Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division VI

OPTIMIZED DESIGN OF METALLIC CONTAINMENT ISOLATION HATCHES IN CANDU NUCLEAR POWER PLANTS

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ABSTRACT

Refurbishment programs of existing multi-unit CANDU®[1] nuclear power plants are underway to extend their operating life via replacement of critical life-limiting components such as the fuel channels, feeders, and steam generators. Due to extended long duration of the refurbishment program, the replacement of these components located in the reactor vault of each unit requires the vault to be isolated from the rest of the operating multi-unit station. The containment isolation is achieved via a few measures including the installation of two hatches (commonly known as horizontal bulkheads) to close the two openings dedicated to the fuelling machine duct located in front of the two faces of the reactor. The integrity of the containment isolation hatches needs to be confirmed according to the Canadian containment design code, i.e., CSA N287.3. In particular, the adequacy of the anchorage of the metallic hatches to the massive steel-lined prestressed concrete vault needs to be demonstrated. Load combinations including a potential accident in an operating unit while the refurbished vault is being tested present higher demand on the isolation system. Coupled and decoupled structural analyses were performed for the refurbished vault including the isolation system. The loads defined per applicable design codes, i.e., CSA N287.3 and ASME BPVC Section III, were applied to a combined model of the vault and the metallic isolation hatches and to a single detailed analysis model of one of the metallic hatches. The integrity of the isolation system along with its anchorage has been demonstrated to meet the acceptance criteria of the applicable design codes. In addition, the analyses highlighted the potential for conservatively estimating the interactions forces between the metallic hatches and the concrete vault.

INTRODUCTION

Refurbishment programs are underway to extend the operating life of existing multi-unit CANDU nuclear power plants via replacement of critical life-limiting components located inside the reactor vault such as the fuel channels, feeders, and steam generators. Due to extended long duration of refurbishment programs, the replacement of these components of one unit requires the vault to be isolated from the rest of the operating multi-unit station. Such isolation will allow safer and easier methods of construction activities and provide additional safety barriers to the workers, public, and environment. Therefore, containment boundary of the multi-unit station must be modified to isolate the unit undergoing refurbishment. The containment isolation is achieved via a few measures including the installation of two isolation bulkhead hatches (commonly known as horizontal bulkheads) to close the two openings dedicated to the fuelling machine duct located in front of the two faces of the reactor. The fuelling machine duct is shared between the station's four identical units and connects them to the vacuum building which is one of the main

[1] CANDU stands for Canada Deuterium Uranium. CANDU is a trademark of Candu Inc.

components of the station's containment boundary. In addition to the hatches, all other miscellaneous openings and process lines between the vault and the duct must be sealed.

After the vault is isolated and before its airlocks are opened for the planned refurbishment, a pressure test of the modified containment is performed to ensure the adequacy of the modified containment boundary. A second pressure test of the vault is carried out after the unit refurbishment is complete and before the isolation hatches are removed and other openings are unsealed to ensure the integrity of the vault's containment boundary before the unit is returned to operation.

Figure 1 illustrates the containment isolation of one unit from the rest of the operating units. The modified containment boundary in the refurbished unit is shown in Figure 2 compared to the normal operation containment boundary.

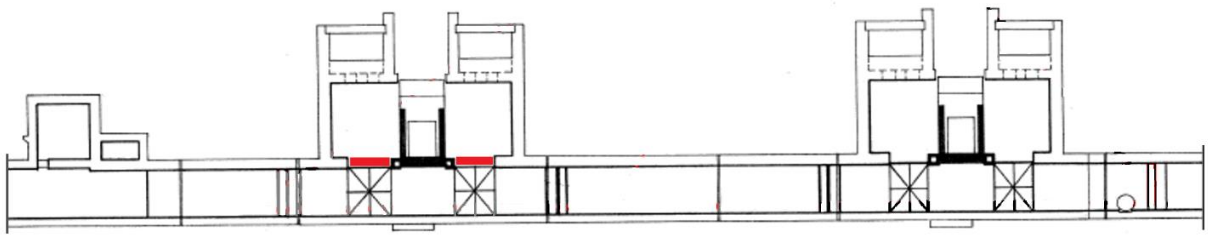
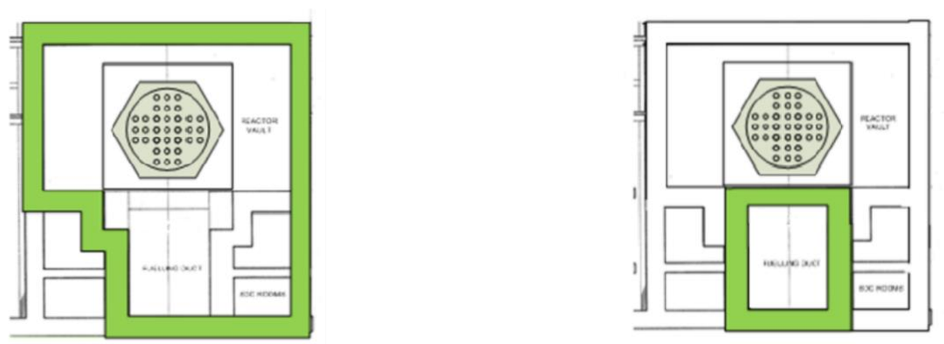


Figure 1. Containment Isolation of Refurbished Unit from Rest of Operating Station



(a) Normal Operation Unit (b) Refurbished Unit

Figure 2. Containment Boundary

To meet the Canadian Nuclear Safety Commission (CNSC) regulatory requirement governing overpressure protection, REGDOC 2.5.2, the integrity of the containment isolation hatches needs to be confirmed for all applicable loading combinations according to the Canadian containment design code, i.e., CSA N287.3. In particular, the adequacy of the anchorage of the metallic hatches to the massive steel-lined prestressed concrete vault needs to be demonstrated. Load combinations including a potential accident in an operating unit while the refurbished vault is being tested present higher demand on the isolation system.

Therefore, structural analyses are performed for the refurbished vault including the isolation system. Two sets of analyses are performed: a coupled analysis and a decoupled analysis. In the coupled analysis, a combined analysis model of the vault and the metallic isolation hatches is developed. A set of analysis load cases defined per the vault concrete containment design code is applied. In the decoupled analysis, a single detailed analysis model of one of the metallic hatches is developed. The analysis load cases were defined per the applicable design codes, i.e., CSA N287.3 and ASME BPVC Section III. The objectives of the analyses are: (a) to assess the stresses and strains developed in different parts, and (b) to determine the interaction forces between the metallic hatches and the concrete vault.

This paper presents a summary of a case study for coupled and decoupled analyses of the metallic isolation hatches for the vault. A set of recommendations for modelling and analysis approaches to deal with such modification to the containment boundary are made.

DESCRIPTION OF ISOLATION HATCHES

The isolation bulkheads form part of the containment system, isolating the reactor vault from the Fuelling Machine Duct (FMD) while other reactors are in operation. The isolation bulkhead panels are installed at the fuelling machine openings on either side of the calandria in the vault slab. The isolation bulkhead for each opening typically consists of eight individual panels that are supported along the walls of the FMD and on a steel structure on the centre line of the FMD. Sealing against the release of contaminated gases and fission products is achieved using elastomeric compression seals between the panels, and between the panels and the adjacent supporting structures. Once installed, the containment isolation bulkheads permit opening both doors of the vault airlocks and the transfer chambers to facilitate access into the vault for in-service testing and inspection, or maintenance of equipment.

Figure 3 presents an outline of the containment isolation bulkhead deign (located on either side of the reactor). The major components of the isolation bulkhead design consist of the following parts:

- Central Support Structure: Existing steel braced frame with three columns supporting a top beam spanning along the centre line of FMD. The column base plates are anchored to the top surface of the reinforced concrete foundation of the FMD.
- Side Support Structures: Two vertical box-shaped structures, each consisting of a top plate, a vertical skin plate and vertical W-shaped sections supported on base plates. The side support structures are placed in depressed areas in the FMD walls adjacent to the fuelling machine bridge columns. The side support structures are anchored to the FMD walls and floors via embedded steel plates.
- Box Beam: A fabricated steel beam section spanning across the FMD adjacent to the side of the calandria, to which the bulkhead panels are sealed.
- Bulkhead Panels: Eight panels are bolted to the ledges along the FMD walls and to the two Side Support Structures and to the Central Support Structure. The panels are supported on the box beam on one side and to the steel-lined vault slab on the other side.
- Elastomeric Compression Seals: Sealing against the release of contaminated gases and fission products is achieved using compression seals between the panels, and between the panels and the adjacent supporting structures. Such seals also provide some flexibility of the differential movements between the panels and the supporting structures under different stress conditions.

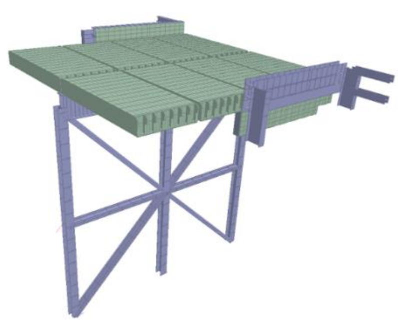


Figure 3. An Outline of The Containment Isolation System

It should be noted that the panels, the side support structures, and the seals are considered parts of the temporary or modified containment boundary. The major function of the central support structure and box beam is to support the parts forming the temporary containment boundary.

GOVERNING LOAD CONDITIONS & LOAD COMBINATIONS

Since individual components are expected to perform different safety functions and are made of different materials. The applicable nuclear codes and standards for the design and assessment of the components of the containment isolation system are: (a) CSA N285, which refers to ASME BVP Code, Section III, Division I, Subsections NE & NF, and (b) CSA N287.3. The first is for the design of pressure-retaining components and the second for the design of concrete containments. In general, the metallic containment boundary formed by the panels, side support structures, seal plates and welds used to connect them are to follow Subsection NE of the ASME BVP Code. The central support structure including all its members and lateral supports is to follow Subsection NF of the ASME BVP Code. Base plates, embedded plates and anchor bolts used in transferring the structural reactions of the isolation system to the reinforced concrete foundation of the FMD are to follow CSA N287.3.

After its construction, the containment isolation bulkhead design will perform its function to isolate the refurbished unit; therefore, it will experience any of the following states:

- State 1: the bulkhead is in normal operation conditions
- State 2: the bulkhead is undergoing either proof or leak rate pressure tests
- State 3: the bulkhead is subjected to pressure & temperature due to accident in any other operating unit
- State 4: the bulkhead is undergoing vault tests AND is subjected to pressure & temperature due to accident in any other operating unit
- State 5: the bulkhead & whole station are subjected to Design Basis Earthquake

The following considerations are made in evaluating the applicable loading conditions and load combination for the design and assessment of the containment isolation system:

- Pressure Tests: The commissioning of the containment isolation system requires proof and leakage rate tests. Both tests will be conducted inside the isolated vault side. After the unit refurbishment is complete, the containment isolation system is removed to return the isolated vault to service. Before the isolation system is removed, a vault pressure test is performed to demonstrate that the isolated vault meets all containment requirements.
- Accidents: An accident in an adjacent operating unit would lead to the highest pressure and temperature transients in the FMD. In addition, inadvertent actuation of any of the instrumented pressure relief valves would cause the lowest sub atmospheric pressure in the FMD.
- Simultaneous Occurrence of Pressure Test and Accidents: The scenario of occurrence of an accident in an adjacent operating unit or an inadvertent actuation of any of the instrumented pressure relief valves during a pressure test need to be considered in the design of the containment isolation system. It should be noted that during the commissioning test, the system is not required to maintain its containment boundary since the isolated vault would be still intact and can effectively withstand any accident. But, for the pressure tests conducted prior to returning the isolated vault to service, the isolation system must be capable of withstanding concurrent loading from the pressure test and any accident from adjacent operating units.
- Earthquakes: According to the CSA N289.3 standard, two earthquake levels are defined for the design of nuclear structures, systems, and components: the Design Basis Earthquake (DBE) and the Site Design Earthquake (SDE). Therefore, both earthquake levels are applied in the design of the containment isolation system.

The various components of the containment isolation system are subjected to the following set of loading conditions per the applicable design codes:

- Dead loads (D)
- Live loads (L)

- Pressure loads: include pressure loads during testing (P_t), pressure loads during normal operation (P_{vo}), design positive accident pressure load (P_a), design negative accident pressure load (P_v), and reduced accident pressure load (P_r)
- Thermal loads: include thermal effect loads during operation & testing (T_o), and design accident thermal effect loads (T_a)
- Seismic loads: include inertia loads generated by the SDE (Q_{ES}) and DBE (Q_{ED})

Following applicable design codes and standards, load combinations are defined to determine the demands due to combined effects of various loading conditions during each of the five states. The safety functions assigned to the isolation system during the five states form the basis for defining individual loading conditions. Loading categories per N287.3 include service, environmental and accident categories. Service Limits per ASME BVC code include design, test, accident, and faulted conditions. A loading category or a service limit includes a set of load combinations that covers possible combined effects of different events. A load combination is formed by applying code-specific load factors to individual loading conditions representing the demands of the combined events. Tables 1 and 2 presents the load combinations used in this study to assess the design of the containment isolation system, per N287.3 and N285; respectively.

Table 1: Applicable Load Combinations per N287.3

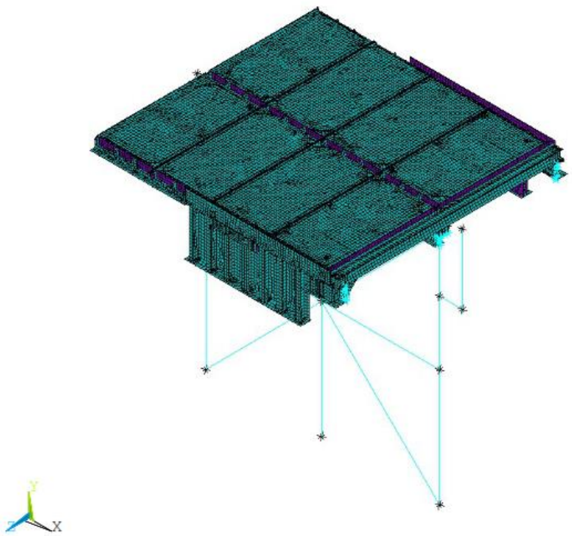
Category	Group	No.	Loads											State
			D	L	P_t	P_a	P_v	P_o	T_o	T_a	P_r	Q_{ES}	Q_{ED}	
Service	Construction	1	1.25	1.5					1.25					1
	Test	2	1.25	1.5	1.25				1.25					2
	Normal	3	1.25	1.5			1.5		1.25			1.5		1
		4	1.25	1.5				1.5	1.25			1.5		1
Abnormal/ Environmental	Abnormal	5	1.0	1.0		1.5				1.0				3
	Environmental	6	1.0	1.0				1.0	1.0				1.0	4
	Abnormal/ Environmental	7	1.0	1.0			1.0		1.0				1.0	4
		8	1.0	1.0					1.0		1.0		1.0	4
		9	1.0	1.0	1.0	1.0				1.0				5
		10	1.0	1.0	1.0		1.0		1.0					5

Table 2: Applicable Load Combinations per N285

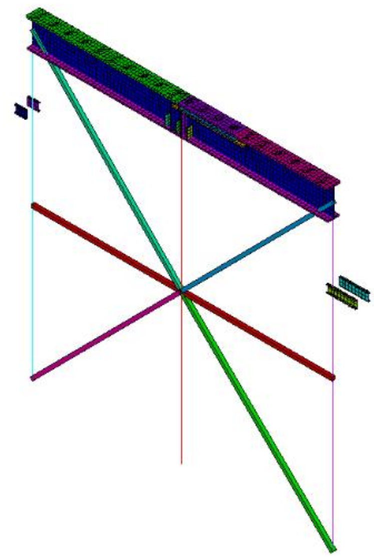
Service Level	No.	Loads											State
		D	L	P_t	P_a	P_v	P_o	T_o	T_a	P_r	Q_{ES}	Q_{ED}	
Testing	2	1.0	1.0	1.0				1.0					2
Design	5	1.0	1.0		1.0				1.0				3
Service Level A	1	1.0	1.0				1.0	1.0					1
Service Level B	3	1.0	1.0			1.0		1.0			1.0		1
	4	1.0	1.0				1.0	1.0			1.0		1
Service: Level C	6	1.0	1.0				1.0	1.0				1.0	4
	7	1.0	1.0			1.0		1.0				1.0	4
	8	1.0	1.0					1.0		1.0		1.0	4
Service Level D	9	1.0	1.0	1.0	1.0				1.0				5
	10	1.0	1.0	1.0		1.0		1.0					5

STRUCTURAL ANALYSES

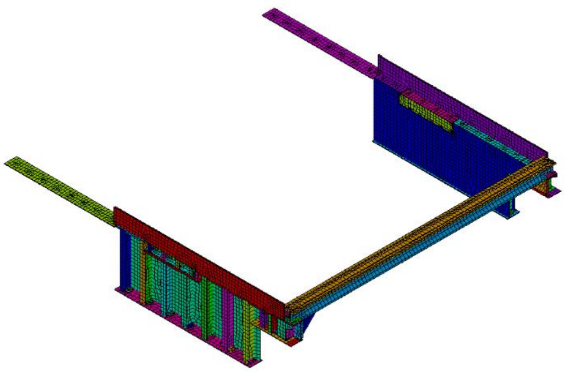
A numerical simulation model of the containment isolation system was developed to determine the governing design parameters in its different components. The model needs to be sufficiently detailed to assess the system when subjected to the combined effects of loading conditions per code-defined load combinations. The analysis model was developed using the general purpose ANSYS program in a logical manner: individual components of the isolation system were modelled first, then the sub-models were assembled in one integrated model. Figure 4 presents the integrated model of the isolation system and its main sub-models.



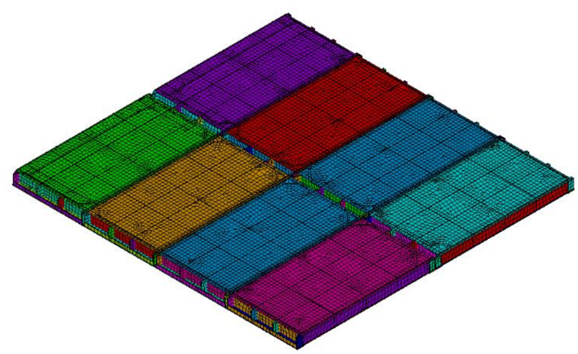
(a) Integrated model



(b) Central Support Structure



(c) Side Support Structures & Box Beam



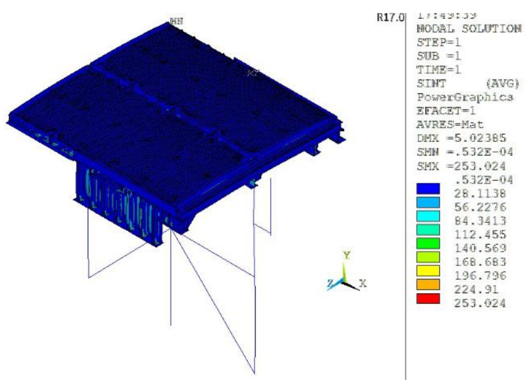
(d) Bulkhead Panels

Figure 4. Numerical Model of The Containment Isolation System

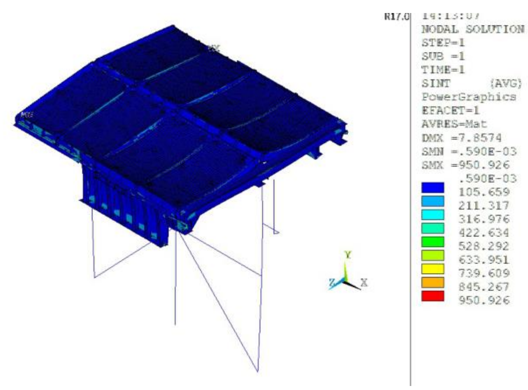
A mixture of finite element types such beam elements, shell elements (thin and thick), and multi-point-constraint element were used in developing the analysis model. Linear elastic material models are selected for the structural steel and plates of the different bulkhead parts. External boundary conditions are applied to the integrated model and internal multi-point connections are defined between the sub-models to simulate the load transfer mechanisms to the supporting reinforced concrete FMD structure. The validity of the model to resist different types of loading conditions was verified before applying loading conditions representing the structural demands on the isolation system.

The loads were applied in the form of concentrated nodal forces, distributed pressures, fields of gravity, nodal temperatures, and inertia effect due to ground shaking. The dead load case is simulated by applying the field of gravitational acceleration to the analysis model. The live load case is simulated by applying 'blanket' pressure load representing construction loads, any equipment load, and operational negative pressure during refurbishment. Two pressure load cases were defined by a general uniform pressure is applied to the surfaces of the containment boundary to reflect the testing and/or accident conditions. In one case, the pressure is applied from the vault side of the bulkhead panels (simulating testing scenarios), and in the other, the pressure is applied from the FMD side (simulating the accident scenarios). The thermal load case is simulated by applying differential temperature loads to the elements of the analysis model, along with a reference temperature reflecting the temperature during construction of the isolation system. In addition, three dynamic load cases were defined to determine the responses to each of the three spatial components of the seismic loads. The response spectrum analysis method is followed using the floor response spectrum defined at the foundation slab of the FMD.

The structural responses of the containment isolation system under each of the different loading conditions were determined by static and seismic analyses. Linear elastic materials behaviour was assumed in solving for the responses to the analysis load cases. Therefore, the design demands for each loading combination were determined by linearly adding the structural responses to individual loading conditions using the applicable load factors. The peak structural responses or governing demands are in the form of stresses and strains (panels and plates), internal forces and moments (structural steel members and their connections), and overall structural reactions (anchor bolts into the concrete). Figure 5 presents the stress response of the isolation systems due to pressure and temperature loading conditions resulting from accidents in other operating units.



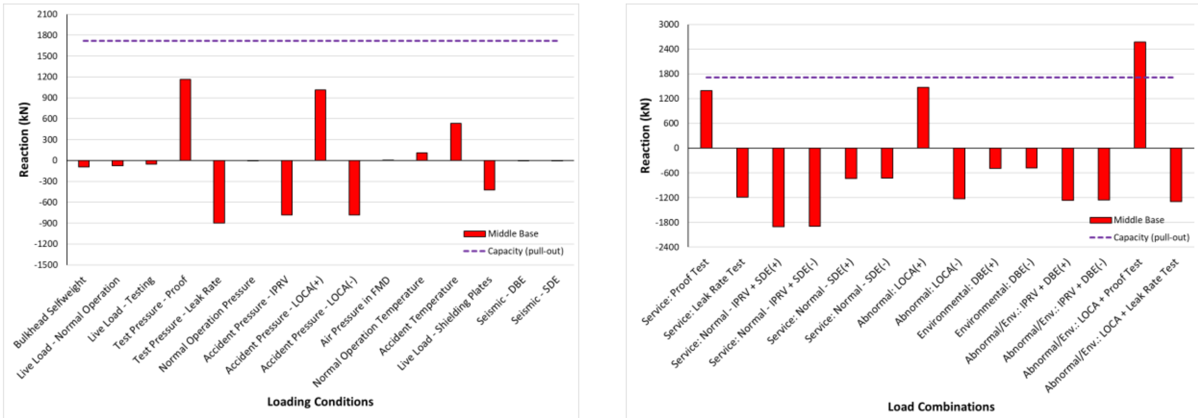
(a) Pressure Loading Condition



(b) Temperature Loading Condition

Figure 5. Stress Response to Accident in Other Operating Units

The adequacy of the isolation system design was investigated. Acceptance criteria per applicable design codes and standards, ensuring serviceability and integrity, were applied to demonstrate the adequacy of each component of the isolation system. This investigation is crucial as some of the existing built components (a.k.a. legacy components) may not be adequate for the updated design loading cases and/or combinations. As such, any inadequate parts during any of the code-based load combinations are identified. Applicable acceptance criteria are defined for each component of the isolation system. Therefore, nominal capacities and/or limits for different components were, first, determined; then, compared against the peak structural responses or governing demands. Under the shown loading combinations, the adequacy of anchors supporting the middle column of central support structure could not be demonstrated as the reaction response due to the abnormal load combination representing the event of an accident in another operating unit while the vault is undergoing testing exceed its nominal capacity. Figure 6 presents the vertical reaction of the middle column due to individual load cases and all loading conditions. Design modifications to the existing base connection of the middle column to the foundation slab of the FMD will be necessary unless the issue of the inadequate response was resolved. Such design modifications of legacy components will require tedious construction planning and execution time since they must be completed inside the un-isolated reactor vault. This means workers must be wearing full personal protective equipment including respirators for extended periods of time. These constraints will add to the safety complexity, in addition to the additional costs of the modification and extended time of the project schedule.



(a) Loading Conditions (b) Load Combinations

Figure 6. Vertical Reaction at Base of Middle Column

A coupled 3D model of the containment isolation model and a model of the whole concrete vault and the shield tank encasing the reactor was developed. A duplicate mirror-image isolation model needed to be included in the coupled model. The purpose of the coupled model is to investigate the response of the containment isolation system for the accident pressure loading conditions, while accounting for interaction effects with the massive supporting vault and shield tank. Figure 7 presents the coupled analysis model of the isolation system, the vault, and the shield tank. The coupled analysis model was validated by performing (a) a static analysis to determine the response to gravitational acceleration, and (b) a modal analysis to determine the dominant modes of vibration. The two analyses confirmed the effective coupling of the decoupled containment isolation and vault models.

After the coupled analysis model is validated, two pressure loading conditions were applied in the form of two static analysis cases: (a) Duct Accident Pressure Load, and (b) Vault Testing Pressure Load. Linear elastic behaviour was assumed for the materials of the two sub-models. Key structural responses of the isolation and vault models to the two pressure cases were determined. Figure 8 demonstrates the deformation response of the vault and the axial forces in the structural steel columns of the central support structure. The coupled analysis realistically accounts for the interaction effects between the isolation system and the reinforced concrete vault. The interaction effects are developed at locations where the isolation system is supported on both the FMD walls, the FMD foundations slab and the shield tank (it is supported on the FMD walls as well). The integrated vault, shield tank and the isolation system act as a single structure and responds together to accidents in other operating units and to vault testing.

The vertical reactions of the central support structure developed at the anchor base plates and anchors at the foundation slab of the FMD were determined. The determined reactions based on the coupled analysis of the isolation system and the concrete vault were found to be much less than those determined in the previous decoupled analysis. The vertical reaction at the middle column of the central support structure is reduced from ~1167 kN to ~530 kN due to the duct accident pressure load and from ~1016 kN to ~516 kN due to the vault testing pressure load. That reduction, about 45-50% was sufficient to demonstrate the adequacy of the base and anchors of the middle column of the central support structure. This reduction means that no design modifications or strengthening required to the existing legacy structures, which will mitigate the risk of adding significant costs and time to the project.

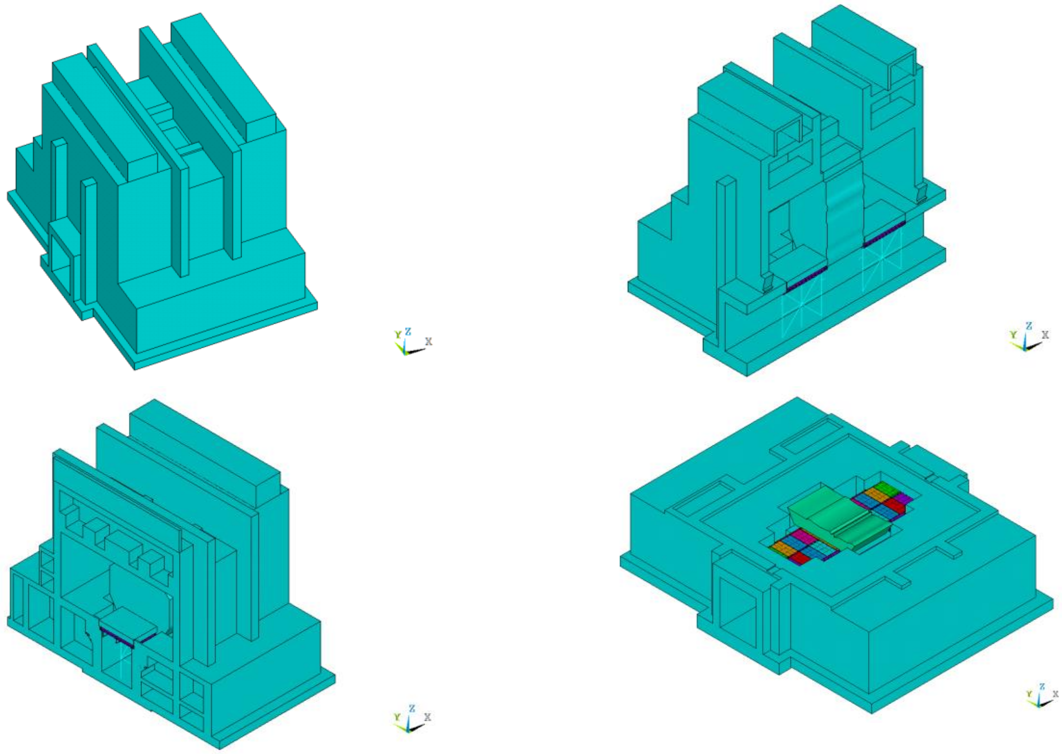
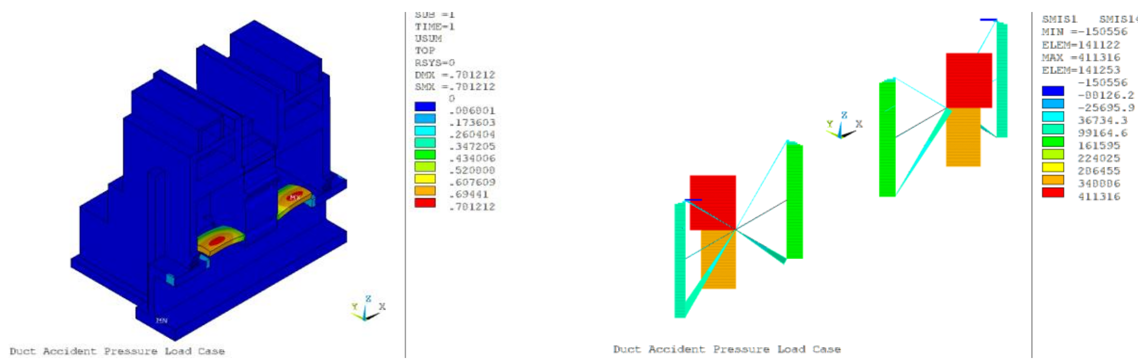
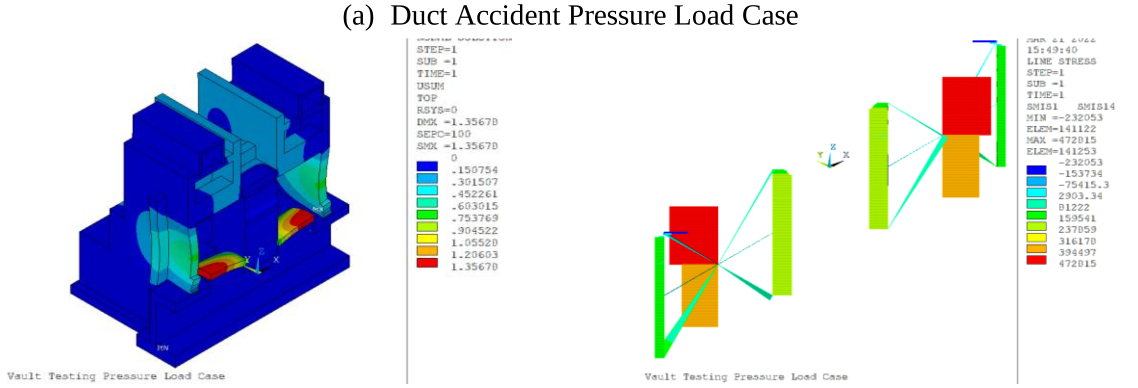


Figure 7. Coupled Analysis Model of Isolation System/Vault



(a) Duct Accident Pressure Load Case



(b) Vault Testing Pressure Load Case

Figure 8. Vault Deformation & Column Tension Response using Coupled Analysis Model

Based on the results of the performed decoupled and coupled analyses, the structural integrity of all components of the containment isolation system could be concluded. In addition, the integrity of the modified containment boundary of the station could be substantiated.

SUMMARY & CONCLUSION

This paper presents an overview of the process followed to demonstrate the design adequacy of the containment isolation system in multi-unit CANDU nuclear power plants. The isolation system in one unit is required to enable its refurbishment while other units of the station are operational. Therefore, the containment boundary of the multi-unit station is modified to isolate the unit undergoing refurbishment. The integrity of the containment isolation system, including original existing (legacy) built components, needs to be confirmed for all loading combinations according to applicable containment design code.

The applicable loading conditions and load combinations for different components of the isolation system are described. The adequacy of the isolation system design was investigated. Acceptance criteria per applicable design codes and standards, ensuring serviceability and integrity, were applied to demonstrate the adequacy of each component of the isolation system. Therefore, structural analyses, using a detailed analysis model of the isolation system, were performed to determine the demands on each of the components of the isolation system. The adequacy of the isolation system design was demonstrated for all its components except for the anchors supporting the middle column of central support structure. The vertical reaction response of that column due to the abnormal load combination representing the event of an accident in another operating unit while the vault is undergoing testing exceeded its nominal capacity.

Therefore, structural analyses, using an integrated analysis model of the concrete vault and the metallic isolation system, were performed for the critical pressure load conditions, i.e., the vault testing and the accident in operating units. The coupled analysis accounts for interaction effects between the isolation system and its massive supporting structure, i.e., the vault, resulted in less demands for the design of anchorage of the isolation system when compared to the demands determined based on the decoupled analysis. The reduction in the demand in this case amounts to about 50%.

The engineering analysis effort usually presents a small percentage of the overall cost of a mega-project such as nuclear power plant refurbishment. In this study, it is demonstrated that one approach of analysis could result in adding significant costs and extended durations of mega-projects. However, applying more than one thorough analysis approach can demonstrate more realistic behaviours that consider the interactions effects and thus result in better informed critical decision that can provide cost and time savings.

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