ACR FUEL STORAGE ANALYSIS: FINITE ELEMENT HEAT TRANSFER ANALYSIS OF DRY STORAGE

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ABSTRACT

Over the past decade Atomic Energy of Canada Limited (AECL) has designed and licensed air-cooled concrete structures used as above ground dry storage containers (MACSTOR®) to store irradiated nuclear fuel from CANDU plants. A typical MACSTOR® 200 module is designed to store 12,000 bundles in 20 storage cylinders. MACSTOR® 200 modules are in operation at Gentilly-2 in Canada and at Cernavoda in Romania. The MACSTOR® module is cooled passively by natural convection and by conduction through the concrete walls and roof.

Currently AECL is designing the Advanced Candu Reactor (ACR®) with CANFLEX slightly enriched uranium fuel to be used. AECL has initiated a study to explore the possibility of storing the irradiated nuclear fuel from ACR in MACSTOR modules. This included work to consider ways of minimizing footprint both in the spent fuel storage bay and in the dry storage area.

The commercial finite element code ANSYS has been used in this study [1]. The FE model is used to complete simulations with the higher heat source using the same concrete structural dimensions to assess the feasibility of using the MACSTOR design for storing the ACR irradiated fuel.

This paper presents the results of the analysis. The results are used to confirm the possibility of using, with minimal changes to the design of the storage baskets and the structure, the proven design of the MACSTOR® 200 containment to store the ACR fuel bundles with higher enrichment and burnup. This has thus allowed us to confirm conceptual feasibility and move on to investigation of optimization.

KEYWORDS

Finite Element Analysis, Thermal Analysis, Dry Storage, Nuclear Spent Fuel.

INTRODUCTION

AECL has designed and licensed an air-cooled concrete structure (MACSTOR) for above ground dry storage to store irradiated fuel bundles for CANDU plants in Romania and Canada. The MACSTOR is designed to store 12,000 bundles in 20 storage cylinders. Each storage cylinder contains 10 storage baskets, and each basket holds 60 bundles. The storage cylinders are organized in 2 rows inside the concrete vault. The design assumes that the reference fuel is a CANDU 6 fuel bundle that has been water-cooled for at least 6 years before being stored in the dry storage. The corresponding heat release of each bundle is 6 W/bundle. The MACSTOR module is primarily cooled passively by natural convection. Experimental tests and field measurements have shown that the maximum concrete temperature was below the temperature limitations set by the CAN/CSA N287.3-93 standards [1].

Currently AECL has been developing the ACR (Advanced CANDU Reactor) to meet customer needs for reduced capital cost and enhanced safety features. MACSTOR is being analyzed as a dry storage of ACR spent fuel.

A 2-D finite element (FE) model was developed to carry out the heat transfer analysis in which both the solid (concrete structure) and fluid (air) are modelled explicitly. The objective of this model is to calculate the temperature distribution in the concrete structure and the flow field of the air inside the structure.

A second model is developed to simulate the details of the basket, storage cylinder, cover gas and air. The thermal analysis in the second model is intended to evaluate the temperature distribution inside the storage cylinder, baskets and bundles, especially at the surface of the bundles.

The objective of this analysis is to obtain the temperature distribution in the concrete structure to confirm the maximum number of ACR fuel bundles that can be safely stored in a MACSTOR module with minimum or no change to the design. To achieve this objective, a steady state heat transfer analysis is performed to evaluate the peak concrete temperature as well as the fuel surface temperature during the dry storage and ensure they are below the acceptance criteria.

ANALYSIS METHODOLOGY

The FE method has been used in this analysis employing the heat transfer and the flow modelling capabilities of ANSYS multiphysics program [1]. ANSYS FLOTRAN is a finite element CFD module to model transient and steady state fluid/thermal systems that involve fluid and solid regions. The element used in this analysis is FLUID 141 from the ANSYS element library. This element has temperature, pressure, and velocities as degrees of freedom at each node. The flow problem is non-linear and the governing equations are coupled together. FLOTRAN uses a segregated sequential solution, where each matrix system derived for (temperature for thermal and pressure + velocities for flow) is solved separately. The sequential solution of all the governing equations combined with the update of the temperature and/or pressure dependant properties, constitutes a global iteration. The number of iterations needed to achieve a converged solution depends on the size and stability of the problem. For natural convection problems, the mesh should be very fine especially close to the walls in order to achieve a converged solution. This module is used in a model to simulate the air movement by natural convection. This model included the concrete structure, storage cylinders and air. This model was used to calculate the concrete structure temperature distribution based on ACR heat release value of the spent fuel. Some of the results from this model are used as input to the second model. This model is referred to as the dry storage model.

A second model simulated details of the basket, storage cylinder, cover gas and air. The thermal analysis in the second model was intended to evaluate the temperature distribution inside the storage cylinder, baskets and bundles, especially at the surface temperature of the bundles. The modes of heat transfer in this model are conduction and radiation. This model is referred to as the storage cylinder model.

ACCEPTANCE CRITERIA

The acceptance criteria are based on the following temperature limits.

Concrete Temperature Limit

The maximum concrete temperature is based on CAN/CSA 287.3-93 [2]. The standard states that during normal operation or post-accident conditions over any prolonged periods, the concrete temperatures shall not exceed,

- 65°C maximum temperature over large areas.
- 100°C over local areas in the proximity of penetrations for hot piping.

Fuel Temperature Limit

For CANDU 6 fuel, the temperature limit is 160° C. This temperature was based on studying the fuel oxidation using experimental data of tests performed at the Whiteshell Laboratory of AECL. In these tests air was used as the cover gas inside the basket.

In another study by Japan Atomic Energy Research Institute (JAERI) 160°C is also reported as the allowable upper limit of storage temperature of failed spent fuel in air atmosphere [3]. The temperature limit for CANDU 6 fuel was recently reviewed and adjusted to be 169°C [4] after considering more field data. For the purpose of this analysis 160°C will, conservatively, be considered as the temperature limit for fuel storage in air.

DESIGN DESCRIPTION

Geometry Description of the MACSTOR Module

The overall dimensions of the MACSTOR dry storage are 21.6 m in length, 7.5 m in height, and 8.1 m in width as shown in Figure 1 [4]. The number of spent fuel storage cylinders is 20 arranged in 2 rows. The distance between the centres of the two rows is 2.235 m (88 in). The bottom of each storage cylinder is 0.1m (4 in) above the concrete base. There are five air inlets and 6 air outlets located at the bottom and top, respectively, of each of the two exterior sidewalls.

Geometry Description of the Storage Cylinder

The overall dimensions are shown in Figure 2. The basket inside diameter for ACR is ~ 0.80 m and wall thickness is 3 mm. The basket is assumed to store 36 bundles on a triangular pitch to form a hexagonal array of bundles inside the basket. The clearance between the storage cylinder and the basket is 25.4 mm (1 inch). The space between the basket and storage cylinder is occupied by air. The space between the bundles inside the basket is filled by either air or helium as cover gas. The analysis presented in this paper used air as cover gas.

MODEL DESCRIPTION

The MACSTOR module is a 3-dimensional structure with many inlets and outlets. A coupled heat transfer-flow analysis of the whole structure would require a very fine (large) mesh and computational time. The solution can be bounded by two simpler 2-dimensional models as discussed below.

Model Description of the Dry Storage

A 2-D FE model is developed to model a typical vertical cross section in the middle of the MACSTOR module. The model is, conservatively, based on a cross-section where the clearance between the storage cylinder and the concrete wall is minimum. Figure 3 shows a schematic of the main components simulated in the FE model. Since the MACSTOR module is symmetric at the center, only ½ of the physical arrangement cross-section has been modelled. The inlets are designed with an offset in the axial direction such that 5 inlet openings on the outer side of the wall become 6 inlet openings in the inside part of the wall. There is an inner plenum between them. This has been simplified in the FE model to be aligned on the same vertical plane. The same simplification is applied to the outlet openings at the top of the model. This simplification implies that the air inlets and outlets are modelled as long ducts in the third dimension, which adds extra volume of air in the FE model than in reality. On the other hand, the storage cylinder is modelled as a long slab in the third dimension, which reduces the amount of air surrounding the storage cylinder in the FE model than in reality. Combining both effects, the total amount of air inside the FE model is less than that of the real arrangement. This indicates that the FE model is still conservative.

The model consists of 16,600 elements. The type of finite element selected for the simulation was FLUID141 from the ANSYS elements library, which has temperature, pressure, and velocity as degrees of freedom.

The thermal load and boundary conditions used in the model are listed below:

- The cylinders loaded with irradiated fuel bundles held in baskets were modelled as a solid slab called 'storage cylinder' in Figure 3.
- This heat load is applied to each element of the storage cylinder part of the model as a uniform heat generation load (W/m^2).
- Natural convection is assumed at the outer (right side) and top surfaces of the model.
- Air temperature outside the concrete structure is assumed to be 40°C and the heat transfer coefficient is 5 $W/m^2.K$. This is a typical conservative value based on natural convection in air.
- Air inside the concrete structure is modelled explicitly by flow elements to simulate the airflow due to natural convection. Thermal and physical properties of the air inside the model will automatically be calculated by ANSYS based on its current conditions.
- The air pressure at the outlet is atmospheric.
- The ground below the MACSTOR is considered to have low conductivity and is not modelled. Accordingly, the bottom of the model is conservatively assumed insulated.
- Symmetric conditions are considered on the left side (center) of the model.

The main objective of this model is to determine the maximum temperature in the concrete wall.

Model Description of the Storage Cylinder

Another 2-D FE model is developed to model a typical horizontal cross section in the middle of the storage cylinder. Air and cover gas are considered stagnant inside this model. Taking advantage of the hexagonal symmetry, a 30-degree sector of the storage cylinder is considered in this model. Figure 4 shows the main components used in the model. The model has four bundles, which are modelled as homogenous solid material, and one bundle that is modelled in detail. The model has 14,569 elements and 14,814 nodes. The elements type is PLANE55 from ANSYS elements library, which has temperature as a degree of freedom. The thermal load and boundary conditions used in this model are summarized below:

- The heat generation per unit area in the bundles corresponds to heat release of ACR spent fuel. A one value (3100 W/m^2) is applied to the homogenous-modelled bundles. Different heat generation values are applied to the pencils in ring 1, ring 2, ring 3, and ring 4 of the detailed bundle, respectively (ring 1 is at the centre of the bundle while ring 4 is on the outside). This load is applied to each fuel element of each ring of the bundle, part of the model, as a uniform heat generation load.
- Natural convection is assumed on the surface of the storage cylinder. The bulk temperature of the air outside the storage cylinder is, conservatively, assumed to be 80^{o}C and the heat transfer coefficient is 2 $W/m^2.K$. This bulk temperature is higher than the predicted air temperature from the dry storage thermal analysis above.
- Symmetric conditions are considered at the two cut edges of the thermal model (i.e., the horizontal line and at a line 30° from the horizontal).
- Radiation between the basket and the storage cylinder surfaces has been considered, as well as radiation between the bundles inside the basket.

The main objective of this model is to determine the maximum temperature in the basket wall and the fuel sheath.

Material Properties

Thermal Properties of Basic Material (Non-Fuel)

The material properties used in the dry storage model are listed in Table -1.

Table -1
Material Properties at 40°C – for Dry Storage Model

Material	Density (kg/m^3)	Specific Heat (J/kg.K)	Thermal Conductivity (W/m.K)
Air	1.128	1.004E+3	27.3E-3
Storage Cylinder	7813	473	42.0
Concrete	2300	880	1.4

The concrete and the storage cylinder material properties are extracted from [6]. The material properties of air are function of temperature and are provided by ANSYS multiphysics during the iterative solution procedure.

A summary of the material properties used in the storage cylinder model is listed in Table -2. The cylinder, basket, and air properties are extracted from Reference [6].

In order to simplify the storage cylinder model, some of the bundles are modelled as homogenous material. The effective thermal conductivity has been calculated taking into account the volumetric ratio of the various elements, cover gas and zircalloy. Following this approach, the effective thermal conductivity of the fuel bundle is given below.

$K_e = 4.304$ W/(m.K)

Table -2
Thermal Conductivities at 177°C (400°K) – for Storage Cylinder Model

Material	Thermal Conductivity, W/(m.K)	Reference
Air	30.09E-03	Reference [6]
Storage Cylinder, Carbon Steel	42.0	Reference [6]
Basket and Bundle sleeves, Stainless Steel	16.6	
Enriched Uranium 2.1%	5.2	

Uranium with 7.5% Dy	3.911	
Fuel as Homogenous material	4.304	

CANDU 6 RESULTS (VALIDATION OF THE DRY STORAGE MODEL)

In order to validate the model, a run was completed using a heat release equivalent to CANDU 6 spent fuel after 6 years of storage in water-cooled bay (6 W/bundle). The results from the current analysis are compared with results from experimental results conducted by AECL.

The analysis considers that the storage cylinder has 10 baskets and each basket has 60 bundles. The total heat from one storage cylinder is about 3600 Watts.

The results from the model show that the heat from the storage cylinder walls is transferred to the ambient air. Some of the heat is conducted to the concrete, but most of it will be transferred to the ambient air through the movement of the internal air due to natural convection. The heat balance results show that 93.5% of the heat is removed by natural convection while 6.5% of the heat is removed by conduction through the concrete. Figure 5 shows the air velocity distribution in the model. It shows how the air is moving from inlet opening at the bottom to the storage cylinder, up to the outlet opening. This air movement is as expected due to natural convection.

Figure 6 shows the general temperature distribution in the model. The highest temperature is in the storage cylinder, 107°C. Figure 7 shows the temperature distribution in the concrete, with the highest temperature at 68°C. Results from the experimental data of tests performed at AECL show that the concrete temperature is between 28°C and 33°C above the ambient. Considering that the ambient temperature is 40°C, the concrete temperature is between 68°C to 73°C. Comparison of the results from the experimental tests and the current ANSYS analysis shows that the model has simulated the experiment and shows good agreement. Another analysis of field data from CANSTOR 2 of Gentilly 2 showed that the concrete temperature on the inside vertical wall is at about 57^{o}C while the maximum concrete temperature at the ceiling is about 68^{o}C. The current FE model predicted the same thermal behaviour as shown in Figure 7.

ACR THERMAL ANALYSIS

This section presents and discusses the results of the two models as applicable to ACR reactor.

Dry Storage Model

Two simulations have been completed for the concrete structure of the MACSTOR module. The first case is to provide the temperature in the concrete wall based on the heat release from ACR fuel bundles. The second case is similar to the first except that the dimensions of the storage cylinder are changed. The heat generation per unit area Q" (340 W/m^2) in this component corresponds to heat release of spent fuel (12 W/bundle). This represents the heat release from 36-ACR bundles passing through the cylindrical wall of a basket.

Case 1 – MACSTOR Type

For the purpose of this analysis it is assumed that the MACSTOR will have storage cylinders organized similar to the current design of the MACSTOR. However, it has been assumed that each basket has only 36 bundles instead of 60 bundles. Consequently, the total heat source from one storage cylinder is 4248 Watts. This represents an increase in the heat release by 16.4% compared to the heat release from CANDU 6 fuel bundles.

The results from this simulation show that 93.8% of the heat is removed by natural convection while 6.2% of the heat is removed by conduction through the concrete.

Figure 8 shows the general temperature distribution in the model. The highest temperature within the storage cylinder is 116°C. The concrete temperature distribution is shown in Figure 9, and the highest temperature is 72°C. It is important to note that although the increase in heat release is 16.4%, the increase in the highest temperature is less than 8% compared to CANDU 6. This is due to the increase of airflow velocity around the storage cylinder carrying the thermal energy by natural convection. However, the highest temperature on the concrete surface (72°C) is higher than the acceptance criterion (65°C).

Case 2 – Alternative Model

In Case 1 above, it has been assumed that the size of the storage cylinder is the same in spite of reducing the number of bundles in each basket from 60 bundles to 36 bundles where the clearance between the cylinder wall and concrete wall is only 0.152 m (6 in).

In order to investigate the effect of reducing the size of the storage cylinder on the concrete temperature, a new simulation is completed with the diameter of the storage cylinder reduced from 1.117 m (44 in) to 0.89 m (35 in). The new diameter is based on basket with diameter 0.756 m (29.75 in) to hold 36 bundles welded together in a hexagonal array and about 0.0635 m (2.5 in) clearance between basket and the storage cylinder.

The results of the analysis are shown in Figures 10 and 11. As expected, the highest concrete temperature has dropped from 72°C to 64°C, which is below the acceptance criterion (65°C). This is because the increased distance between the storage cylinder wall and the concrete surface has allowed for more air circulation around the storage cylinder.

The results from both models are considered conservative for the following reasons:

- The dry storage module is assumed to be fully loaded in a short time with spent fuel bundles of equivalent heat load.
- No heat decay is considered after sequential loading of the fuel bundles.
- The ambient air temperature outside the dry storage module is assumed to be 40°C all the time.

Storage Cylinder Model

In this simulation the storage cylinder has a diameter of 0.841 m as shown in Figure 2. The clearance between the storage cylinder and the basket is 0.0254 m (1 in). This is a conservative assumption since the design of the storage cylinder and the basket is not finalized yet. In this model, heat is removed by conduction and radiation only because the air and cover gas are stagnant. The cover gas used in this simulation is air.

Figure 12 shows the temperature distribution in the model. The model shows that the maximum temperature is about 171°C close to the center of the storage cylinder. Figure 13 shows the detailed temperature distribution inside the hottest bundle in the model. This temperature is slightly higher than the allowable fuel temperature for spent fuel stored in air (160°C) as specified earlier. The difference can be accounted for by reducing the conservatism in both the modelling and/or heat loading input.

As a sensitivity analysis, another simulation is completed with the cover gas being helium. Figure 14 shows the general temperature distribution inside the basket in this simulation. The highest temperature in this case is 155° C. The advantage of using inert gas as cover gas is that the allowable temperature will be higher because the oxidation rate of defected bundles is much less in inert gas than in air. The inert gas option is available as an ultimate solution for any design changes that may result in significant temperature increase.

Alternatively, one minor modification to the design of MACSTOR could also provide a solution. For example, increasing the spacing between the storage cylinder or adding chimneys to the outlets will increase the air flow, reducing the bulk temperature of air, which would reduce the fuel temperature.

CONCLUSION AND RECOMMENDATION

Based on this work, we have shown that dry storage is not a risk for ACR as we can use proven technology of MACSTOR, and that we have the analysis tools to allow us to optimize fuel storage to suit customer requirements. Based on other considerations a 36-bundle basket design is assumed for ACR instead of the 60-bundle basket that is currently used in MACSTOR.

A FE model is developed based on the current MACSTOR design and the storage cylinder dimensions where the gap between the storage cylinder and the concrete wall is increased by 0.11m (4.5 in) to account for the reduced number of bundles per basket (36 bundle/basket vs 60 bundles in CANDU 6 baskets). In this model, the maximum temperature is 64°C, which is less than the allowable limit of 65°C

A detailed FE model of the storage cylinder indicates that the maximum temperature of the fuel sheath is 171°C using air as cover gas. Although the temperature is slightly higher than the allowable temperature limit but the difference can be accounted for by reducing the conservatism in both the modelling and/or heat loading input.

The results of this analysis confirm the feasibility of using the current design of MACSTOR to store the ACR fuel bundles with heat load up to 12 W/bundle provided that minor modification to the design of the MACSTOR is introduced

The option of using inert gas as cover gas inside the basket will be evaluated in the final design for instance to offset potential higher sheath temperature should use of higher bundle power is considered

This work has thus allowed us to confirm conceptual feasibility and move on to optimization of the fuel storage bay size and the corresponding area for dry fuel storage modules. Future work is considering options for lower fuel bundle powers on discharge from wet storage and increasing the numbers of fuel bundles in the dry fuel storage modules.

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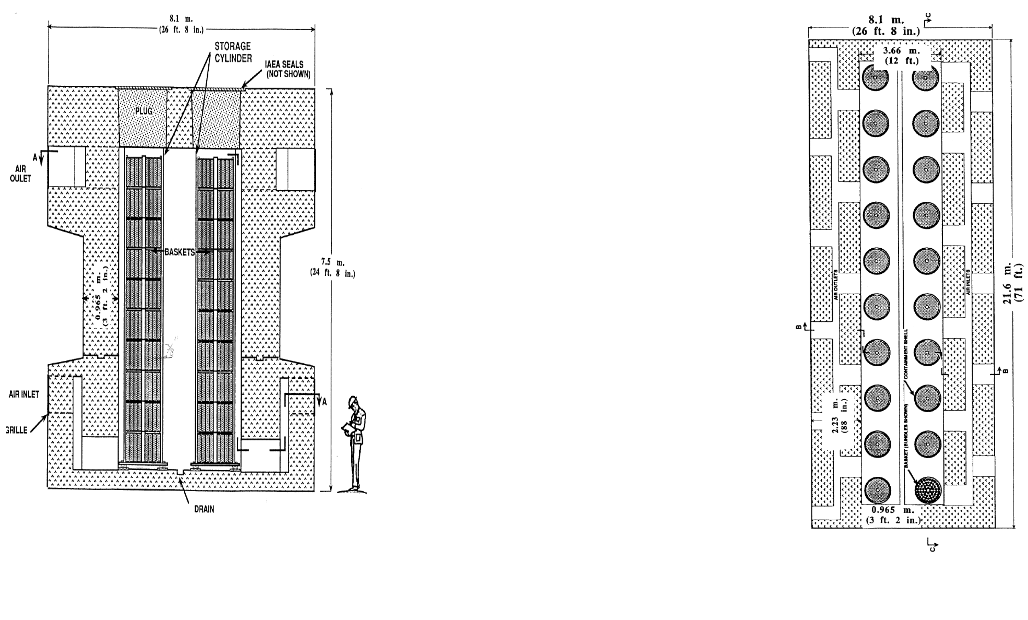

Figure 1 MACSTOR General Dimensions [4]

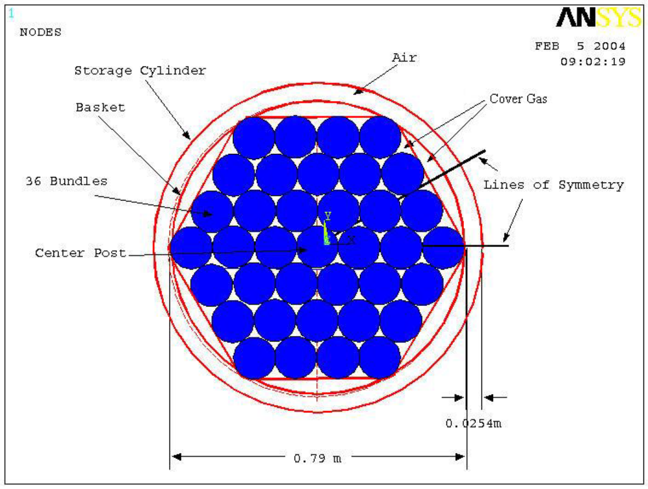

Figure 2 General Dimensions of Cross Section in Storage Cylinder and its Contents

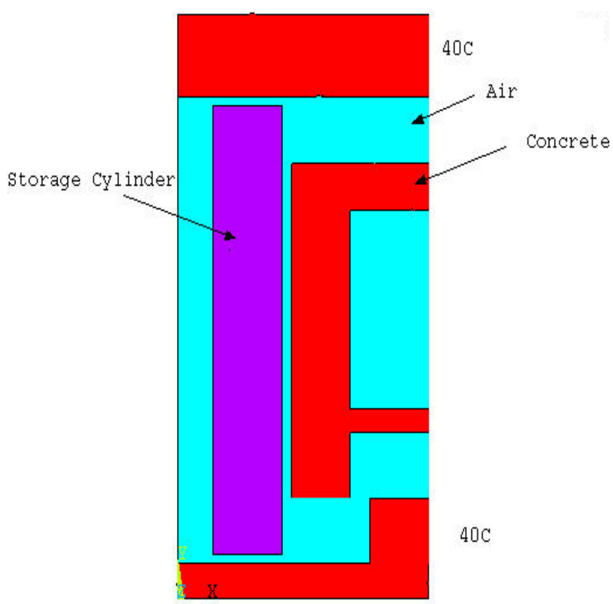

Figure 3 Finite Element Model of the Dry Storage

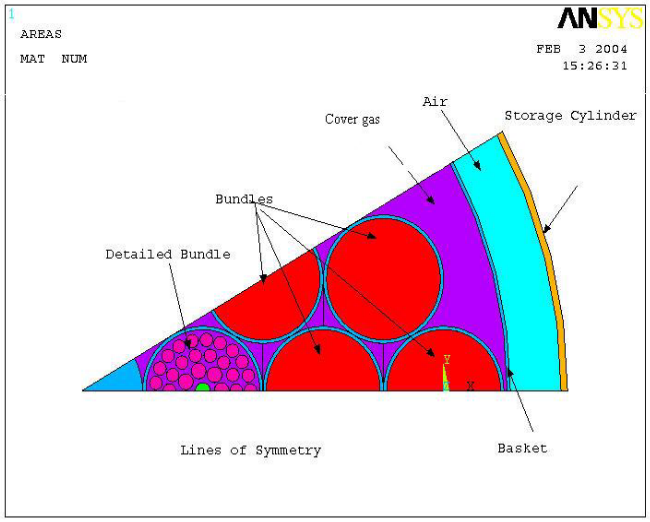

Figure 4 Detailed Finite Element Model

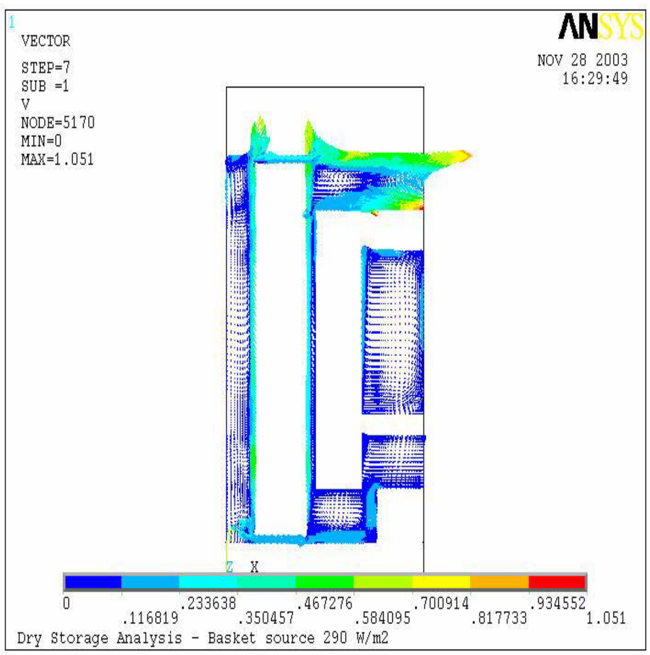

Figure 5 Air Velocity Distribution (m/s), CANDU 6 Model

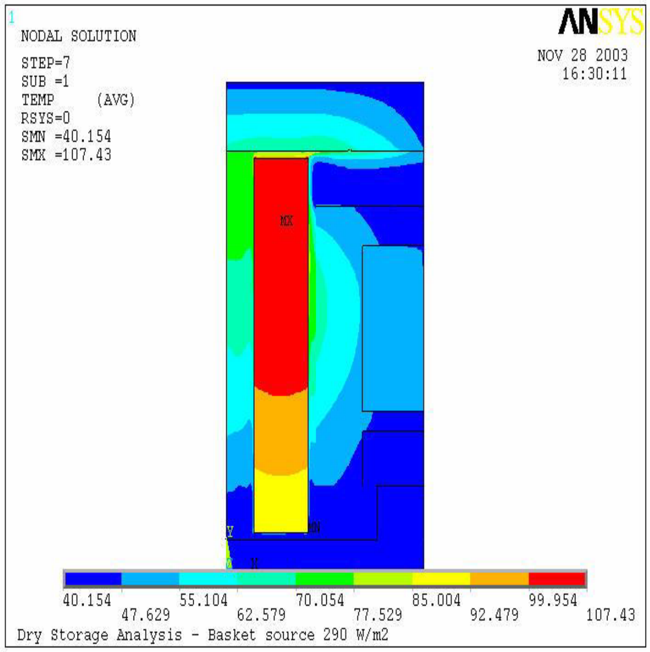

Figure 6 General Temperature Distribution (°C), CANDU 6 Model

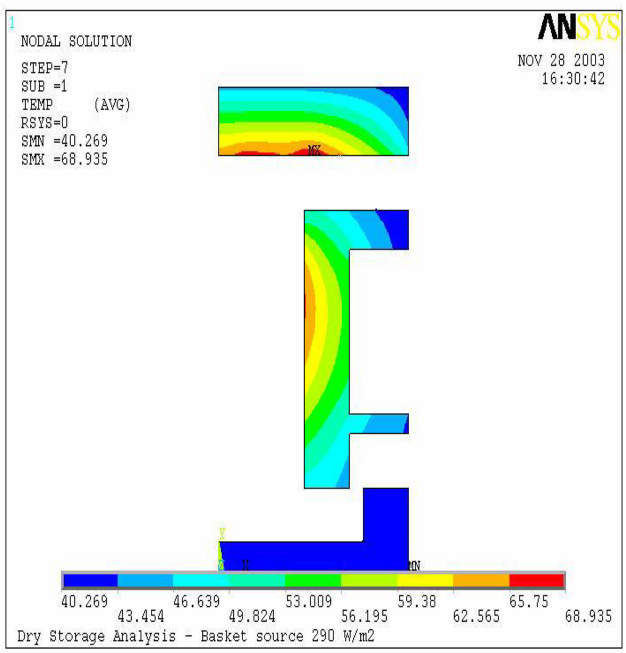

Figure 7 Concrete Temperature Distribution (°C), CANDU 6 Model

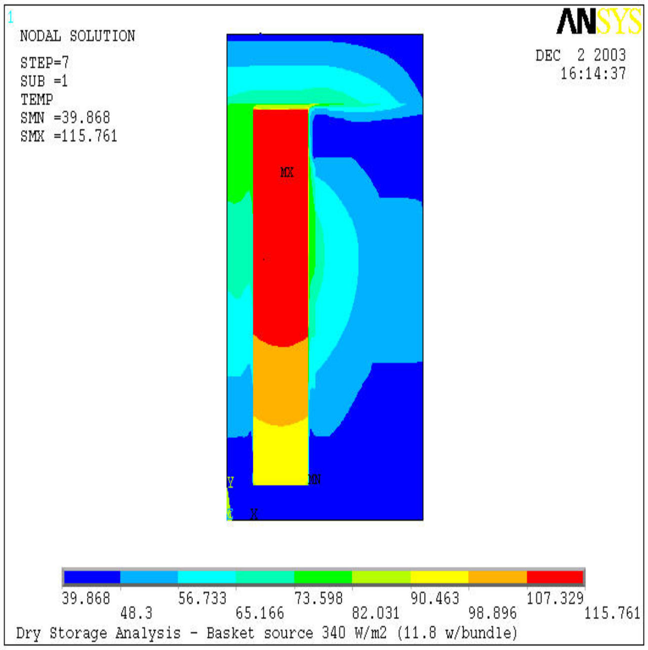

Figure 8 General Temperature Distribution (°C), ACR Model – Case-1

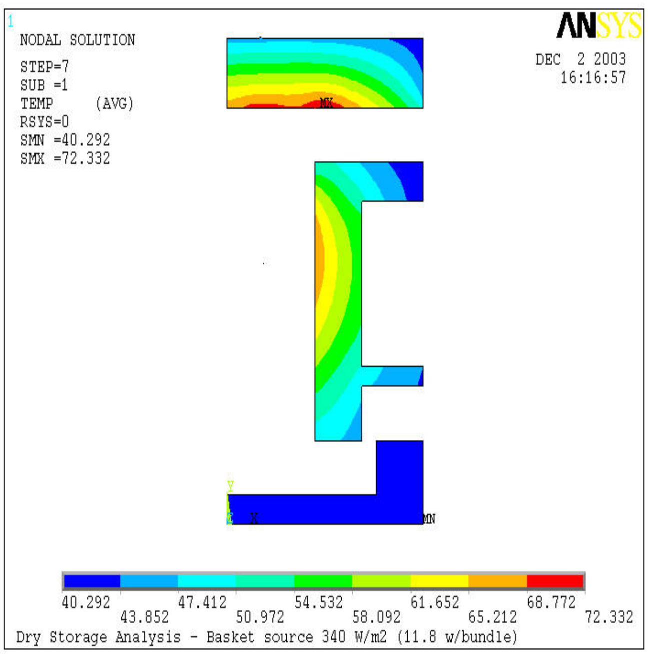

Figure 9 Concrete Temperature Distribution (°C), ACR Model – Case-1

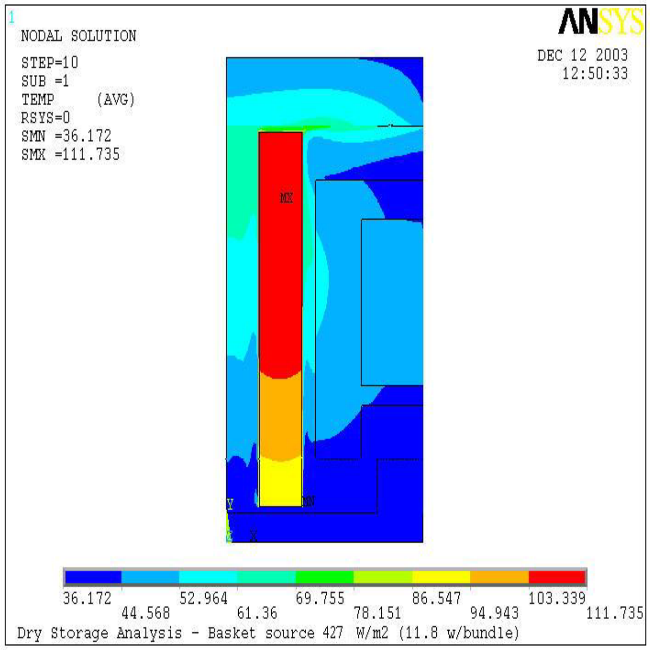

Figure 10 General Temperature Distribution (°C), ACR Model - Case-2

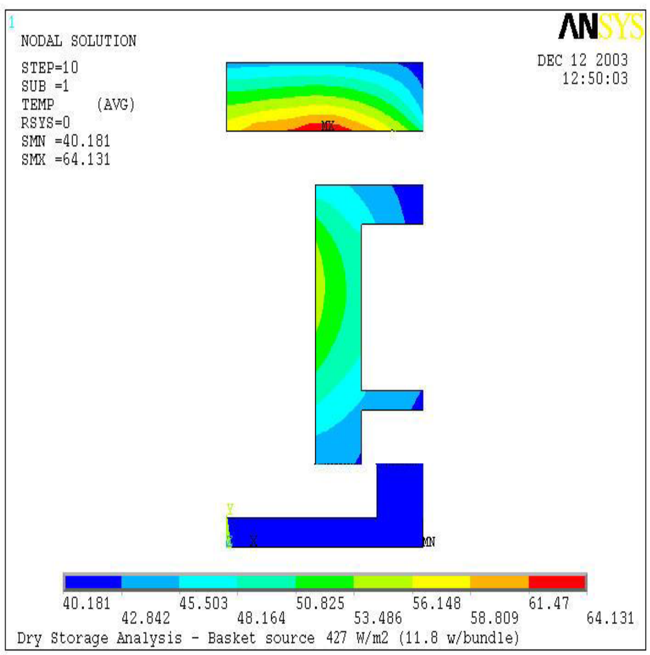

Figure 11 Concrete Temperature Distribution (°C), ACR Model – Case-2

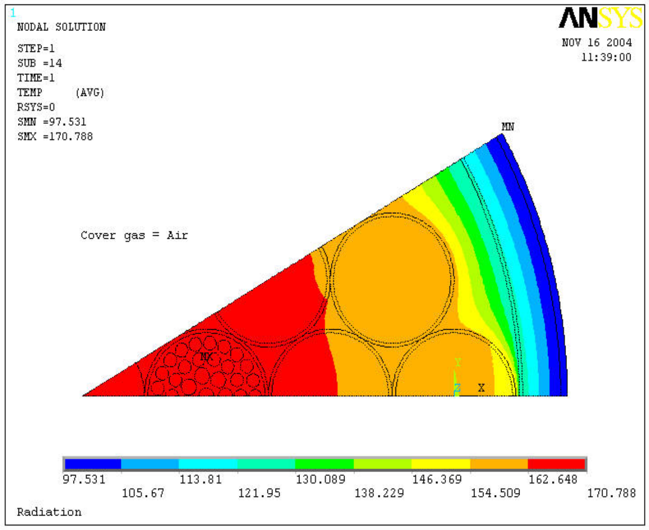

Figure 12 General Temperature Distribution (°C) – Storage Cylinder Model, Air Cover Gas

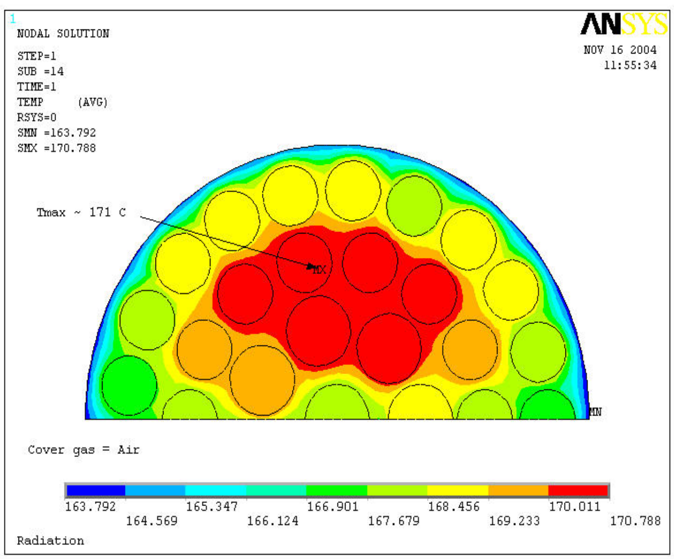

Figure 13 Detailed Temperature Distribution in the Hottest Bundle (°C) – Storage Cylinder Model, Air Cover Gas

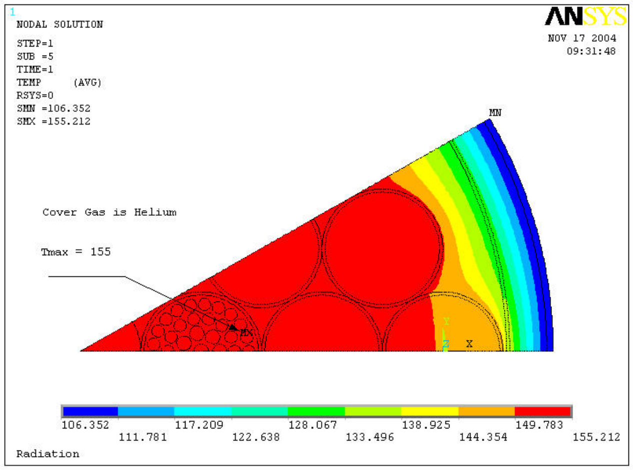

Figure 14 General Temperature Distribution (°C) – Storage Cylinder Model, Helium Cover Gas