CONTAINMENT INTERNAL STRUCTURE DESIGN AND VALIDATION METHODOLOGY

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Revision History

Revision	Page	Description
0	All	Initial Issue - Final
1	All	Clarification of design approach for the CIS. See also NRC Letter ML11214A136.

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ABSTRACT

The purpose of this technical report is to present the overall methodology for executing the analysis and design of the Containment Internal Structure (CIS) and subsequently demonstrating the adequacy and safety of the design. The report describes the objectives and outputs for each of four major tasks.

Design Tasks:

1. Structural Analysis
2. Design Criteria Development and Design Adequacy Verification

Confirmation of Design Tasks:

3. Benchmarking of Nonlinear Finite Element Modeling Approach
4. Pushover Analysis of CIS

Development and acceptance of an overall plan of this nature is necessary for the US-APWR CIS because it is a complex structure that uses multiple structure types, including various Steel-Concrete (SC) type structural elements that provide primary and secondary shielding and support for the reactor coolant system (RCS) equipment. While an extensive experimental and analytical database has been prepared to date in the effort to evaluate the performance of SC structures in nuclear plant applications, there are currently no approved codes or standards available in the United States for direct application to design. Therefore ACI 349 (Reference 1) will be used as the basis for design of SC structures. For SC-specific design issues that are not addressed by the ACI 349 code, or where the ACI 349 based approach is not applicable, the code requirements will be supplemented using conservative engineering approaches, available test data, and research results.

Detailed discussion of each of the four tasks that comprise this framework will be presented in additional technical reports and auditable calculations.

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LIST OF ACRONYMS

The following list defines the acronyms used in this document.

3-D	Three -Dimensional
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ARS	Amplified Response Spectra
CIS	Containment Internal Structure
FTM	Force Transfer Mechanism
HCLPC	High Confidence of Low Probability of Failure
ISRS	In-Structure Response Spectra
LEFE	Linear Elastic Finite Element
NIFE	Nonlinear Inelastic Finite Element
RC	Reinforced Concrete
RCS	Reactor Coolant System
RSA	Response Spectrum Analysis
RWSP	Refueling Water Storage Pit
SC	Steel-Concrete
SSE	Safe Shutdown Earthquake
SSI	Soil-Structure Interaction
U.S. NRC	United States Nuclear Regulatory Commission

1.0 INTRODUCTION, BACKGROUND, AND OBJECTIVE

The US-APWR CIS is a complex structure that includes several different types of structure categories. The layout and details of these structure categories are discussed in Section 2.0. A significant portion of the CIS consists of 4 ft. thick steel-concrete (SC) composite walls. The primary shield structure is also a type of SC, consisting of three steel plates (two faceplates on the surfaces and a third plate in the middle) and varying between approximately 10 and 15 feet in thickness. These special wall types make the CIS a unique structure in terms of its behavior and design requirements.

As shown in MUAP-11005 (Reference 2), experimental investigations have been conducted in Japan to evaluate the behavior of the CIS, primary shield structure, and SC walls as follows:

1) 1/10th scale cyclic pushover test of a complete CIS (See Figure 1-1)
2) 1/6th scale cyclic pushover test of the primary shield structure (See Figure 1-2)
3) Component in-plane shear tests of SC walls with flanges (more than 15 specimens)
4) Component tests of SC wall panels without flanges subjected to combined axial compression and cyclic in-plane shear (more than 11 specimens)
5) Component out-of-plane shear tests of SC beams (more than 16 specimens)
6) Component tests of effects of thermal gradients on cracking and mechanical behavior of thermally cracked SC walls (12 specimens)

The experimental results and findings from these tests are very important and useful. They demonstrate the excellent seismic performance of the CIS and SC wall design. However, there are several limitations to the applicability of the testing to the US-APWR, as summarized in subsections 1.1 – 1.3. The component and structure test results and associated research have been used to develop industry design guidelines for SC walls in Japan and Korea. In the US, these test results are being used to develop design specifications for SC walls. However, these specifications are not currently published and therefore are not endorsed by the United States Nuclear Regulatory Commission (U.S. NRC.)

The ACI 349 code has been available for the design for reinforced concrete (RC) structures for nuclear facilities in the US for several decades and has been endorsed by the U.S. NRC. SC walls are similar to RC walls, as they both consist of thick concrete sections that are reinforced by steel. In SC, the concrete section is reinforced with steel faceplates that are anchored to the concrete using shear studs and connected to each other using steel tie bars. In RC, the concrete section is reinforced with orthogonal grids of steel rebars that are embedded within the concrete.

In some aspects of structural behavior such as axial tension, compression, flexure, and out-of-plane shear, the behavior of SC walls is similar to that of RC walls. For other aspects like in-plane shear, combinations of in-plane and out-of-plane forces, or thermal effects, the behavior of SC walls can be different from that of RC walls. Additionally, some aspects of section detailing to address limit states of steel plate local buckling, concrete delamination, or interfacial shear transfer are unique to SC walls and are not addressed within ACI 349. These differences between SC and RC wall behavior are summarized in Section 1.5.

The design of the US-APWR CIS will be based upon ACI 349 code provisions. This report presents a comprehensive plan for the US-APWR CIS to: (1) address the limitations of the small-scale (1/10th and 1/6th scale) tests; (2) demonstrate the applicability and conservatism of the application of ACI 349 code equations; and (3) develop and confirm the conservative engineering approaches when ACI 349 does not include design provisions or is not applicable.

1.1 1/10th Scale Test of CIS

The experimental results from the 1/10th scale test are valuable demonstration or proof of concept that SC walls can be used to build the CIS. However, the 1/10th scale test was conducted on a CIS that is similar but not identical to the CIS of the US-APWR. The differences between the two are reported in detail in MUAP-11005 (Reference 2), and are briefly summarized here for reference:

(1) Structure geometry differences: The 1/10th scale test structure did not include the massive RC structures, the steel structures (referred as structure categories 5 and 6, respectively, in Section 2.0), and did not include the refueling water storage pit (RWSP) structure. Also, the scaling of some of the wall thickness was not 1:10 relative to the US APWR CIS. For example, the primary shield structure scale is about 1:20 (i.e., the primary shield structure in the US-APWR is much larger). The pressurizer walls were scaled about 1:7 in some locations. The structure heights were scaled about 1:14 to 1:20.

(2) Material property differences: The material properties used in the 1/10th scale test were slightly different from those specified for the US-APWR CIS. For example, the concrete compressive strength in the 1/10th scale test was 2500 psi (measured), whereas the specified strength for the US-APWR CIS is 4000 psi (nominal). The steel plate yield stress for the 1/10th scale test was 43 ksi (measured), whereas the specified yield stress for the US-APWR CIS is 50 ksi (nominal). The yield strength of the shear reinforcement (tie bars) for the 1/10th scale test was 82 ksi (measured), whereas the specified value for the US-APWR CIS is 50 ksi (nominal).

(3) Fabrication differences: In the 1/10th scale test structure, SC walls below the center height of the first layer wall used web plates to connect the steel faceplates. SC walls above that height used shear bars (tie bars) to connect the steel faceplates. The shear bars (tie bars) were attached to the steel plates using double nuts (from the inside and outside). Additionally, in the 1/10th scale structure, the SC walls were fully embedded into the concrete base using embedded steel shapes, plates, shear connectors, etc. The US-APWR CIS does not utilize these exact fabrication details; however, to the extent possible, equivalent fabrication details will be used. See Figure 2-8 for a graphic of the typical SC wall geometry.

(4) Loading differences: The 1/10th scale test structure was subjected to cyclic but unidirectional lateral loading. It did not evaluate the effects of combinations of different earthquake directions, or the effects of accident thermal loading on the seismic response of the CIS.

Completion of the comprehensive plan presented in this report provides the framework for applying the results from the 1/10th scale testing to the US-APWR CIS in a conservative and rational manner.

1.2 1/6th Scale Test of Primary Shield Structure

The 1/6th scale test described in Reference 2 was conducted on a primary shield structure that is identical to the one being used in the US-APWR CIS. As explained earlier, the primary shield structure of the US-APWR is unique: It consists of three steel plates, two on the surface and one in the middle. The three steel plates are connected by web plates leading to a multi-cellular arrangement of steel plates. The total thickness of the primary shield structure varies from 9.9 – 15.3 ft. Additionally, the walls of the structure are curved (cylindrical walls).

The 1/6th scale test was conducted by subjecting a portion of the primary shield structure with shear span (height / length) ratio of 0.55 to unidirectional cyclic lateral loading. Like the 1/10th scale test, the effects of different earthquake directions and combinations and the effects of accident thermal loading on the seismic behavior were not included.

The experimental results are very important for evaluating the lateral load (primarily in-plane shear) behavior of the primary shield structure. However, the comprehensive plan presented in this report evaluates the behavior of the primary shield structure for other loading conditions and combinations and will demonstrate the conservatism provided.

1.3 Component Tests of SC Walls

The SC wall component tests presented in Reference 2 cover a wide range of material, geometric, loading, and thermal condition parameters. They typically envelope the parameters for the SC walls used in the US-APWR, and provide data for assessing: (i) in-plane shear strength, (ii) compression plus in-plane shear strength, (iii) out-of-plane shear strength, and (iv) effects of thermal cracking on in-plane shear strength of SC walls.

There are some differences in the section details and fabrication details of the US-APWR SC walls with respect to those in the experimental database. The comprehensive plan presented in this report evaluates these differences, and, if needed, tests may be performed to demonstrate the adequate performance of US-APWR SC walls with project specific section detailing and fabrication.

1.4 ACI 349 Code Equations

As explained earlier, SC walls are similar to RC walls in that they both consist of thick concrete sections reinforced with steel. In aspects of behavior such as axial tension, compression, flexure, and out-of-plane shear, the behavior of SC walls is very similar, if not identical, to that of RC walls. ACI 349 code equations for flexural strength, out-of-plane shear strength, axial tension strength, and axial compressive strength will be applicable to SC walls because their behavior is similar, if not identical. The applicability and conservatism of these equations will be demonstrated using the available test data for SC components.

1.5 Unique Aspects of SC Design

For aspects like in-plane shear, combinations of in-plane and out-of-plane forces, and thermal effects, the behavior of SC walls can be different from that of RC walls. The ACI 349 code may not address these issues directly, or might be inapplicable. For example:

(1) SC walls include steel plates instead of rebar. Rebar is continuously bonded to the concrete, and the concept of development length and fully developed bars is central to the

ACI 349 code. This cannot be applied directly to SC modules because they consist of plates with discrete connections to the concrete in the form of shear studs.

(2) SC walls consist of steel plates that are continuous in both directions and provide additional in-plane shear stiffness. RC walls, which have orthogonal grids of rebar that are almost independent of each other, have only longitudinal stiffness in the directions of the rebar. The resulting in-plane shear behavior and interaction between different force demands is therefore different for SC walls and RC structures.

(3) SC walls have tie bars or direct connectivity between the two steel faceplates to prevent a delamination type failure mode through the plain sandwiched concrete. There are no requirements in ACI 349 to address this potential failure mode.

(4) The tie bars in SC walls are subjected to interfacial shear stresses at the steel plate to concrete interface in addition to the axial tension resulting from out-of-plane shear demand. The shear stirrups in RC structures are made from rebar that is continuously bonded to the concrete, and thus not subjected to this additional interfacial shear stress. There are no corresponding requirements in ACI 349 for the design of tie bars in SC walls for these stresses.

(5) The steel plates of SC walls are anchored to the concrete infill at discrete locations using shear connectors. These plates can potentially undergo local buckling between the shear connector lines if the spacing is not properly designed. The ACI 349 code addresses continuously bonded and supported rebar that can undergo buckling between the tie bars after concrete spalling. It does not include recommendations for designing SC walls to prevent local plate buckling before yielding in compression.

(6) ACI 349 has no direct interaction equations that address multiple, concurrent loading directions/combinations. The steel plates are continuous in both directions and provide resistance to all force demands. There are no independent orthogonal grids of rebar as in RC structures, so direct interaction equations are needed.

(7) ACI 349 has no direct connection design recommendations. In RC structures, the same rebar that are the primary load resisting components in the walls are continued and sufficiently embedded into the connected walls or components to transfer forces. This cannot be done easily in SC modules. While the ACI 349 Appendix B can be used for the design of relevant connectors, the actual connection design, detailing, and qualification approach will be developed and outlined by MHI.

(8) The guidelines in ACI 349.1R (Reference 3) were developed for RC walls where the steel rebars are embedded in the concrete with adequate clear cover. They are not directly applicable to SC walls where the steel faceplates are directly subjected to accident thermal loading. The thermal cracking behavior and its influence on the seismic behavior of the CIS with SC walls are not directly addressed by ACI 349 or associated reports.

The comprehensive approach presented in this report has been developed to address areas where the ACI 349 code is lacking or is not applicable for the design of SC walls.

1.6 Overall Goal

The overall goal for the methodology presented herein is to demonstrate the design adequacy and safety of the US-APWR CIS, including the SC walls.

1.7 Report Objective

The objective of this report is to give an overall outline of the comprehensive and integrated approach that will be used to: (i) perform analysis and design of the CIS and (ii) demonstrate the adequacy and safety of the design. Detailed discussion of each task required by this approach will be provided subsequently in supplemental reports, as shown in Table 1.

1.8 Outline of Tasks

The methodology for executing the analysis and design of the CIS and subsequently demonstrating the adequacy and safety of the design will consist of four major tasks.

The fundamental design will consist of two major tasks:

(1) Structural analysis for determining force and moment demands for all components of the CIS, accounting for effects of soil-structure interaction, concrete cracking, and accident thermal loading.

(2) Design of all components for the force and moment demands using ACI 349 design strength equations supplemented with conservative engineering approaches that are correlated to available test data, research literature, and industry recognized design methods.

The design confirmation consists of two major tasks:

(3) Development and benchmarking of a detailed nonlinear inelastic finite element (NIFE) modeling approach that reasonably correlates to the measured and observed global and local behavior of: (a) the 1/10th scale demonstration test of a CIS structure, (b) the 1/6th scale test of the primary shield structure, and (c) several component level tests that are relevant to the design (i.e., Task 2).

(4) Pushover analysis of a NIFE model (based on the benchmarked modeling approaches of Task 3) of the actual US-APWR CIS that: (a) demonstrates adequate global and local behavior of the entire structure for seismic plus operating thermal loading combinations and seismic plus accident thermal loading combinations, and (b) estimates the seismic margin from strength and drift perspectives.

Tasks (1) and (2) establish the design methodology and tasks (3) and (4) confirm that the design of the US-APWR CIS will provide a safe and acceptable response to the challenges presented by the worst case conditions of the design earthquake concurrent with accident thermal loading.

2.0 STRUCTURE CATEGORIES

The CIS is unique among the reactor building complex structures because it is comprised of a variety of structure types with differences in their construction and expected behavior. The structures in the CIS are grouped into six categories to enable the use of appropriate analysis models and design methodologies for each type of structure. These six structure categories in the CIS include three SC-type and three non-SC type categories as explained in the following subsections. Figures 2-1 through 2-7 show several plan and elevation views of the US-APWR CIS that identify the six structure categories using a color-coded scheme. These figures have been developed from the drawings provided in References 4 and 5.

2.1 SC-type Structure Categories

The composite stiffness and strength of SC walls have been well established in experiments involving walls with overall thickness less than or equal to 56 in. Typical SC designs evaluated in these experiments consist of a single concrete core between two steel faceplates, as shown in Figure 2-8. The steel faceplates are typically connected to the concrete core using headed stud anchors. The two steel faceplates are typically connected to each other using embedded steel shapes, tie bars, or web plates. The steel faceplate reinforcement ratios (ρ) in the experimental database vary between 1.5% and 5.0%, with ρ defined as follows:

$$\rho = \frac{2 \cdot t_p}{T}$$

where t_p = single faceplate thickness and T = thickness of overall section.

Most of the SC-type walls in the US-APWR CIS have material and geometric parameters that are within the range evaluated by the aforementioned experimental database. However, some of the walls have overall thicknesses and/or steel plate geometries that exceed this range. While a 1/6th scale test was also performed to evaluate the thick primary shield walls, further study is required to assess their stiffness and strength. As a result, the SC-type walls in the CIS are divided into the following three categories:

<u>Category 1</u>: *SC Walls with thickness ≤56 in.* These SC walls have material and geometric parameters that are within the range of the experimental database. This category includes the majority of the secondary shielding walls in the CIS. The most common SC wall is 48" thick with 0.5" thick steel faceplates.

<u>Category 2</u>: *SC Walls with thickness greater than 56 in.* This category includes a relatively small portion of the CIS SC walls with thicknesses ranging from 58.5 in. to 67 in.

<u>Category 3</u>: *Primary Shield Walls.* The primary shield walls are below elevation 35'-11" and range in thickness from 9'-11" to 15'-4". These walls have a multi-cellular arrangement comprised of two steel faceplates, a mid-thickness steel plate, and numerous transverse web plates.

2.2 Non-SC Structure Categories

The non-SC type walls in the CIS are also divided into three structure categories:

Category 4: *Reinforced concrete (RC) slabs.* Standard RC floor slabs are used at various elevations throughout the CIS.

Category 5: *Massive reinforced concrete.* This category includes the thick reinforced concrete blocks at the base of the CIS that support the steam generators and reactor coolant pumps. These blocks are anchored to the basemat of the reactor building complex with steel reinforcement.

Category 6: *Steel structures with nonstructural concrete infill*. These structures consist of steel plates or steel shape grillages with nonstructural concrete provided for shielding purposes.

3.0 TASK 1: DYNAMIC ANALYSIS

3.1 Task 1-A: Dynamic Soil-Structure Interaction Analysis

In this task, the dynamic response of the CIS subjected to seismic loading will be computed while accounting for the effects of soil-structure interaction (SSI) and the effects of concrete cracking on the structure stiffness and damping.

This SSI analysis will be conducted using a three-dimensional (3-D) linear elastic finite element (LEFE) model of the reactor-building complex including the CIS and the soil foundations. The effective stiffness and damping values for the finite element model of the CIS will be based on its stiffness before or after concrete cracking as applicable. For seismic plus operating thermal loading conditions, the concrete is expected to be mostly uncracked, and for the seismic plus accident thermal loading conditions, the concrete is expected to be cracked for the category 1 and 2 SC walls as well as the category 4 RC slabs.

To sufficiently bound the range of stress levels and associated cracking anticipated for the CIS, two separate SSI analyses will be performed; one with the higher stiffness (uncracked) associated with seismic plus operating thermal loading conditions, and one with the lower stiffness (cracked) associated with seismic plus accident thermal loading conditions. Additional details regarding the effective stiffness and damping for each of these analyses are provided in Reference 6.

3.1.1 Task 1-A Results

The results from Task 1-A include: (i) the in-structure response spectra (ISRS) for equipment and attachments, (ii) the acceleration plots, and (iii) the translational amplified response spectra (ARS) in the three orthogonal directions at the base of the CIS. These results will represent the envelope of responses obtained by conducting dynamic analyses of the LEFE models with the two stiffness and damping levels described above. The Task 1-A analysis and results will be discussed in a calculation report as identified in Table 1.

3.2 Task 1-B: Seismic Analysis for Structural Design

The results from Task 1-A will be used in this task to conduct equivalent static and / or dynamic response spectrum analysis (RSA) of the CIS and thus determine the force and moment demands in the various components (walls and slabs) of the CIS for design.

These analyses will also be conducted using LEFE models of the CIS, but the finite element mesh will be more refined than the mesh in Task 1-A, and the loading will be defined using the acceleration bubble plots or the response spectra at the base of the CIS from Task 1-A. The stiffness and damping values for the detailed LEFE models of the CIS will be computed based on their effective stiffness before and after concrete cracking as applicable, and will be consistent with the values assigned for the two dynamic SSI analyses performed in Task 1-A.

3.2.1 Task 1-B Results

The result from Task 1-B is a calculation that includes the magnitudes and distributions of the: (i) in-plane forces (membrane axial and shear), (ii) out-of-plane shear forces, and (iii) out-of-plane moments including twisting moment for each of the walls and slabs of the CIS.

4.0 TASK 2: STRUCTURAL DESIGN AND DETAILING

4.1 Task 2-A: Basis of Design Strength Equations and Interaction Equations

This task will focus on the development of design strength and interaction equations for each of the three SC-type structure categories (1-3). Design strength equations will be established for: (i) in-plane force demands, (ii) out-of-plane force demands, (iii) out-of-plane moment demands, and (iv) combinations of in-plane force and out-of-plane moment demands.

The ACI 349 code for RC structures will be used as the basis and the starting point for these design strength and interaction equations. For the category 1 SC walls, the applicability and conservatism of ACI 349 code equations will be confirmed using the available experimental data described in technical report MUAP-11005 (Reference 2) and research literature. Where ACI 349 does not address SC specific design issues or applicability cannot be confirmed, the ACI 349 code equations will be supplemented with equations or requirements developed using conservative engineering approaches that are correlated to available test data, research literature, and industry recognized design methods. If necessary, the conservatism of supplemental engineering approaches for the US-APWR project specific SC design may be subsequently confirmed through testing.

The category 2 and 3 SC-type walls are expected to have very low demand-to-capacity (utility) ratios. As there is limited experimental data for these structure categories, their design will be based on ACI-349 code recommendations implemented with conservative resistance (Φ) factors. Where ACI 349 does not address specific design issues or applicability cannot be confirmed, the ACI 349 code equations will be supplemented with equations or requirements developed using conservative engineering approaches that are correlated to available test data, research literature, and industry recognized design methods. The conservatism of these designs and their overstrength (very low demand-to-capacity ratios) relative to the Safe Shutdown Earthquake (SSE) demands and beyond-SSE demands will be further confirmed in Tasks 3 and 4.

For structure categories 4 and 5, which are reinforced concrete structures, the applicable provisions of the ACI 349 Code equations will be used.

Category 6 structures include walls and slabs consisting of steel shapes or plate members with non-structural concrete infill. The design adequacy of the steel members in these structures will be confirmed using applicable provisions of the American Institute of Steel Construction (AISC) N690 Code (Reference 7).

4.1.1 Task 2-A Results

The results from Task 2-A will include the design strength and interaction equations for checking the design adequacy of each structural component in the CIS. Results of this task will also include the determination of any required confirmatory tests. The Task 2-A results will be discussed in a technical report as identified in Table 1.

4.2 Task 2-B: Design Adequacy Check

The results from Task 1-B and Task 2-A will be used to check the design adequacy of the various structure categories and components (walls and slabs) of the CIS. Demand-to-capacity ratios will be computed for each of the individual force and moment demands calculated in Task 1-B, and for the interaction of the in-plane force and out-of-plane moments. Capacities will be computed using the category-specific design strength equations developed in Task 2-A. The adequacy and conservatism of the SC wall designs (particularly categories 2 and 3) for SSE demands will be documented and discussed.

4.2.1 Task 2-B Results

As shown in Table 1, the result of Task 2-B is a calculation that documents the demand-to-capacity (utility) ratios calculated for each wall and slab in the CIS.

4.3 Task 2-C: Anchorage/Connection Design and Adequacy Check

The anchorage of the CIS to the reinforced concrete basemat and the connections between the members (walls and slabs) of the various structure categories will be evaluated using the design force demands calculated in Task 1-B. These design force demands will include in-plane membrane (axial and shear) forces, out-of-plane shear forces, and out-of-plane moment demands per unit length of anchorage or connection.

For each individual demand type, a conservative connection design philosophy will be selected from the following: (i) full strength with respect to connected components, or (ii) overstrength with respect to seismic force demands, or (iii) ductile design providing adequate structure drift capability.

Clearly identifiable force transfer mechanisms (FTM) will be provided for each of the individual design force demand types using commonly used connectors, namely, reinforcing bars, steel headed stud anchors, welds, tie bars, concrete bearing etc. These connectors will be designed for the individual force / moment demands and their combinations using existing design codes; for example, ACI 349-01 Appendix B or AISC N690 for bolts and welds etc.

Additionally, for each individual demand type, the applicable FTM and connectors will be detailed to ensure ductile behavior and/or sufficient overstrength for SSE and beyond SSE loading. For example, the basemat anchorages will be detailed such that the available tensile strength is greater than 125% of the nominal yield strength of the weaker of the connected components, which is also required by the ACI 349 Code.

If considered necessary, some of the anchorage and connection designs will be tested to demonstrate their design adequacy for individual force demands.

4.3.1 Task 2-C Results

The results of Task 2-C will include the following for each of the connection types in the CIS:

(i) A clearly stated connection design philosophy

(ii) Clearly identifiable force transfer mechanisms and connectors for each individual force / moment demand

(iii) Connector and connection design and detailing using existing design codes, for example, ACI 349-01 Appendix B or AISC N690, and

(iv) Connection qualification for individual force / moment demands and their combinations.

The connection qualification may involve confirmatory testing, or the use of available experimental data supplemented with conservative engineering approaches correlated to test results and existing research literature. The Task 2-C design criteria and calculation results will be contained in a technical report and calculation report, respectively, as identified in Table 1. Results of this task will also include the identification of any confirmatory tests.

4.4 Task 2-D: SC Section Detailing

The composite sections of the category 1, 2, and 3 SC walls will be detailed to ensure adequate composite action between the steel plates and the concrete infill, and also to prevent splitting (delamination) failure of the concrete infill. This will entail providing adequate shear connector size and spacing to develop composite action and delay local buckling of the steel plates. This will also entail providing adequate structural integrity in the composite section by providing adequate tie bar size, spacing, and adequate tie bar-to-steel plate connections.

If deemed necessary, full-scale tests of the tie bar-to-steel plate connections will be conducted to demonstrate their behavior and ductility.

4.4.1 Task 2-D Results

The results of Task 2-D will be a calculation that includes the detailed design for shear connector and tie bar size, spacing, and connections that ensure composite action and structural integrity for the SC wall geometries in the CIS. Results of this task may also include the determination of any required additional tests necessary to qualify the performance of the section components.

5.0 TASK 3: BENCHMARKING OF NONLINEAR FINITE ELEMENT MODELING APPROACH

This task will focus on the development and benchmarking of detailed nonlinear inelastic finite element models that can be used to predict:

(i) The experimental behavior of the 1/10th scale test representative of the CIS

(ii) The experimental behavior of the 1/6th scale test of the primary shield structure

(iii) The experimental behavior of individual SC wall components with a range of material and geometric parameters subjected to different in-plane and out-of-plane loading scenarios (including thermal loading).

5.1 1/10th Scale Test

A detailed 1/10th scale test was performed for a structure that is similar to the CIS in the US-APWR (see Figure 5-1). The results of this test provide a valuable demonstration of overall behavior and proof of concept for the use of SC walls to build a safe containment internal structure. Since this test was performed nearly 25 years ago, there are some differences between the 1/10th scale structure and the actual CIS in the US-APWR, which were identified in Section 1.1.

In spite of these differences, the 1/10th scale test provides valuable data that can be used to benchmark a NIFE modeling approach to capture the essential behavior of the SC structures in the elastic (cracking), inelastic (material yielding), and failure (inelastic buckling, crushing, and fracture) ranges of response.

A detailed nonlinear finite element model of the 1/10th scale structure will be developed and analyzed for the same loading conditions applied in the experiment. This model will explicitly account for the effects of concrete cracking, steel yielding, and composite action. The model will include cyclic hysteresis relationships for the steel and concrete materials, and will be subjected to cyclic pushover loading similar to the test loading.

The results from the finite element analysis will be benchmarked to the load-displacement curves, local strain measurements, and overall behavior observed in the 1/10th scale test.

5.2 1/6th Scale Test of Primary Shield

A 1/6th scale in-plane shear test was conducted of the US-APWR primarily shield structure (see Figure 5-2) in Japan. As explained in Section 1.2, the experimental results from this 1/6th scale test provide an excellent demonstration of the seismic behavior of the primary shield structure, and valuable data that can be used to benchmark a NIFE modeling approach to capture the essential behavior in the elastic, inelastic, and failure ranges of response.

A detailed NIFE model of the 1/6th scale test will be developed and analyzed for the same loading conditions applied in the test. The NIFE model will explicitly account for the effects of concrete cracking, steel plate yielding, and composite interaction between the steel plates (longitudinal and transverse) and the concrete cores. The results from the finite element analysis will be compared and benchmarked using the test results. Furthermore, the results of the test and finite element analysis will be used to confirm the design adequacy and conservatism (very low demand to capacity utility ratios) of the primary shield walls.

5.3 SC Wall Component Tests

Numerous SC wall component tests have been conducted in Japan and other countries to evaluate their fundamental behavior. Report MUAP-11005 (Reference 2) summarizes tests that have been conducted in Japan, and includes English translations of the relevant Japanese papers published in journals and conference proceedings. The various component tests that been conducted include:

1) In-plane shear tests of SC walls with and without flange walls

2) Axial compression + in-plane shear tests of SC walls without flanges

3) Axial tension tests of SC wall-to-RC basemat anchorage

4) In-plane shear tests of SC wall-to-RC basemat anchorage

5) Out-of-plane shear behavior of SC walls

6) Concrete thermal cracking behavior of SC walls

7) In-plane shear behavior of SC walls after thermal cracking

The experimental results from these component tests provide significant insight into the behavior of SC walls, and permit detailed evaluation of the design strength and interaction equations selected for the US-APWR CIS.

These experimental results also provide valuable data that will be used to benchmark NIFE models to capture the fundamental and essential behavior of SC walls subjected to various loading conditions and combinations. The NIFE models will explicitly account for the effects of concrete cracking, steel yielding, and composite action, and will be benchmarked for a range of material and geometric parameters and loading conditions (including thermal cracking).

The benchmarked NIFE modeling approach will be used to:

1. Confirm the conservatism of the design strength and interaction equations used in Task 2B for category 1, 2, and 3 SC walls.
2. Confirm the SC wall anchorage, connections, and section details in Tasks 2-C and 2-D as applicable and appropriate.
3. Further evaluate any new experiments conducted as part of Tasks 2-C and 2-D to demonstrate the behavior of SC wall anchorage, connections, and section details.

5.3.1 Task 3 Results

The fundamental outcome of this task will be a benchmarked NIFE modeling approach for category 1-3 SC walls, anchorages, and connections in the US-APWR CIS.

This modeling approach will be used in Task 4 to develop a similar NIFE model of the entire US-APWR CIS for evaluating its overall structure performance and ductility.

6.0 TASK 4: OVERALL STRUCTURE PERFORMANCE CONFIRMATION

6.1 Task 4-A: Overall Structure Performance for SSE Loads

The benchmarked NIFE modeling approach developed in Task 3 will be used to develop a NIFE model of the US-APWR CIS. This model will also explicitly account for the effects of concrete cracking, steel yielding, composite interaction between the various steel and concrete components, and the other various complexities of behavior including fracture.

In Task 4-A, the NIFE model of the US-APWR CIS will be used to evaluate its overall cyclic pushover behavior for SSE level loads in the presence of: (i) operating thermal, and (ii) accident thermal loading conditions.

The results from these analyses will also be also used to confirm the stiffness and dynamic characteristics of the LEFE models of the CIS structure used in Tasks 1-A and 1-B.

6.1.1 Task 4-A Results

The result of this task will be the analytical confirmation of the overall behavior of the US-APWR CIS at SSE level loads, particularly in the presence of: (i) operating thermal, and (ii) accident thermal loading conditions. Additionally, Task 4-A will also confirm the stiffness and dynamic characteristics of the LEFE models used in Tasks 1-A and 1-B.

6.2 Task 4-B: Overall Structure Performance for Beyond-SSE Loads

The NIFE model of the US-APWR CIS developed in Task 4-A will also be used to assess its behavior for beyond-SSE loads by conducting monotonic pushover analyses. The global and local behavior of the CIS for monotonically increasing pushover forces will be monitored.

Limit states for local behavior and failure (for example, strain limits in the plates, shear connectors, tie bars, concrete damage models, etc.) will be identified based on the experimental results and the benchmarked NIFE models developed in Task 3. If needed, these damage modes and strain limits will be supplemented using values and data in research literature.

These local strain limits will be used to establish the range of acceptability of the NIFE analysis results, and thus establish ‘analytical failure’ of the NIFE model of the CIS. The ‘analytical failure’ state and the corresponding applied seismic forces and structure drift levels will be used to assess the seismic margin of the CIS structure with respect to SSE forces and drift, and confirm its beyond-SSE performance adequacy.

6.2.1 Task 4-B Results

Task 4-B will be used to assess the seismic margin of the structure, from strength and drift perspectives, for beyond-SSE loading. Additionally, Task 4-B will identify the local failure criteria that led to 'analytical failure' of the NIFE model for the CIS, and discuss its potential repercussions (i.e. propagation or stabilization of local failure).

In summary, Task 4 will confirm the structural design adequacy and conservatism of the CIS for seismic loading, including the effect of accidental thermal loads and the response to beyond-SSE loads. The benchmarked nonlinear analyses will be used to confirm the seismic margin and ductility of the CIS. They will also be used to confirm the effective stiffness values that were used for the analyses supporting the structural design (Task 1).

7.0 REFERENCES

1. American Concrete Institute*, "Code Requirements for Nuclear Safety Related Concrete Structures"*, ACI 349-01, February 2001.
2. Mitsubishi Heavy Industries, Ltd., *"Research Achievements of SC Structure and Strength Evaluation of US-APWR SC Structure Based on 1/10th Scale Test Results"*, MUAP-11005, Revision 0, January 2011.
3. American Concrete Institute*, "Reinforced Concrete Design for Thermal Effects on Nuclear Power Plant Structures"*, ACI 349.1R-07, May 2007.
4. U.S. Nuclear Regulatory Commission, *"Damping Values for Seismic Design of Nuclear Power Plants",* Regulatory Guide 1.61, Revision 1, March 2007.
5. Mitsubishi Heavy Industries, Ltd., *"US-APWR Concrete Outline Drawings for Inner Structure of Containment"*, NO-EHC0001 through NO-EHC0012, Revision 3, October 2010.
6. Mitsubishi Heavy Industries, Ltd., *"Containment Internal Structure: Stiffness and Damping for Analysis"*, MUAP-11018, Revision 0, August 2011.
7. American Institute of Steel Construction, "*Specifications for the Design, Fabrication and Erection of Steel Safety-Related Structures for Nuclear Facilities*," ANSI/AISC N690-94 including Supplement 2 (2004), 1994 and 2004.

8.0 TABLES

TASK	Description	Report	Type
1-A	Definition of stiffness and damping values for analysis models	MUAP-11018: "CIS: Stiffness and Damping for Analysis"	Docket
	Dynamic soil-structure interaction analysis	Calculation RB-13-05-113-002: " R/B Standard Design SSI Analysis"	Internal
1-B	Seismic analysis for structural design	Calculation CIS-13-05-230-004: "Basic Analysis and Design of CIS"	Internal
2-A	Basis of design strength equations and interaction equations	MUAP-11019: "CIS: SC Wall Design Criteria"	Docket
2-B	Wall and slab design adequacy check	Calculation CIS-13-05-230-004: "Basic Analysis and Design of CIS"	Internal
2-C	Anchorage/connection design criteria	MUAP-11020: "CIS: Anchorage, Connection, and Section Design and Detailing"	Docket
	Anchorage/connection design adequacy check	Calculation CIS-13-05-230-004: "Basic Analysis and Design of CIS"	Internal
2-D	Section detailing	Calculation CIS-13-05-230-004: "Basic Analysis and Design of CIS"	Internal
3	Benchmarked analysis of 1/6th scale test of primary shield	Report: "Benchmarked NIFE Models for 1/6th Scale Primary Shield"	Internal
	Benchmarked analysis of 1/10th scale test for both SSE and beyond-SSE loading	Report: "Benchmarked NIFE Model for 1/10th Scale CIS"	Internal
	Benchmarked analysis of SC components	Report: "Benchmarked NIFE Models for SC Components"	Internal
4-A/B	Benchmarked pushover analysis of actual US-APWR CIS for both SSE and beyond-SSE loading	Report: "US-APWR CIS Pushover Analysis"	Internal

Table 1 Matrix of Reports and Calculations for CIS Design and Validation

9.0 FIGURES

Figure 2-1 CIS Structure Categories, Elevations 3'-7" to 21'-0"

Figure 2-2 CIS Structure Categories, Elevations 21'-0" to 35'-11"

Figure 2-3 CIS Structure Categories, Elevations 37'-9" to 62'-4"

Figure 2-4 CIS Structure Categories, Elevations 62'-4" to 76'-5"

Figure 2-5 CIS Structure Categories, Elevations 76'-5" to 139'-6"

Figure 2-6 CIS Structure Categories, Centerline Section Looking West

Figure 2-7 CIS Structure Categories, Centerline Section Looking North

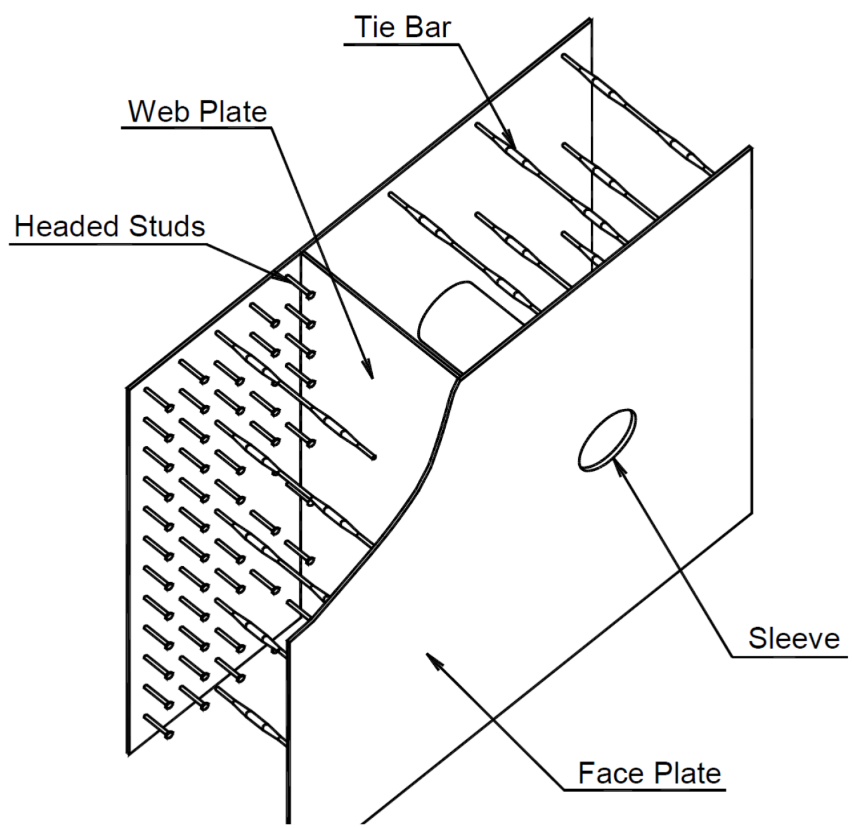

Figure 2-8 Typical SC Module Geometry

Figure 5-1 1/10th Scale Test of Japanese Pressurized Water Reactor CIS Using SC Walls

Figure 5-2 1/6th Scale Test of US-APWR Primary Shield Wall

(a) Test arrangement; (b) Test specimen (concrete fill not shown)