3.0 DETAILED ANALYSIS

3.1 Scenario Selection

Sequences were selected for MCCI analysis based on their core damage frequencies and bounding features. The following ten sequences are indentified having high core damage frequencies:

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Table 3-1: Ten PRA Sequences with High Core Damage Frequencies

Out of the ten sequences, four were selected for MCCI analysis. These include: total loss of essential service water (R1_TLOES-003-MCCI), Medium LOCA (R2_MLOCA003-MCCI), Temporary Loss of AC power (R3_LOOP-004-MCCI), and Loss of AC power with turbine-driven AFW off after 2 hours (R9_SBO-006-MCCI). The other six sequences were ignored because they will lead to significantly delayed core damage, therefore, not being the limiting sequences for MCCI analysis. In addition to the four PRA sequences, a Large LOCA sequence from containment performance analysis (LLOCA-C04-NoECSBS-MCCI) was also selected, because it leads to very quick core damage and vessel breach. Equipment availability and sequence progression for each of those sequences is discussed next.

3.1.1 Sequence Identifier: R1-TLOES-003-MCCI

The initiating event of this sequence is a loss of Essential Service Water (ESW) at full power, resulting reactor scram almost immediately. Following the initial event, auxiliary feedwater, safety injection pump, and charging pump are all assumed lost. RCS depressurization through SDVS is assumed at 30 minutes after core damage. Containment flooding system (CFS) is available, but

the containment spray system (CSS) is unavailable. Due to the loss of ESW, a 21 gpm per pump seal LOCA is assumed to occur half an hour into the sequence.

The following table summarizes availabilities of key systems in this sequence.

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Table 3-2: Run Equipment Availability for R1_TLOES-003-MCCI

3.1.2 Sequence Identifier: R2_MLOCA003-MCCI

The initiating event of this sequence is a medium break LOCA occurring at full power. The break is equivalent to a 6 inch diameter hole in loop 1 hot leg. Four Safety Injection Tanks and Motor-Driven AFW are available. Charging Pumps are assumed to be unavailable. Safety Injection pumps are available initially but are assumed to fail 2 hours into the sequence at the time of switchover to hot leg injection. RCS depressurization using the SDVS, CFS actuation, and alignment of the Three-Way Valves to the steam generator compartment, are assumed to occur 30 minutes after the onset of core damage. ECSBS (Emergency Containment Spray Backup System) is assumed not to be available for this sequence.

The following table summarizes availabilities of key systems in this sequence:

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Table 3-3: Run Equipment Availability for R2_MLOCA003-MCCI

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Table 3-3: Run Equipment Availability for R2_MLOCA003-MCCI

3.1.3 Sequence Identifier: R3_LOOP-004-MCCI

The initiating event for this sequence is a loss of AC power causing reactor scram almost immediately. Following the initiating event, charging pumps, safety injection pumps, and AFW pumps are lost. Although the diesel generator starts in 10 minutes, charging pump, safety injection pumps and AFW do not recover. One hour into the sequence, two POSRVs are manually opened by operator to relieve RCS pressure.
The following table summarizes availabilities of key systems in this sequence.

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Table 3-4: Run Equipment Availability for R3_LOOP-004-MCCI

3.1.4 Sequence Identifier: R9_SBO-006-MCCI

The initiating event for this sequence is a sudden loss of AC power at full reactor power. Following the loss of AC power, safety injection pumps, charging pump, and motor-driven AFW are unavailable. Turbine-driven AFW is assumed available, until 2 hours into the sequence, once the when battery runs out.

The following table summarizes availabilities of key systems in this sequence.

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Table 3-5: Run Equipment Availability for R9_SBO-006-MCCI

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Table 3-5: Run Equipment Availability for R9_SBO-006-MCCI

3.1.5 Sequence Identifier: LLOCA-C04-NoECSBS-MCCI

The initiating event for this sequence is a large break occurring at full power. The break is equivalent to a 9.5 inch diameter hole in the loop 1 hot leg. Four safety injection tanks (SITs) are available, but safety injection pumps and charging pumps are unavailable.
The following table summarizes availabilities of key systems in this sequence.

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Table 3-6: Run Equipment Availability for LLOCA-C04-NoECSBS-MCCI

3.2 Results of analysis

3.2.1 Sequence Identifier: R1-TLOES-003-MCCI

This sequence is defined as a loss of Essential Service Water (ESW) at full power resulting in reactor scram at sequence initiation. Four Safety Injection Tanks are available. Auxiliary Feedwater, Safety Injection Pumps, Containment Spray Pumps, and Charging Pumps are assumed to be unavailable. RCS depressurization using the SDVS, CFS actuation, and alignment of the

Three-Way Valves to the steam generator compartment, are assumed to occur 30 minutes after the onset of core damage. ECSBS is assumed not to be available for this sequence. Due to the loss of ESW, a 21 gpm per pump seal LOCA is assumed to occur half an hour into the sequence.
Figure 3-1 to Figure 3-4 show RCS pressure, core exit temperature, SG pressures and SG levels. Once reactor scram occurs and main feedwater is isolated, the steam generators begin to boil off their inventories. Because AFW is assumed unavailable, SG 1 and 2 quickly boil dry at 2546 seconds, and stop removing decay heat. Half an hour into the sequence, a 21 gpm per pump seal LOCA occurs, but the flow rate is not sufficient to depressurize the RCS. The primary system heats up and pressurizes, reaching the POSRV relief set points at about 2900 seconds, and causing the valves to open. Primary system inventory is steadily lost through the POSRVs and RCP seals, causing the core water level to decrease. The discharge from the POSRVs is sparged into the IRWST, condensing the steam and preventing additional containment pressurization. The core is soon uncovered, causing the core exit temperature to reach 1,200˚ F, signaling the onset of core damage.

Thirty minutes after the onset of core damage (30 minutes after 5168 seconds), operators are assumed to align the Three-Way Valves to the steam generator compartment and open all four POSRVs to depressurize the primary system into the containment atmosphere. At the same time, operators are assumed to actuate the CFS, allowing for gravity-driven water flow from the IRWST into the reactor cavity. Depressurization of the primary system allows the available Safety Injection Tanks to inject. However, injection of the SITs is not sufficient to quench the core. The core begins to melt and relocate to the RPV lower plenum.

Figure 3-5 shows the remaining mass in the core, corium mass in the lower plenum, and corium mass in the reactor cavity. The molten corium in the reactor vessel lower plenum eventually causes the vessel to fail at low pressure. About 124 metric tons of corium, which is 62% of the molten material that has accumulated in the lower plenum, is relocated into the flooded reactor cavity at 24,257 seconds. As previously stated, the effects of initial jet breakup were ignored. This results in a molten corium pool that is capable of ablating the concrete at the bottom of the flooded reactor cavity. Figure 3-6 shows the ablation depths in the concrete floor and sidewall. The corium causes the water pool in containment to heat up and boil. Due to boiling in the cavity, and non-condensable gas generation during decomposition of concrete, containment steadily pressurizes. Figure 3-7 shows pressure in the containment dome. Heat removal by the overlying water pool eventually halts concrete ablation and quenches the corium. At the time when the corium is quenched, the concrete ablation depth of about 7.1 cm is well short of the depth of the steel containment liner (about 90 cm into the floor) in the reactor cavity.

The quenched core debris at the bottom of the reactor cavity continues to steam away the cavity water pool for the duration of this sequence. The containment pressure does not reach the FLC of 8.5 bar within 24 hours of the onset of core damage. However, due to a lack of ECSBS availability for this sequence, containment pressurization continues unabated. Containment failure eventually occurs due to overpressure.

3.2.2 Sequence Identifier: R2-MLOCA003-MCCI

This sequence is defined as a medium break LOCA occurring at full power. The break is equivalent to a 6 inch diameter hole in one of the hot legs. Four Safety Injection Tanks, and Motor-Driven

AFW, are available. Charging Pumps and Containment Spray Pumps are assumed to be unavailable. Safety Injection pumps are available initially, but are assumed to fail 2 hours into the sequence, at the time of switchover to hot leg injection. RCS depressurization using the SDVS, CFS actuation, and alignment of the Three-Way Valves to the steam generator compartment, are assumed to occur 30 minutes after the onset of core damage. ECSBS is assumed not to be available for this sequence.
Figure 3-8 to Figure 3-11 shows RCS pressure, core exit temperature, SG pressures and levels. Due to the 6 inch break, primary system pressure rapidly drops and generates an SI signal. The SI signal causes the reactor to scram and actuates the available Safety Injection Pumps. The RCS break effluent rapidly pressurizes the containment. Injection from the Safety Injection Pumps and the Safety Injection Tanks keep the core covered and cooled.

Two hours into the sequence, Safety Injection Pumps are assumed to become unavailable. RCS injection stops and primary system inventory is quickly lost out the hot leg break. Core uncovers and begins to heat up at 7,954 seconds. Core exit temperature reaches 1,200˚ F at 8,861 seconds, signaling the onset of core damage.

Thirty minutes after the onset of core damage, operators are assumed to align the Three-Way Valves to the steam generator compartment and open all four POSRVs. At the same time, operators are assumed to actuate the CFS, allowing for gravity-driven water flow from the IRWST into the reactor cavity. Since the break size is large, actuation of the SDVS has no impact on primary system pressure. The core begins to melt and relocate to the RPV lower plenum (Figure 3-12) at 13,302 seconds. This produces a brief pressure spike in the RCS due to the rapid steaming of the water pool that exists in the lower plenum.

The molten corium in the reactor vessel lower plenum eventually causes the vessel to fail, as shown in Figure 3-12. About 128 tons, or 82% of this molten material, is relocated to the reactor cavity at the time of this low-pressure vessel failure. As previously stated, the effects of initial jet breakup were ignored. This results in a molten corium pool that is capable of ablating the concrete at the bottom of the flooded reactor cavity. Figure 3-13 shows the ablation depths of the concrete floor and sidewall. The corium causes the water pool in containment to heat up and boil. Due to boiling in the cavity and non-condensable gas generation during the decomposition of concrete, containment steadily pressurizes. Figure 3-14 shows the pressure in the containment dome. Heat removal by the overlying water pool eventually halts concrete ablation and quenches the corium. At the time that the corium is quenched, the concrete ablation depth of 13.1 cm is well short of the depth of the steel containment liner in the reactor cavity.

The quenched core debris at the bottom of the reactor cavity continues to steam away the cavity water pool for the duration of the sequence. The containment pressure does not reach the FLC within 24 hours after the onset of core damage. However, due to a lack of ECSBS availability for this sequence, containment pressurization continues unabated. Containment failure eventually occurs due to overpressure.

3.2.3 Sequence Identifier: R3_LOOP-004-MCCI

This sequence is defined as a Loss of Offsite Power (LOOP) at full power resulting in reactor scram at sequence initiation. Diesel Generators are assumed to be started to provide backup power. Four Safety Injection Tanks are available. Auxiliary Feedwater, Safety Injection Pumps,

Containment Spray Pumps, and Charging Pumps are assumed to be unavailable. RCS depressurization using the SDVS, CFS actuation, and alignment of the Three-Way Valves to the steam generator compartment, are assumed to occur 30 minutes after the onset of core damage. ECSBS is assumed not to be available for this sequence.
Figure 3-15 to Figure 3-18 shows RCS pressure, core exit temperature, SG pressures and levels. Once the LOOP occurs, steam generators begin to boil off their inventories. Diesel Generators are assumed to start successfully, but no ESF systems are recovered. Because AFW is unavailable, both steam generators quickly boil dry at 2,698 seconds and stop removing decay heat. Primary system heats up and pressurizes, soon reaching the POSRV relief setpoints at 2,984 seconds, and causing the valves to open. Primary system inventory is steadily lost through the POSRVs, causing the core water level to decrease. The discharge from the POSRVs is sparged into the IRWST, condensing the steam and preventing containment pressurization. The core is soon uncovered, causing the core exit temperature to reach 1,200˚ F, signaling the onset of core damage.

Thirty minutes after the onset of core damage (thirty minutes after 4,896 seconds), operators are assumed to align the Three-Way Valves to the steam generator compartment and open all four POSRVs to depressurize the primary system into the containment atmosphere. At the same time, operators are assumed to actuate the CFS, allowing for gravity-driven water flow from the IRWST into the reactor cavity. Depressurization of the primary system allows the available Safety Injection Tanks to inject. However, injection of the SITs is not sufficient to quench the core. The core begins to melt and relocate to the RPV lower plenum.

The molten corium in the reactor vessel lower plenum eventually causes the vessel to fail at 20,039 seconds, as shown in the Figure 3-19. About 107 tons, or 80% of this molten material, is relocated to the flooded reactor cavity at the time of this low-pressure vessel failure. As previously stated, the effects of initial jet breakup were ignored. This results in a molten corium pool that is capable of ablating the concrete at the bottom of the flooded reactor cavity. Figure 3-20 shows the ablation depths in the concrete floor and sidewall. The corium causes the water pool in containment to heat up and boil. Due to this boiling in the cavity and non-condensable gas generation during concrete decomposition, containment steadily pressurizes. Figure 3-21 shows the containment pressure. Heat removal by the overlying water pool eventually halts concrete ablation and quenches the corium. At the time that the corium is quenched, the concrete ablation depth of 16.8 cm is well short of the depth of the steel containment liner in the reactor cavity.

The quenched core debris at the bottom of the reactor cavity continues to steam away the cavity water pool for the duration of the sequence. The containment pressure does not reach the FLC within 24 hours after the onset of core damage. However, due to a lack of ECSBS availability for this sequence, containment pressurization continues unabated. Containment failure eventually occurs due to overpressure.

3.2.4 Sequence Identifier: R9_SBO-006-MCCI

This sequence is defined as a loss of AC power at full power resulting in reactor scram at sequence initiation. Turbine-driven AFW is available initially, but assumed to fail 2 hours into the sequence, when batteries run out. Four Safety Injection Tanks are available. Motor-driven Auxiliary Feedwater, Safety Injection Pumps, Containment Spray Pumps, and Charging Pumps are all assumed to be unavailable. ECSBS is assumed not to be available for this sequence.

Figure 3-22 to Figure 3-25 shows RCS pressure, core exit temperature, and SG pressures, and levels. Once the loss of AC power occurs, reactor scrams, and the steam generators begin to boil off their inventories. Turbine-driven AFW (TDAFW) starts to inject water into the secondary side of the SGs at 2,293 seconds, when SG levels drop below the TDAFW setpoint. This increases SG water level and keeps the RCS pressure lower than the POSRV setpoint. One hour into the sequence, operators are assumed to: align the Three-Way Valves to the steam generator compartment (to prevent hydrogen accumulation in the IRWST), actuate the CFS (to allow for gravity-driven water flow from the IRWST into the reactor cavity), and open the POSRVs (to depressurize the primary system). The discharge from the POSRVs is sparged into the IRWST, condensing the steam, and preventing containment pressurization. Primary system inventory is quickly lost through the POSRVs, causing the core water level to decrease. Core is uncovered at 6822 seconds, causing the core exit temperature to reach 1,200˚ F at 10,061 seconds, which in turn signals the onset of core damage. Core begins to melt and relocate to the RPV lower plenum at 19,198 seconds.

Figure 3-26 shows the masses of the remaining core, corium in the lower plenum, and corium in the reactor cavity. Molten corium in the reactor vessel lower plenum eventually causes the vessel to fail at a low pressure, at 24,878 seconds. About 93 tons of corium is relocated from the lower plenum to the completely flooded cavity at the time of vessel failure, which is about 68% of the molten material accumulated in the lower plenum. Shortly after, as the remaining 54 tons of core material collapses, additional molten material drops into the cavity. As previously stated, the effects of initial jet breakup were ignored. This results in a molten corium pool that is capable of ablating the concrete at the bottom of the flooded reactor cavity. Figure 3-27 shows the ablation depths in the concrete floor and sidewall. The corium causes the water pool in containment to heat up and boil. Due to boiling in the cavity and non-condensable gas generation during the decomposition of concrete, containment steadily pressurizes. Figure 3-28 shows the containment pressure. Heat removal by the overlying water pool eventually halts concrete ablation and quenches the corium. At the time when the corium is quenched, the concrete ablation depth of 13 cm is well short of the depth of the steel containment liner in the reactor cavity.

The quenched core debris at the bottom of the reactor cavity continues to steam away the cavity water pool for the duration of the sequence. The containment pressure does not reach the FLC within 24 hours after the onset of core damage. However, due to a lack of ECSBS availability for this sequence, containment pressurization continues unabated. Containment failure eventually occurs due to overpressure.

3.2.5 Sequence Identifier: LLOCA-C04-NoECSBS-MCCI

This sequence is defined as a large break LOCA at full power resulting in reactor scram at sequence initiation. The break area is equivalent to a 9.5 inch diameter hole in loop 1 hot leg. Motor-driven AFW and four Safety Injection Tanks are available. Safety Injection Pumps, Containment Spray Pumps, and Charging Pumps are all assumed to be unavailable. RCS depressurization using the SDVS is assumed unnecessary. CFS actuation and alignment of the Three-Way Valves to the steam generator compartment are assumed to occur 30 minutes after the onset of core damage. ECSBS is assumed not to be available for this sequence.

Figure 3-29 to Figure 3-32 shows RCS pressure, core exit temperature, SG pressures, and levels. As the large break occurs, RCS inventory is quickly lost. Four Safety Injection Tanks start to inject water almost immediately, but the injection flow rate is much smaller than the break discharge flow rate. Core is quickly uncovered at 152 seconds, causing the core exit temperature to reach 1,200° F at 1,360 seconds, signaling the onset of core damage. By 4,044 seconds, the core is severely damaged, and a fraction of molten mass is relocated into the lower plenum, causing a brief RCS pressure spike.

Thirty minutes after the onset of core damage, operators are assumed to align the Three-Way Valves to the steam generator compartment. At the same time, operators are assumed to actuate the CFS, allowing for gravity-driven water flow from the IRWST into the reactor cavity.

Figure 3-33 shows the remaining mass in the core, corium mass in the lower plenum, and corium mass in the reactor cavity. The molten corium in the reactor vessel lower plenum eventually causes the vessel to fail at low pressure at 7,258 seconds. The reactor vessel fails because penetration tube weld in the second (axial) row of the lower plenum wall melts. About 107 tons of molten corium is relocated from the vessel into the completely flooded reactor cavity at the time of vessel failure, which is about 80% of the molten material accumulated in the lower plenum. About 5,900 seconds later, another major relocation occurs, as the remaining 24 tons of core material collapses into the lower plenum, dumping additional molten material into the reactor cavity. As previously stated, the effects of initial jet breakup were ignored. This results in a molten corium pool that is capable of ablating the concrete at the bottom of the flooded reactor cavity. Figure 3-34 shows the ablation depths in the concrete floor and sidewall. The corium causes the water pool in containment to heat up and boil. Due to boiling in the cavity and non-condensable gas generation during decomposition of concrete, containment steadily pressurizes. Figure 3-35 shows the containment pressure. Heat removal by the overlying water pool eventually halts concrete ablation and quenches the corium. At the time when the corium is quenched, the concrete ablation depth of 24 cm is well short of the depth of the steel containment liner in the reactor cavity.

The quenched core debris at the bottom of the reactor cavity continues to steam away the cavity water pool for the duration of the sequence. The containment pressure does not reach the FLC within 24 hours after the onset of core damage. However, due to a lack of ECSBS availability for this sequence, containment pressurization continues unabated. Containment failure eventually occurs due to overpressure.

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Figure 3-1: Pressure in RCS for the PRA sequence of loss of essential service water (R1_TLOES-003-MCCI)

TS

Figure 3-2: Core exit temperature for the PRA sequence of loss of essential service water (R1_TLOES-003-MCCI)

TS

Figure 3-3: Pressures in steam generators for the PRA sequence of loss of essential service water (R1_TLOES-003-MCCI)

TS

Figure 3-4: Water levels in steam generators for the PRA sequence of loss of essential service water (R1_TLOES-003-MCCI)

TS

Figure 3-5: Masses in the core, lower plenum and reactor cavity for the PRA sequence of loss of essential service water (R1_TLOES-003-MCCI)

TS

Figure 3-6: Ablation depth in floor and sidewall for the PRA sequence of loss of essential service water (R1_TLOES-003-MCCI)

TS

Figure 3-7: Pressure in containment dome for the PRA sequence of loss of essential service water (R1_TLOES-003-MCCI)

TS

Figure 3-8: Pressure in RCS for the PRA sequence of medium break LOCA (R2_MLOCA003-MCCI)

TS

Figure 3-9: Core exit temperature for the PRA sequence of medium break LOCA (R2_MLOCA003-MCCI)

TS

Figure 3-10: Pressures in steam generators for the PRA sequence of medium break LOCA (R2_MLOCA003-MCCI)