Pressurizer Sizing and Overpressure Protection Evaluation

Revision 0

Non-Proprietary

January 2018

REVISION HISTORY

Rev.	Date	Page	Description
0	Jan. 2018	All	First Issue

ABSTRACT

This report documents the evaluation of the APR1400 Pressurizer (PZR) sizing, and the adequacy of overpressure protection provided for Reactor Coolant System (RCS) and the Steam Generators (SGs) of the APR1400.

The APR1400 PZR sizing is designed to prevent reactor trip and safety valve opening from Performance Related Design Bases Events (PRDBEs). The PRDBEs are Nuclear Steam Supply System (NSSS) transient occurrences that must be accommodated by the design of the plant. All PRDBEs should not initiate a reactor trip and open any primary/secondary safety valves. The PZR steam volume and spray flow have sufficient capacity to mitigate the consequence of the RCS pressurization PRDBE and maintain the PZR pressure at the normal operating range.

The overpressurization of RCS and SGs is precluded by means of PZR Pilot-Operated Relief Safety Valves (POSRVs), Main Steam Safety Valves (MSSVs) and Reactor Protection System (RPS). Pressure relief capacity for RCS and SGs is conservatively sized to satisfy the overpressure requirements of the ASME Boiler and Pressure Vessel Code, Section III. The safety valves in conjunction with the RPS are designed to provide overpressure protection for a loss-of-load event with a delayed reactor trip.

The main contents include the overpressure protection analysis, but the PZR sizing analysis is described in Appendix A. A part of major contents is presented in APR1400 DCD Chapter 5 for information on the overpressure protection design. On the other hand, the PZR sizing evaluation in Appendix A includes the simulation results of some PRDEBs pressurizing the RCS. From the evaluation, it has been concluded that APR1400 PZR is properly sized to prevent reactor trip and safety valve opening during normal operational transient.

KISPAC computer code has been used for evaluation of PZR and spray sizing and for overpressure protection analysis.

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ACRONYMS AND ABBREVIATIONS

APR1400	Advanced Power Reactor 1400
CPC	Core Protection Calculator
FWCS	Feedwater Control System
HPP	High Pressurizer Pressure
IRWST	In-Containment Refueling Water Storage Tank
MSSV	Main Steam Safety Valve
MWt	megawatts thermal
NSSS	Nuclear Steam Supply System
PLCS	Pressurizer Level Control System
POSRV	Pilot-Operated Safety Relief Valve
PPCS	Pressurizer Pressure Control System
PRDBE	Performance Related Design Bases Event
PZR	Pressurizer
RCS	Reactor Coolant System
RPCS	Reactor Power Cutback System
RPS	Reactor Protection System
RRS	Reactor Regulating System
SBCS	Steam Bypass Control System
SG	Steam Generator
VOPT	Variable Overpower Trip

1.0 INTRODUCTION

Overpressure protection for the RCS and the SGs of APR1400 NSSS is in accordance with the requirements set forth in the ASME Boiler and Pressure Vessel Code, Section III. Overpressure protection is provided via pressurizer POSRVs, MSSVs, and RPS. The worst-case transient, loss-of-load, in conjunction with a delayed reactor trip, is the design basis event for evaluating the adequacy of pressurizer POSRVs. The pressurizer POSRVs, MSSVs, and RPS are designed to maintain the RCS pressure below 110% of design pressure during the worst-case transient. The MSSVs are sized conservatively to release steam flow equal to the proposed licensed power level of 4,000 MWt. SG pressure is limited to less than 110% of SG design pressure during the worst-case transient.

The adequacy of APR1400 PZR sizing is verified by performing analysis of PRDBEs which results in increase of RCS pressure. The results are presented in Appendix A.

2.0 ANALYSIS

2.1 Method

The design basis event for verifying the overpressure protection system is a loss-of-load with a delayed reactor trip, which is the most conservative event among transients such as loss-of-feedwater or loss-of-load, described as expected system pressure transients in the ASME Code Sec. III, Division 1, NB 7000.

The digital computer code used in the transient analysis includes reactor kinetics and thermal-hydraulic performance of the RCS and the SGs. The computer simulation includes the effects of reactor coolant pump performance, elevation heads, inertia of surge line water, and friction drop in the surge line.

The worst-case initial condition and nuclear parameters are assumed for the parametric analysis. The reactor is assumed to trip at the pressurizer pressure of 169.8 kg/cm^{2}A (2,415 psia), while the pressurizer POSRVs are assumed to lift at the pressure of 177.1 kg/cm^{2}A (2,519.4 psia). The first, second, and third banks of MSSVs are assumed to lift at 86.9, 89.1 and 91.0 kg/cm^{2}A (1,235.7, 1,267.9 and 1,293.9 psia), respectively.

As shown in Figure 1, POSRVs open with [ ]TS of dead time and 0.3 seconds of opening time after opening setpoint is reached. The characteristics of MSSVs is modeled conservatively according to the requirements (Reference 5.1) for safety valve as shown in Figure 2.

In order to determine the appropriate pressurizer POSRV capacity, a sensitivity study was performed to evaluate the effect of valve capacity on the maximum RCS pressure during the design basis event (Figure 3).

2.2 Computer Code

The KISPAC computer code was used to perform the overpressure protection analysis for the NSSS. The KISPAC code is a best-estimate simulation code developed to evaluate the performance related design bases events and was used for overpressure protection and natural circulation cooldown analyses of APR1400. The KISPAC code uses a detailed node and flow path methodology to model the transient behavior of the fluid systems and components of the NSSS. The performance of the code was successfully verified by comparing it to the operating plant data.

The KISPAC code performs a mass, energy, and volume balance on each node and a momentum balance on each flow path. The momentum balance includes the effects of inertia, elevation, and frictional and geometric losses. This ensures that all RCS pressures (especially the maximum RCS pressure which exists at the reactor coolant pump discharge) are correctly predicted. The reactor coolant pump model consists of a detailed representation that considers the relationship among pump speed, flows, and discharge heads. The individual primary and secondary safety valves are modeled in detail. Conservative values for the primary and secondary safety valve flow capacities are used for the overpressure protection analysis. The code contains models for all plant control and protection systems.

2.3 Assumptions

a. At the onset of a loss-of-load transient, the reactor coolant and main steam systems are at maximum rated output plus a 2% uncertainty margin. By choosing the highest possible power output, the heatup rate of the primary loop is maximized; hence, the rate of pressurization is also maximized.

b. Moderator temperature coefficient is zero. Analytical studies supported by core data show that the moderator temperature coefficient can vary between zero and negative value for various phases of core life. Therefore, a coefficient of zero is chosen to maximize the power and pressure increase.

c. The least negative value for Doppler coefficient is used in the loss-of-load analysis. By choosing the least negative Doppler coefficient, the reduction in reactivity with increasing fuel temperature is minimized, thereby maximizing the rate of power increase.

d. No credit is taken for letdown, charging, pressurizer spray, turbine bypass, control rod motion and feedwater addition (main and auxiliary) after turbine trip in the loss-of-load analysis. Letdown and pressurizer spray both act to reduce primary pressure. By not taking credit for these systems, the rate of pressurization is increased. By not taking credit for control rod motion, reactor power is not decreased by insertion of the control rod. By not taking credit for the addition of feedwater, the SG secondary inventory will be depleted at a faster rate. This in turn reduces the capability of the SG to remove heat from the primary loop, thereby maximizing the rate of primary pressurization.

e. The analysis reflects consideration of plant instrumentation error and pressurizer POSRV setpoint uncertainties. For example, all pressurizer POSRVs are assumed to open at their maximum opening pressure of 177.1 kg/cm^{2}A (2,519.4 psia). This extends the period of time before energy can be removed from the system. The reactor trip setpoint uncertainties are always assumed to act in such a manner that they delay reactor trip and result in maximum pressurization.

f. A parametric study on the initial pressurizer pressure and level summarized in Table 1 shows that the maximum RCS pressure can be achieved with 152.9 kg/cm^{2}A (2,175 psia) of pressurizer pressure and 45 % of pressurizer water level.

g. The reactor scram is assumed to be initiated by the second safety grade signal from the RPS.

3.0 RESULTS

3.1 Parametric Analysis on Initial PZR Condition

The loss of load event is analyzed with various initial PZR pressures and water levels to determine the initial values which can maximize the RCS pressurization. The ranges of initial conditions used in the parametric studies are consistent with those used in the DCD Table 15.0-3. The nominal full power values are 2,250 psia and 50% for the PZR pressure and water level, respectively.

The analyzed cases and their results for the RCS pressurization point of view are summarized in Table 1.

The results summarized in Table 1 show that the reactor trip time and the POSRV opening time can be delayed by using a lower initial PZR pressure for the same initial PZR water level. This is due to the more margin to the high pressure reactor trip setpoint with a lower initial PZR pressure. However, the first bank MSSV opening time remains almost same regardless of the initial PZR pressure resulting in energy removal after the reactor trip and the POSRV opening. The third bank MSSVs have not experienced opening except cases s1, s2, s5 and s9. An early opening of POSRVs due to a high initial PZR pressure results in primary energy relief by POSRVs before the energy relief through MSSVs.

The parametric analysis results also show that the case with a higher initial PZR water level results in a faster reactor trip and RCS pressurization compared to the cases with a lower initial PZR water level.

As a result, the case with initial PZR pressure of 2,175 psia and initial PZR water level of 45% is selected as the limiting case for the maximum RCS pressurization point of view.

As shown in Table 1, the longer the time span between the event initiation and the reactor trip is, the higher the SG peak pressure is. And the maximum peak pressure of secondary system occurred with the case with initial PZR pressure of 2,200 psia and initial PZR water level of 21% (i.e. case s2).

Table 1 Parametric Study Results for Initial Pressurizer Pressure and Level

Case	Input Parameters		Output					
	Initial PZR Level (%)	Initial PZR Pressure (psia)	Reach HPP SP (sec)	POSRVs Open (sec)	1st MSSVs Open (sec)	2nd MSSVs Open (sec)	SG Peak Pressure (psia)	RCS Peak Pressure (psia)
s1	21	2175	6.52	8.20	7.49	9.14[1)]	1293.9	2693.1
s2		2200	6.07	7.80	7.50	9.15[2)]	<u>1294.0</u>	2693.4
s3		2250	5.12	6.98	7.50	9.24	1291.1	2689.7
s4		2325	3.56	5.66	7.56	9.76	1272.8	2671.8
s5	45	2175	5.59	7.00	7.46	9.14[3)]	1293.9	<u>2699.1</u>
s6		2200	5.21	6.67	7.46	9.19	1292.3	2696.6
s7		2250	4.45	6.00	7.48	9.37	1280.4	2689.7
s8		2325	3.16	4.91	7.60	10.15	1272.8	2674.2
s9	50	2175	5.37	6.73	7.45	9.16[4)]	1293.9	2698.2
s10		2200	5.01	6.42	7.45	9.22	1289.0	2695.8
s11		2250	4.29	5.77	7.48	9.43	1278.3	2688.4
s12		2325	3.06	4.73	7.61	10.28	1272.6	2674.3
s13	55	2175	5.16	6.46	7.44	9.18	1291.7	2697.7
s14		2200	4.82	6.16	7.45	9.26	1286.1	2695.0
s15		2250	4.13	5.54	7.48	9.50	1276.5	2687.4
s16		2325	3.00	4.59	7.63	10.36	1271.9	2675.6
s17	60	2175	4.96	6.20	7.43	9.22	1288.6	2696.1
s18		2200	4.64	5.91	7.44	9.31	1283.5	2693.6
s19		2250	3.97	5.30	7.49	9.59	1275.1	2685.7
s20		2325	2.90	4.41	7.65	10.50	1270.8	2676.7

1) 3rd MSSVs open at 11.79 seconds
2) 3rd MSSVs open at 12.16 seconds
3) 3rd MSSVs open at 13.20 seconds
4) 3rd MSSVs open at 14.27 seconds

3.2 Main Steam Safety Valve Sizing Verification

The MSSVs are conservatively sized to release the excess steam flow. This limits SG pressure to less than 110% of SG design pressure during the worst-case transient. The MSSVs consist of three banks of valves with the different set pressures. The valves are spring-loaded type safety valves procured in accordance with the ASME Boiler and Pressure Vessel Code, Section III. The discharge piping serving the MSSVs is designed to accommodate rated relief capacity without imposing unacceptable backpressure on the safety valves.

Figure 4 depicts the SG pressure transient for this worst-case loss-of-load event. As shown in Figure 4, the SG pressure remains below 110% of design pressure during the event.

3.3 Pressurizer POSRV Sizing Verification

The IRWST and the inlet and discharge piping are sized to preclude unacceptable pressure drop and backpressure rise which would adversely affect valve operation.

The design basis event for verifying the sizing of the pressurizer POSRV is a loss-of-load in which the reactor is not immediately tripped. The reactor trip is assumed to occur with a safety-grade trip signal generated secondly by the RPS, namely by the primary pressure related core protection calculator (CPC) auxiliary trip. No credit is taken for any pressure-reducing devices except the pressurizer POSRVs and the MSSVs. In reality, the event would be terminated by a number of reactor trips, including the following:

a. Steam generator low level trip

b. High pressurizer pressure trip (first RPS trip)

c. Manual trip

If the first and second high pressurizer pressure trips were to become inoperative, other reactor trip would proceed to shut the reactor down as their setpoints were exceeded.

A series of loss-of-load cases were run with various sizes of pressurizer POSRVs. As shown in Figure 3, after the pressurizer POSRV capacity increases to a certain value, additional increase in capacity has small effect in reducing the maximum system pressure experienced during the loss-of-load transient. Pressurizer POSRVs are sized such that the maximum pressure experienced during the loss of load transient is kept to a minimum.

Figures 4, 5 and 6 represent time dependent changes of the SG pressure, reactor coolant system pressure, and reactor power, respectively, during the worst- case loss-of-load event. As shown in Figures 2 and 3, the maximum SG pressure and reactor coolant system pressure remain below 110% of design pressure during this worst-case transient.

The first, second and third bank MSSVs open at approximately 7.46, 9.14 and 13.20 seconds, respectively. The MSSVs remove energy from the reactor coolant system and thus mitigate the pressure excursion. The pressurizer POSRVs are conservatively assumed to open at 177.1 kg/cm^{2}A (2,519.4 psia). The pressurizer POSRVs open at 7.00 seconds after the initiation of the event.

The analysis of a complete loss-of-load event is described in APR1400 DCD Section 15.2. As demonstrated in this analysis, if a complete loss-of-load occurs with a delayed reactor trip, the overpressure protection provided by the high pressurizer pressure trip, pressurizer POSRVs and the MSSVs is sufficient to ensure that the integrity of the RCS and SGs is maintained.

3.4 Conformance with the Valve Blowdown Requirements

The pressurizer POSRVs shall be adjusted to close after blowing down to a pressure not lower than 95% of set pressure, otherwise valve blowdown is specified in the valve design specification and the basis for the setting is evaluated in the overpressure protection report in accordance with the ASME, Sec. III requirements. The pressurizer POSRVs are designed to discharge not only steam but also water. Therefore, even though the pressurizer POSRVs blow down to 87% of valve opening setpressure and is below the 95% of set pressure, no adverse effect is expected due to the water discharge that results from pressurizer water level increase in the event of pressurizer POSRVs opening.

4.0 CONCLUSIONS

The SG and RCS of the NSSS are protected from overpressurization in accordance with the guidelines set forth in the ASME Boiler and Pressure Vessel Code, Section III. Peak reactor coolant and SG pressures are limited to less than 110% of design pressures during the worst-case loss-of-load event. Reliable overpressure protection is ensured by the pressurizer POSRVs, the MSSVs, and the RPS.

Through the analysis result of large turbine load decrease event in Appendix A, the adequacy of APR1400 PZR sizing is verified.

5.0 REFERENCES

1. ASME Boiler and Pressure Vessel Code Section III, Article NB-7000, "Overpressure Protection," The American Society of Mechanical Engineers, 2007 Edition with 2008 Addenda.

2. NUREG-0800, Standard Review Plan 5.2.2, Overpressure Protection," U.S. Nuclear Regulatory Commission, March 2007.

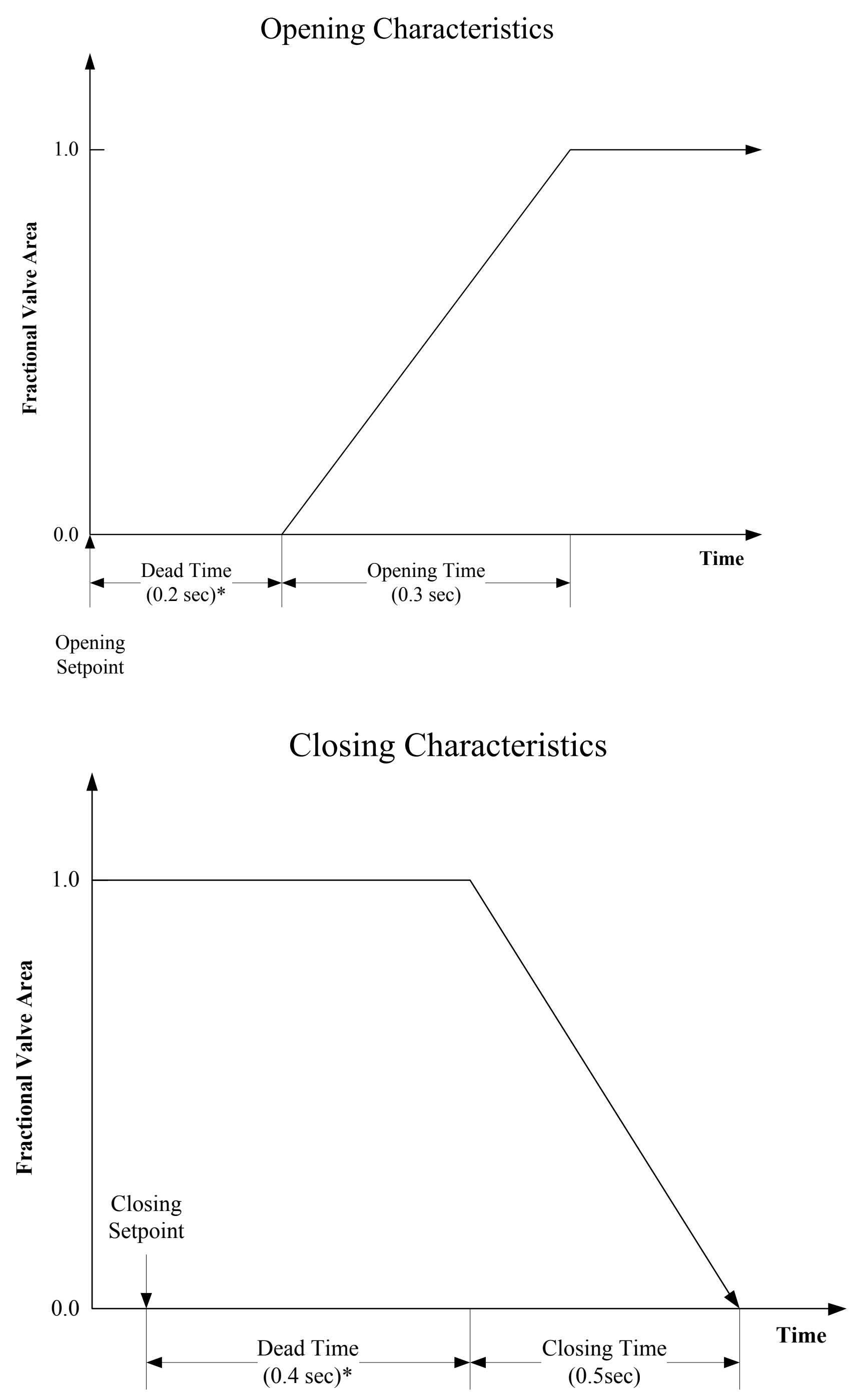

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Figure 1 Characteristics of Pressurizer POSRV

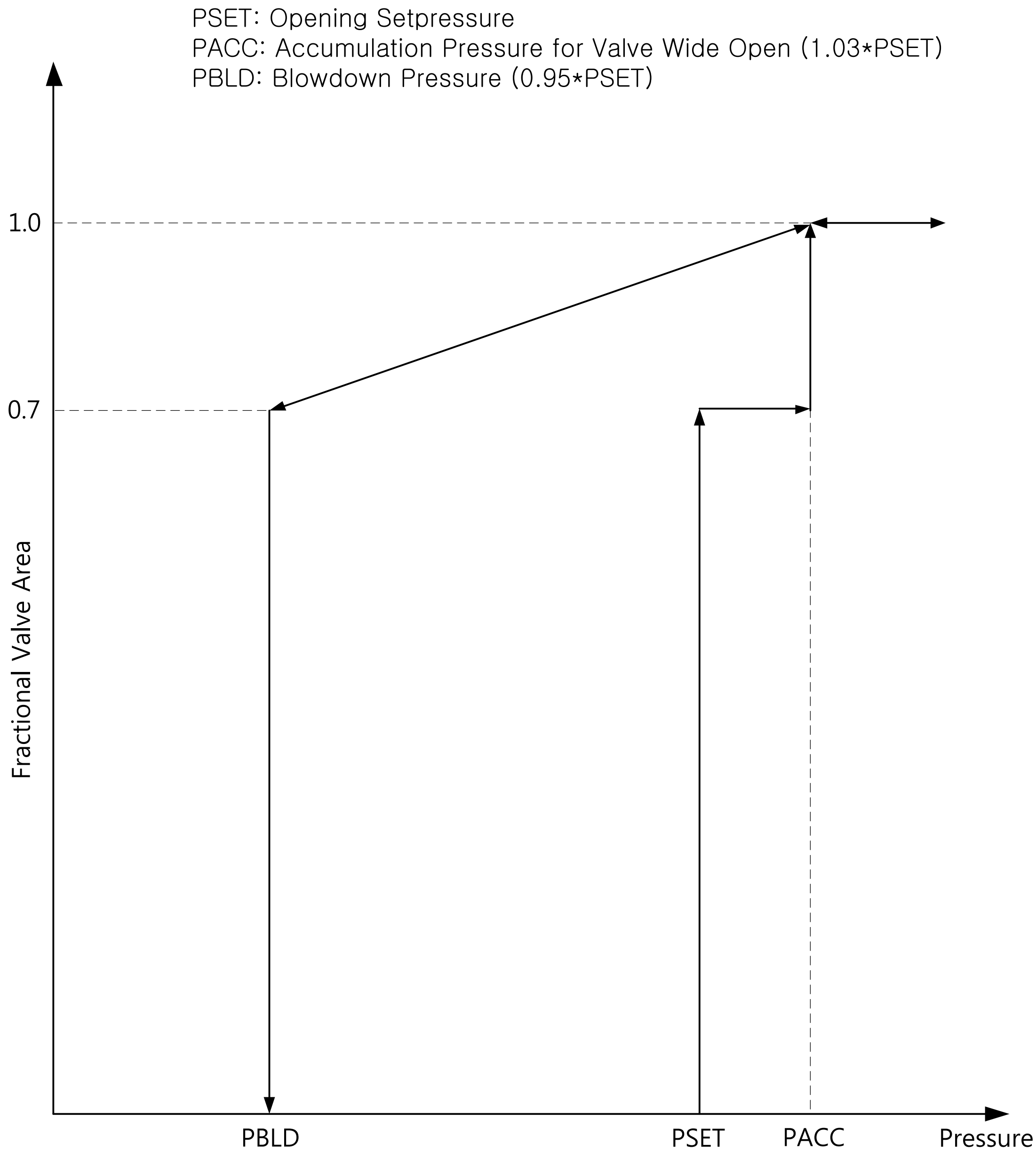

Figure 2 Characteristics of Main Steam Safety Valve

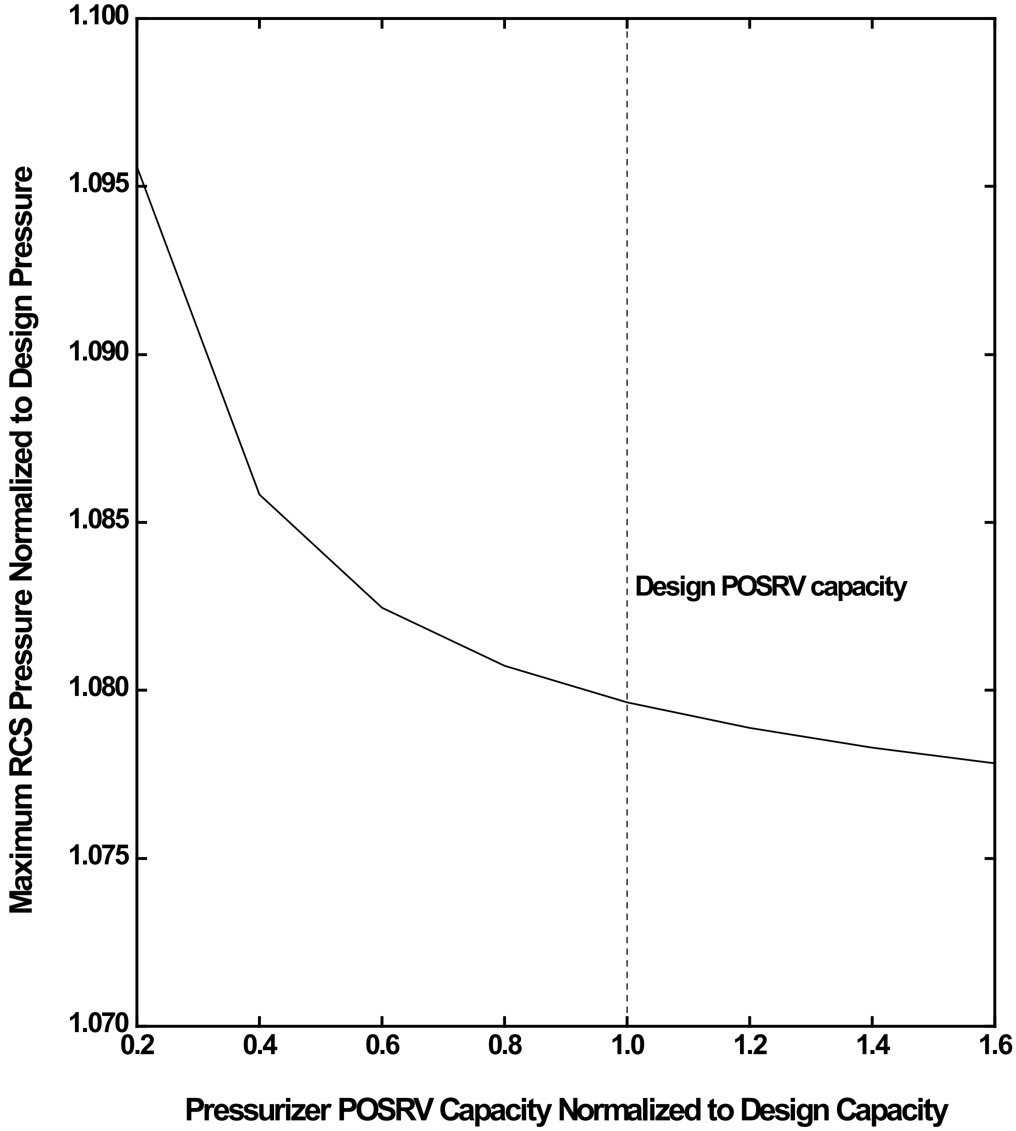

Figure 3 Worst-Case Loss-of-Load Event:

Maximum RCS Pressure Normalized to Design Pressure

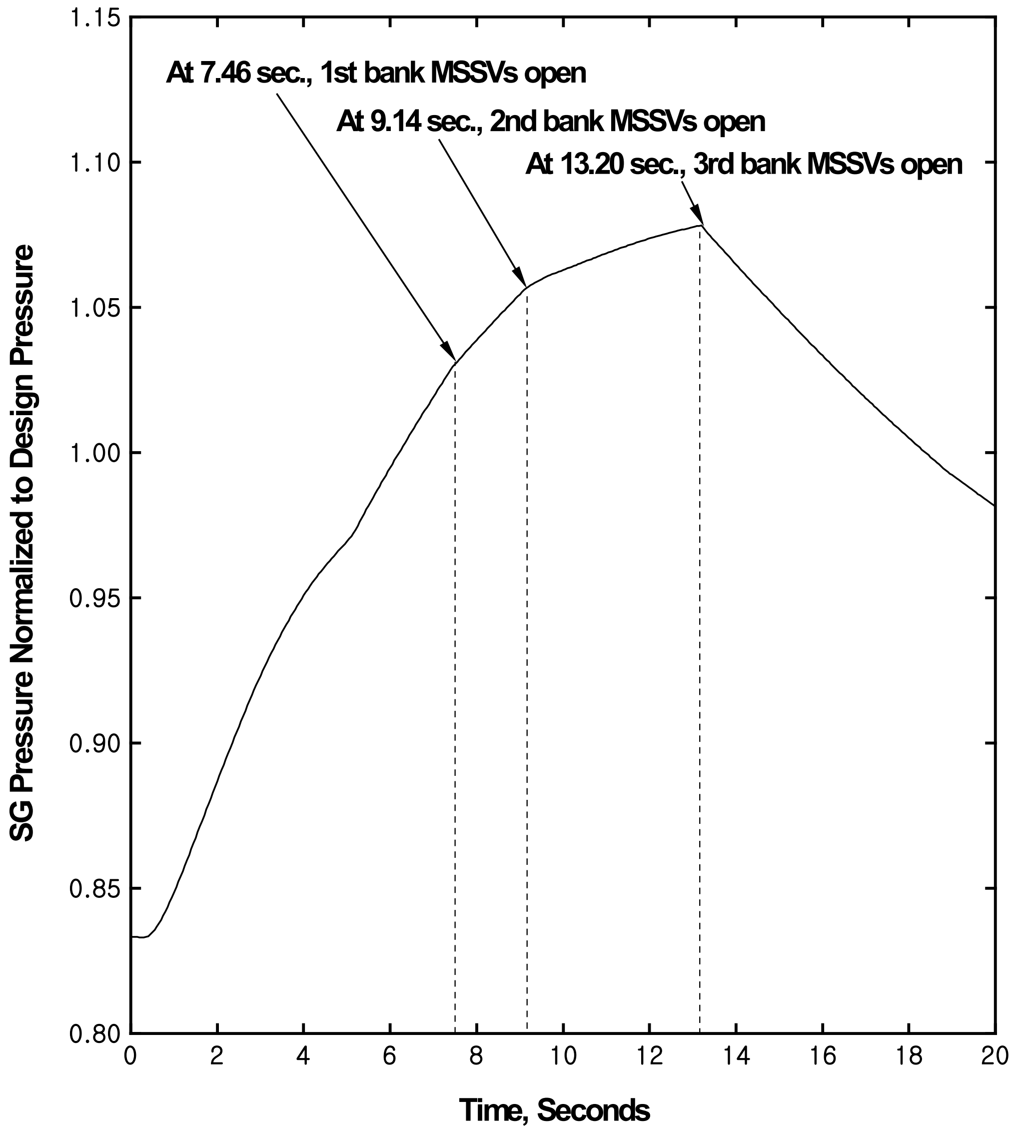

Figure 4 Worst-Case Loss-of-Load Event:

SG Pressure Normalized to Design Pressure

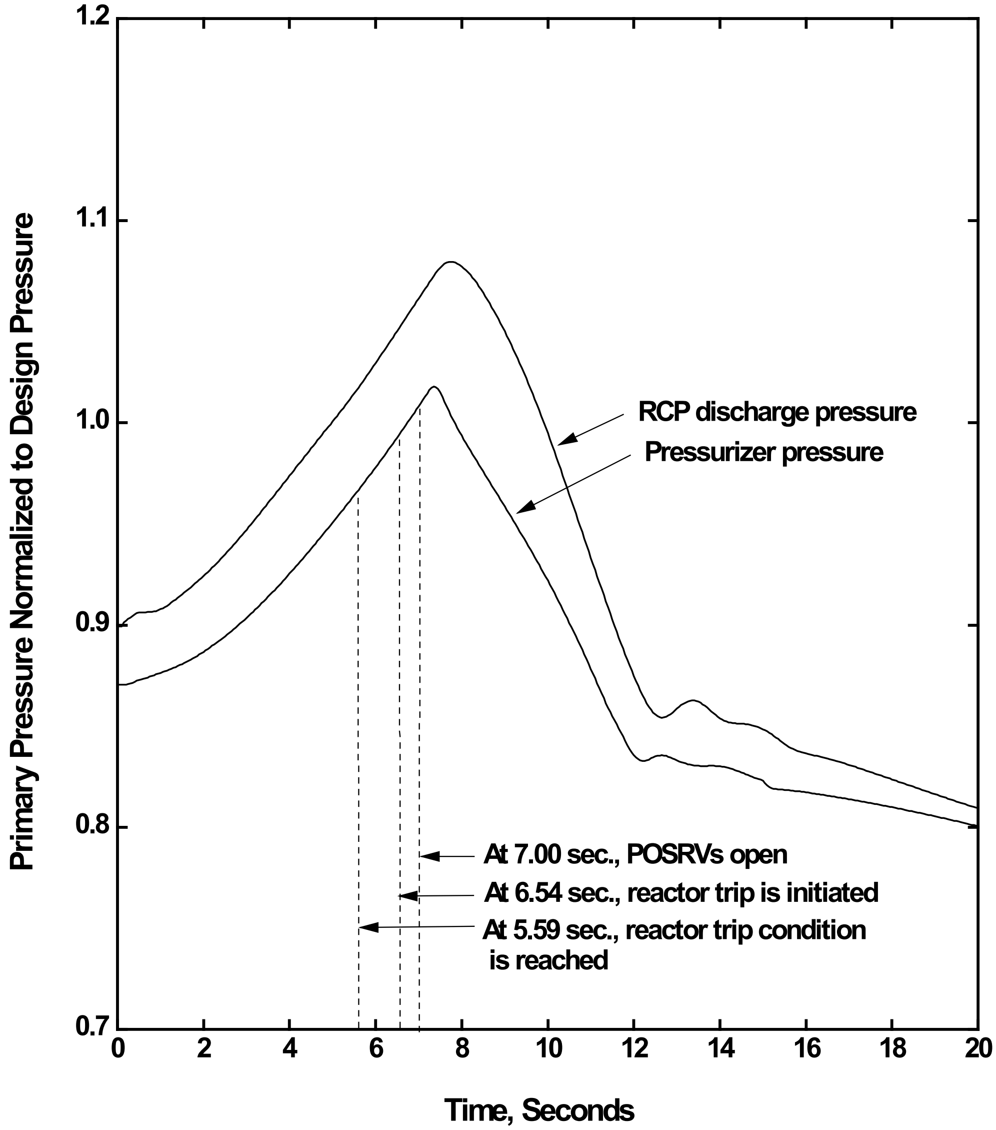

Figure 5 Worst-Case Loss-of-Load Event:

Primary Pressure Normalized to Design Pressure

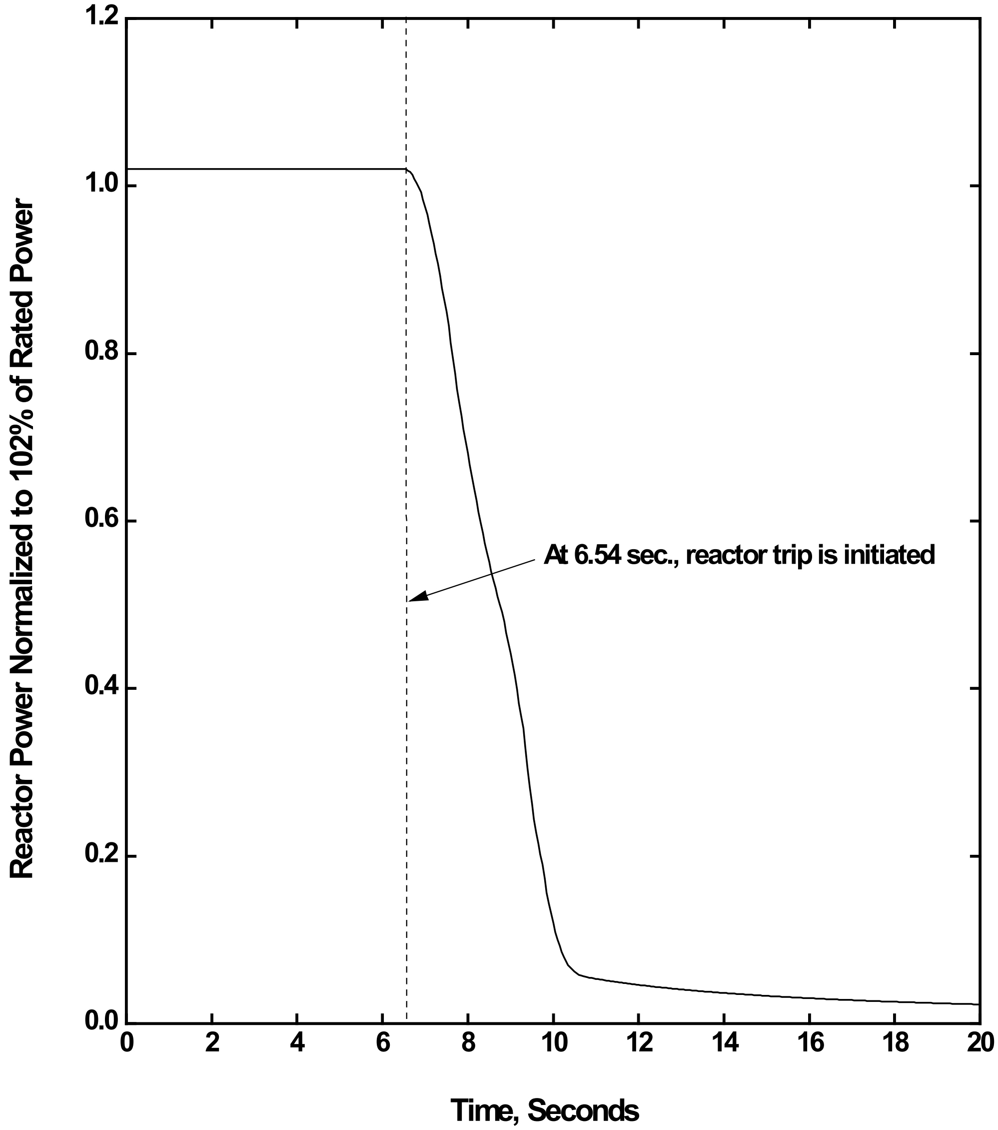

Figure 6 Worst-Case Loss-of-Load Event:

Reactor Power Normalized to 102% of Rated Power

APPENDIX A PRESSURIZER SIZING EVALUATION

The adequacy of APR 1400 PZR sizing, including the spray flow, is verified by performing analysis of PRDBEs which results in increase of RCS pressure. Major RCS pressurization is caused by a large turbine load decrease event, such as turbine trip.

A.1 Scope

APR1400 is designed to continue power operation without reactor trip and opening of PZR POSRVs and SG MSSVs during normal operation. This capability of APR1400 is demonstrated by evaluation of the conformance of the PRDBEs to the applicable acceptance criteria. With respect to the consequence following large turbine load decrease, RCS pressurization is mitigated by sufficient PZR sizing allowing continued power operation without reactor trip or safety valve opening.

A.2 Acceptance Criteria

The followings are applicable acceptance criteria for the PRDBEs analyzed in this Appendix.

a. Reactor Protection System is not activated.

- High PZR Pressure trip setpoint : 2377 psia

b. Primary safety valves does not open.

- POSRV opening setpoint : 2470 psia

A.3 Assumption

Acceptable plant responses to PRDBEs are accomplished by utilizing the inherent design margin of the NSSS components (e.g., PZR size, RCS volume and SG size) and the automatic response of the NSSS control systems. These include Feedwater Control System (FWCS), Steam Bypass Control System (SBCS), Reactor Regulating System (RRS), PZR Level Control System (PLCS), PZR Pressure Control System (PPCS) and Reactor Power Cutback System (RPCS). The ability of the NSSS to successfully accommodate PRDBEs is predicted based on all NSSS control systems being available in the automatic mode and operating normally (e.g., the full capacities of the PZR heaters, PZR spray, letdown, charging, feedwater, and steam bypass system are available).

A.2 Analysis Method and Results

The following large turbine load step decrease events are categorized as normal events and the APR1400 is designed to continued power operation without activating the reactor trip and opening of PZR POSRVs.

(1) Turbine Trip

(2) Turbine generator runback to house load

(3) Turbine load rejection of up to 50% of rated power

Turbine trip is an event caused by a mechanical or electrical problem. During this event, the integrated response of the NSSS control systems mitigates the large primary and secondary parameter variations that occur. The SBCS monitors secondary steam flowrate to detect load changes and controls secondary pressure directly, and primary pressure indirectly, by bypassing steam around the turbine. The RPCS, if necessary, rapidly reduces reactor power to minimize the primary/secondary power mismatch immediately after the event initiation by dropping pre-selected CEA control banks. The RRS then slowly reduces reactor power to a pre-determined setpoint to match secondary power. The PLCS reduces the transient of the primary inventory by adjusting the charging and letdown flow rates to maintain the programmed PZR level. The PPCS controls the PZR heaters and main spray to maintain the primary system pressure within acceptable limits. During this event, reactor trip and opening of primary/secondary safety valves do not occur. (Figure A-1)

Turbine generator runback to house load event, which is switch-over to house load operation from full power with steam dump to the condenser, is a loss of offsite load with the turbine running back to house load. The plant is controlled by NSSS control systems without a reactor trip for turbine generator runback to house load event, and stabilizes at house load operation condition. During this event, reactor trip and opening of primary/secondary safety valves do not occur. (Figure A-2)

Turbine load rejection of up to 50% of rated power makes the turbine load from full power to half, and primary and secondary pressure increase immediately. As shown in Figure A-3, reactor trip and opening of primary/secondary safety valves do not occur during the turbine load rejection of 50% power event.

During these events, RCS pressure increase is limited below the reactor trip setpoint with the help of plant control systems such as turbine bypass valves, PZR spray, RPCS and RRS.

A.3 Conclusion

The results of the analysis of the PRDBEs that result in RCS pressurization during normal operation transient show the adequacy of PZR sizing. All the simulation results demonstrate that the RCS pressurization following the turbine load decrease events does not challenge reactor trip or safety valve opening.

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Figure A-1 Turbine Trip event

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Figure A-2 Turbine Runback to House Load event

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Figure A-3 Load Rejection of 50% Power event