suggests that these important variations are mainly due to changing wind conditions. The median temperature difference between cylinder 6 and the outlet air is greater than the temperature difference between cylinder 15 and the outlet air (11 °C versus 9 °C). This indicates a wind effect since cylinder 15 contains hotter fuel than cylinder 6 (2520 W versus 1848 W) and the wind comes predominantly from the west, where cylinder 15 is located. CATHENA correctly predicts the temperature difference between cylinder 6 and the outlet air and overestimates the temperature difference between the inlet and outlet air and the temperature difference between cylinder 15 and the outlet air. All predictions are within experimental variations. The CATHENA analysis shows that about 10 % of the heat is dissipated by conduction through the walls and roof and 90 % is removed by convection through the air circuit.

COMPARISON BETWEEN CATHENA AND BASKET MOCK-UP MEASUREMENTS

Inside the CANSTOR module, each storage cylinder (also called liner) contains 10 baskets each holding 60 CANDU fuel bundles. A mock-up of the basket, containing 60 heated metal cylinders simulating bundles, was also tested for an earlier storage project at Point Lepreau (see Figures 5 and 7). Heat transfer and internal air circulation patterns inside the basket are different and far more complex than the air circulation inside the module. The CATHENA model assumes that the air flows upwards around each metal cylinder simulating a bundle, then horizontally at the top of the basket, downwards along the basket walls and again horizontally at the bottom of the basket to complete the loop. The CATHENA model of the basket consists of the air circuit described above and stagnant air between the basket and the liner. The solids modelled are the 60 bundle simulators, the basket and the liner. Each bundle simulator generates a power of 6 W for a total of 360 W. The heat transfer between all surfaces and the air is calculated with the McAdams correlation [5]. This correlation, which is an option in CATHENA, was developed for free convection in single phase flow. This is exactly what we have in the basket mockup experiment. Thermal radiation between the bundle simulators and the basket and between the basket and the liner is modelled. The liner is maintained at a constant temperature of 96 °C by heaters. The emissivity of the bundle simulators was measured (0.61), but the emissivities of the stainless steel basket and the carbon stell liner were not measured. For carbon steel and stainlees steel, compendiums give values between 0.3 and 0.8, thus the assumed emissivities had to be varied in CATHENA.

Temperature measurements were taken at middle height of different bundle simulators and of the basket and liner, as shown in Figure 5. Table 2 shows the comparisons between the CATHENA predictions and the experimental measurements for two assumed emissivities of the metal surfaces. T bun 1 indicates the inner ring bundle simulators surface temperature, T bun 2 the second ring up to T bun 4 which indicates the outer ring bundle simulators surface temperature. The CATHENA predictions are very close to the measurements, especially when the emissivity is set at 0.8. CATHENA captures the decrease in temperature from the inner bundle simulators to the outer bundle simulators. The analysis has also shown that the radiative component is very important inside the basket. When thermal radiation is not modelled in CATHENA, the temperature discrepancy becomes very large.

PREDICTIONS FOR IGNALINA

The two comparisons presented above indicate that CATHENA can be used to simulate heat transfer from the enclosed fuel to the external air circuit of the spent fuel dry storage system. From these, a complete model of the MACSTOR module for Ignalina was subsequently created. This module would contain RBMK fuel assemblies having higher heat release than typical CANDU fuel. The storage cylinder contains one basket of the RBMK fuel assemblies instead of 10 baskets of CANDU fuel in the CANSTOR because the RBMK fuel is much longer than CANDU fuel. Each basket contains 102 RBMK fuel assemblies. Figure 6 shows a view of the planned Ignalina spent fuel storage site. The CATHENA model consists of the internal helium circuit cooling the fuel, stagnant air between the basket and the storage cylinder and the MACSTOR module air circuit. It also models the fuel, the fuel tubes, the baskets, the storage cylinders and the concrete walls and roof of the MACSTOR module. The same heat transfer correlations used in the previous comparisons were used for the Ignalina predictions. CATHENA predicts that the maximum fuel temperature is expected to be around 240 °C, giving a wide margin below the maximum allowed temperature of 300 °C.

CONCLUSION

In conclusion, this paper shows that the thermalhydraulic code CATHENA can accurately predict the thermal behavior of AECL's air cooled spent fuel dry storage system.

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ACKNOWLEDGMENTS

The author expresses his gratitude to P. Pattantyus, AECL, and R. Beaudoin, AECL, for their assistance with the work presented in this paper.

Table 1: Comparison between measurements and CATHENA predictions for the Gentilly-2 CANSTOR

	measurements	90-10 interval	CATHENA predictions	dT
T air in - Tair out	8	3 to 13	11	3
T cyl 15 - Tair out	9	4 to 14	14	5
T cyl 6 - Tair out	11	8 to 18	11	0

Table 2: Comparison between measurements and CATHENA predictions for a basket mockup

	measurements	CATHENA predictions em=0.8	dT	CATHENA predictions em=0.6	dT
T bun 1	159.0	157.5	-1.5	167	8.0
T bun 2	155.3	153.5	-1.8	164.5	9.2
T bun 3	148.4	147.5	-0.9	158.5	10.1
T bun 4	139.3	138.5	-0.8	149.5	10.2
T basket	115.2	118	2.8	125.5	10.3
T liner	96.4	96	-0.4	96	-0.4

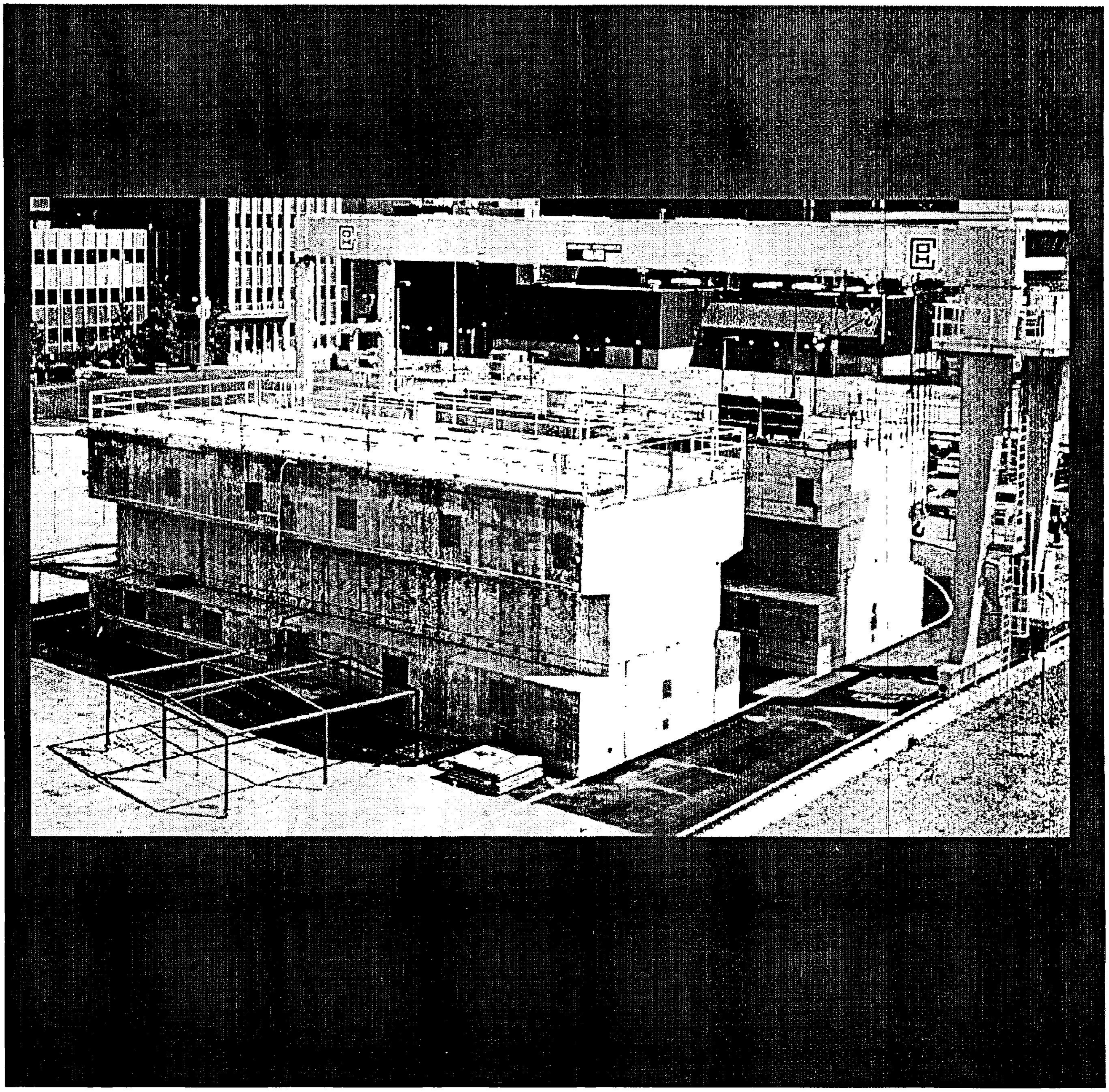


Figure 1. Photo of two CANSTOR modules at the Gentilly-2 site.

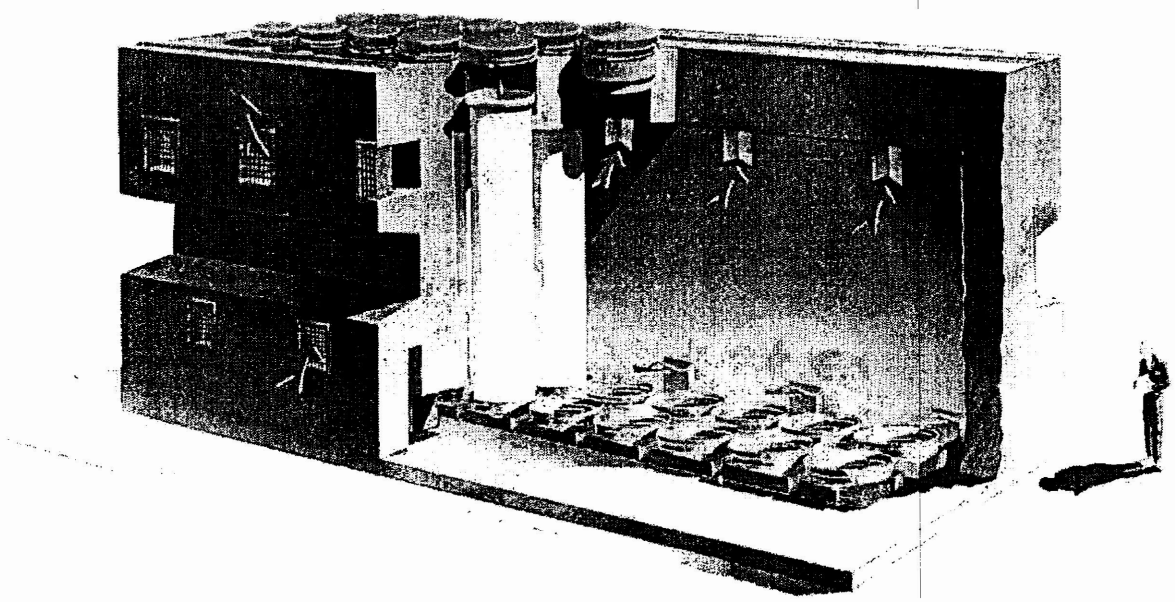


Figure 2. Diagram of air flow inside the CANSTOR module

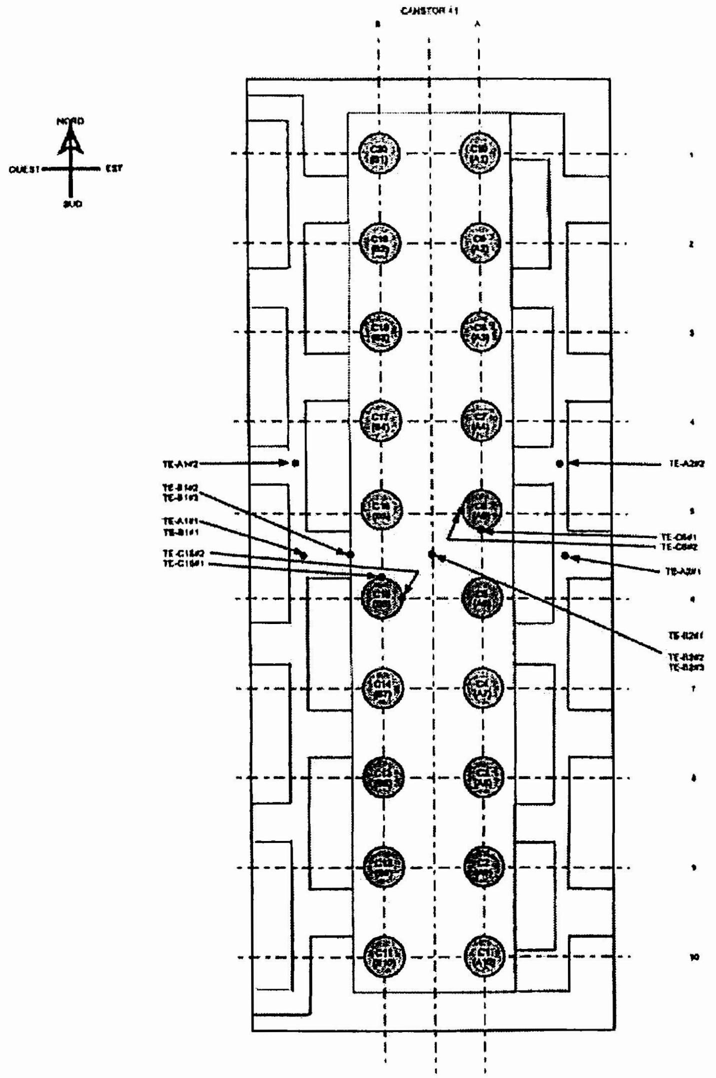


Figure 3. View of the Gentilly-2 CANSTOR module with temperature measurement locations

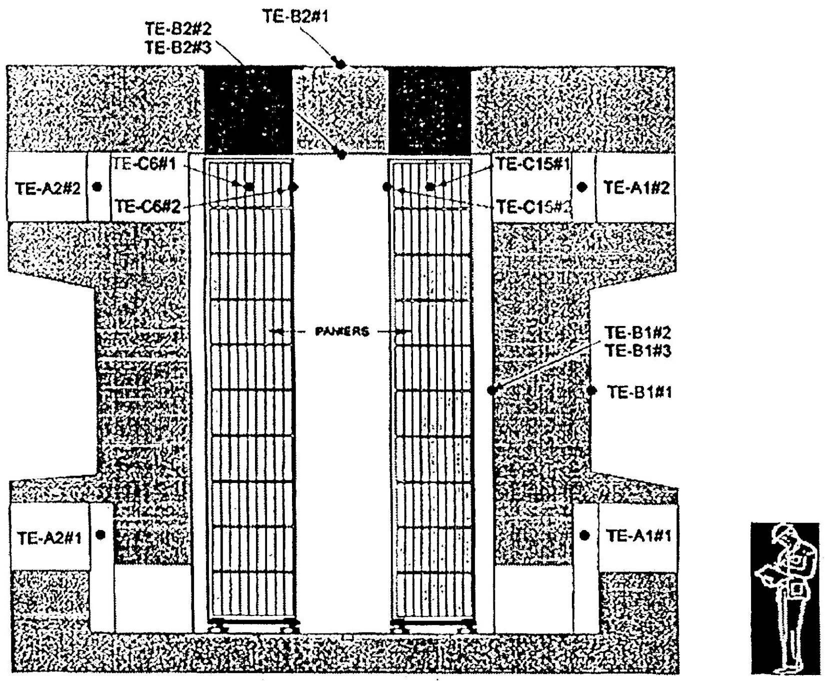
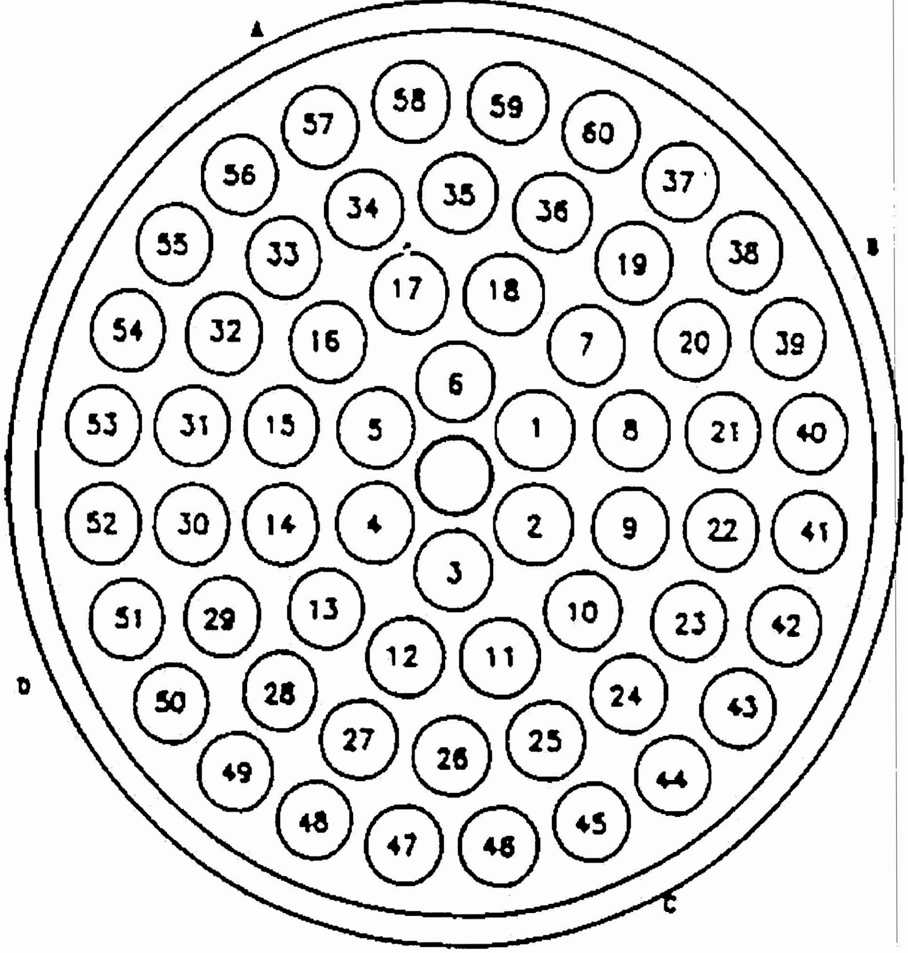


Figure 4. A cut of the Gentilly-2 CANSTOR module with two cylinders containing each 10 baskets



1. Average Liner Temperature (A,B,C,D) - 96°C
2. Average Maximum Fuel Temperature (1,6,4,3) - 159°C

Figure 5. A cut of the basket mock-up with the experimental measurement locations

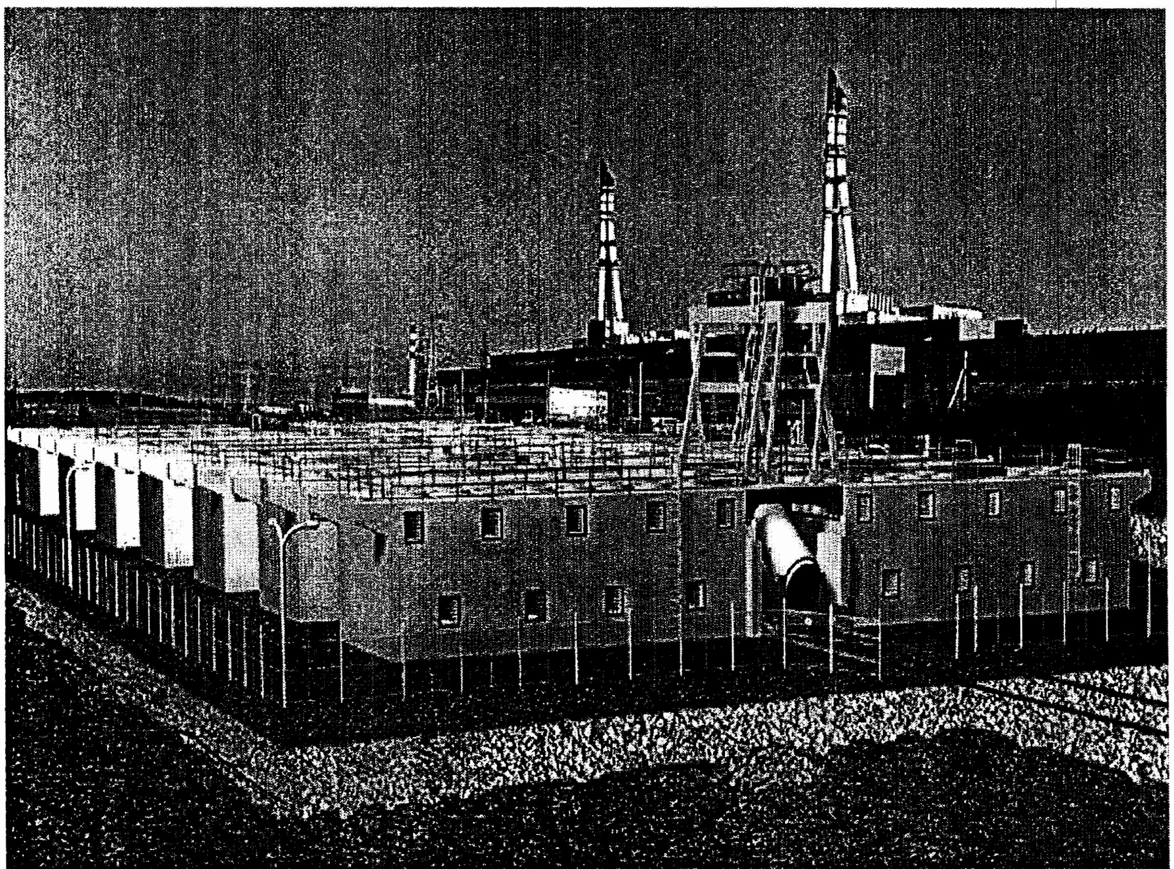


Figure 6. Artist's view of the future MACSTOR storage site at Ignalina NPP

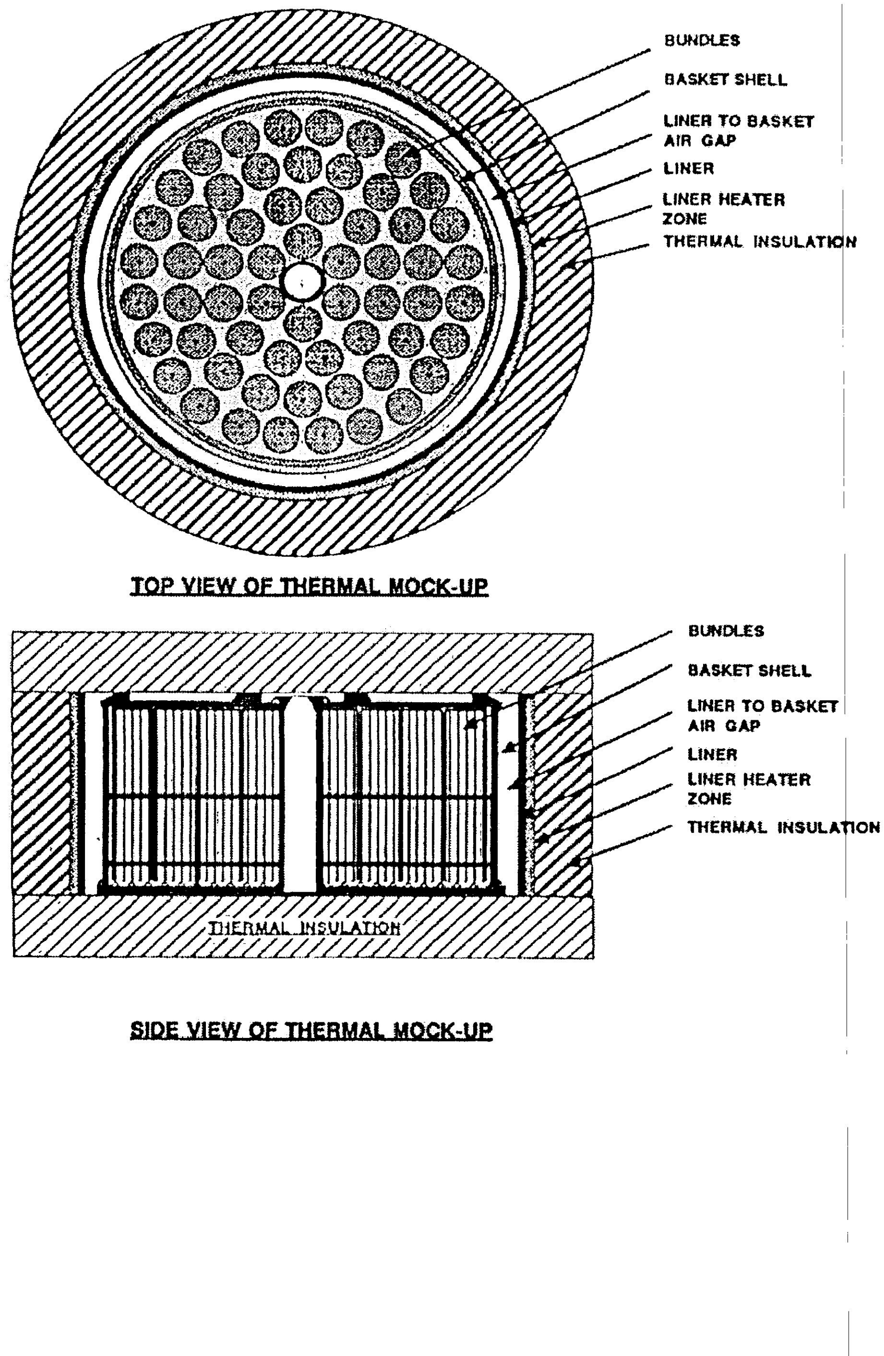


Figure 7. Basket mock-up