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Analysis of Inadvertent Containment Spray Actuation for NPP Krško

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ABSTRACT

Refueling Water Storage Tank (RWST) supplies borated water to the Chemical and Volume Control System, Emergency Core Cooling System and Containment Spray System. In the analyses of the containment external pressure the spray temperature is assumed to be equal to the RWST lower temperature limit. This value ensures that the design negative containment pressure will not be exceeded in the event of inadvertent actuation of the Containment Spray. For NPP Krško the negative containment pressure has to be kept below 0.1 kp/cm^2 to avoid the loss of containment integrity.

This paper presents the analysis of Inadvertent Containment Spray Actuation in order to check the influence of change in RWST water temperature on containment negative pressure. GOTHIC computer code was used for calculation of containment thermal hydraulic behavior during this accident

INTRODUCTION

Inadvertent operation of the containment spray causes depressurization in the containment. There are two distinct phases of the event, short term and long term, characterized by different physical mechanisms and models. The dominant effect in the short term phase is evaporative cooling (superheated water droplets take latent heat energy required for evaporation from containment air), while the long term phase is characterized by normal heat transfer between containment atmosphere, spray droplets and heat structures. The evaporative cooling causes rapid containment depressurization within the first 10 s (decrease of air enthalpy means drop in containment temperature and pressure). The short-term phase is terminated at the time when containment atmosphere becomes saturated and after that the depressurization is determined by normal heat transfer in the containment atmosphere, during long term phase. The limiting negative containment pressure can be reached either during short term or during long term phase. This, as well as the relative significance of each phase, depends on initial conditions in the containment.

Different aspects and influences of inadvertent actuation of containment spray event were examined. That includes the influence of initial containment humidity, the presence of heat structures and the change of the spray temperature and flow rate. The detailed sensitivity analysis demonstrates that the variation of the RWST temperature have influence on peak of containment negative pressure, but sufficient margin to the containment negative pressure design limit exists in all cases. Only the lowest temperature value (4.44 °C) could produce violation of the limit in the unrealistic case of 100% initial relative humidity in the containment.

MATHEMATICAL MODEL AND INPUT ASSUMPTIONS

The computer code GOTHIC, ref.[1], (implemented on Pentium PCs) was used for calculation of containment thermal hydraulic behavior. The code solves conservation of: mass, momentum, and energy equations for multiphase (vapor phase, continuous liquid phase, droplet phase) multicomponent (water, air, hydrogen, noble gases) compressible flow. Constitutive relations predict interaction between phases for nonhomogenous nonequlibrium flow. Heat structures are modeled as 1D heated or unheated structures. Hydraulic volumes use 1D, 2D, 3D or lumped approach. It is possible to simulate operation of engineered safety equipment: pumps, fans, valves and doors, vacuum breakers, spray nozzles, heat exchangers, heaters and coolers, controlled by trip logic based on: time, pressure, vapor temperature, liquid level, conductor temperature. The code is tested and qualified to perform calculations similar to this analysis.

The total free volume of the containment was modeled as one compartment (40776 m^3), compartment number 1 on Figure 1. The containment annulus was modeled as another separate compartment with free volume of 10987 m^3, compartment number 2. The values are taken from ref.[3]. Initial conditions inside containment are consistent with values used for accident analysis and containment design calculation (48.9 °C, 101.325 kPa). The temperature of the outside air is 34 °C.

Containment heat structures were modeled as 13 different heat structures, according to ref.[3]. The heat structures 1 and 2 are used for representing steel liner and structures 3 and 4 are used for concrete containment wall. All other heat structures are internal containment heat structures.

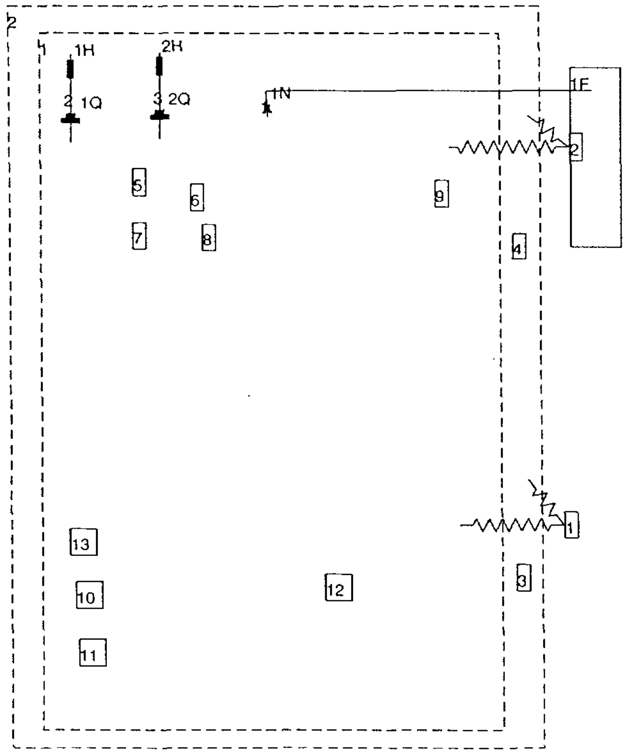

Figure 1. GOTHIC model of NEK containment

One flow boundary condition is used in the model. Boundary condition 1F together with flow path 1 and spray nozzle 1N was used for modeling of RWST and containment spray system. The characteristics of the spray are taken from ref. [3]. Gothic spray nozzle component was used at the end of flow path to convert all water flow to droplets. The average size of droplets was determined based on earlier analysis of spray influence on SLB and LOCA accidents.

Although the reactor containment fan cooler (RCFC) ref. [2] was modeled separately as volumetric fan cooler (1Q, 2Q - Figure 1) they were shut off during calculation of inadvertent spray actuation. The effect of omitting the RCFCs is negligible since, in normal operation, they serve to remove the primary heat losses that were also not taken into consideration during the transient.

ANALYSIS AND RESULTS

The first performed calculation is very similar to original calculation from NEK USAR Chapter 6. Initial containment, annulus and environment temperatures are 48.89 °C, 35 °C, and 33.89 °C respectively. The initial pressures in containment and annulus are 101.325 kPa. Temperature of RWST water is 26.67 °C (80 °F). Conservative assumed volumetric spray flow for each train is 0.08202 m^3/s. The spray flow is initiated at 0 s, and stopped 600 s (10 minute operator action time) after generation of signal of –0.1 psig containment pressure. The signal is generated at 40.9 s in case of 100 % initial RH and this value (that means spray flow in containment between 0 s and 640.9 s) is used in all analyses. In original FSAR calculation the signal was generated at 48 s, but that has no influence on final results.

The calculation was performed for following initial relative humidities in containment: 0, 10, 25, 30, 50, 75, 100% (initial RH in annulus is 30% and change in that value has no influence on calculated containment negative pressure).

The pressure vs. time, for different initial relative humidities in containment, is shown in Figure 2 and corresponding containment air temperatures is shown in Figure 3. The labels used in figures have following meaning: first three numbers are initial relative humidity, last two numbers are RWST temperatures.

For relative humidities 0%, 10%, 25% and 30% dominant effect is short-term evaporation, minimum pressure is reached early in the transient, and pressure drop is larger for lower relative humidities. As soon as relative humidity reaches 100% (corresponds to time of minimum pressure) pressure and temperature start to increase. The rate of increase depends on difference between air temperature at point of minimum pressure (14.4 °C for 100% RH) and temperatures of spray water and heat structures.

For initial relative humidity 100% only long term cooling is active. The heat removal is determined by heat transfer due to temperature difference and due to condensation. The pressure is decreasing up to the point of spray flow termination (or when temperature falls below spray water temperature).

The cases with initial humidities 50% and 75% are transitional cases, but minimum reached pressure is governed by long-term effect. The higher initial relative humidity means larger pressure drop. After termination of spray flow temperature and pressure are increasing due to heat transfer from heat structures. The pressure drop is smaller than containment design limit of 0.1 kp/cm^2 (Table 1).

Table 1. Minimum pressures, referent case

Case	Min. Pressure (kp/cm^2 gauge)	Time of min pressure (s)
0% RH	-0.0936	7.07
10% RH	-0.0765	5.87
25% RH	-0.0563	4.67
30% RH	-0.0503	4.07
50% RH	-0.0413	640.67
75% RH	-0.0521	641.18
100% RH	-0.0631	640.67

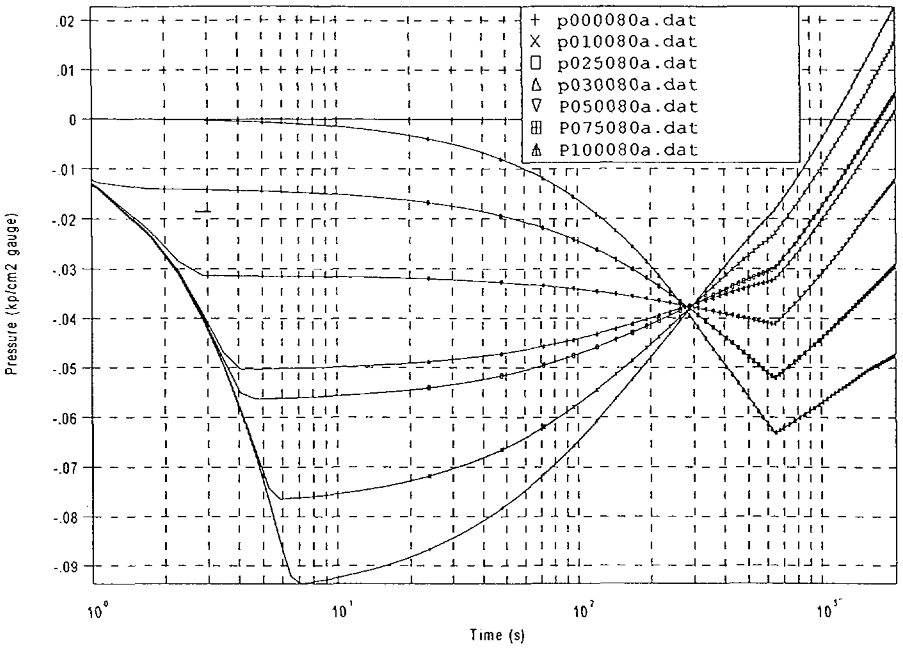

Figure 2. Containment pressure – referent case

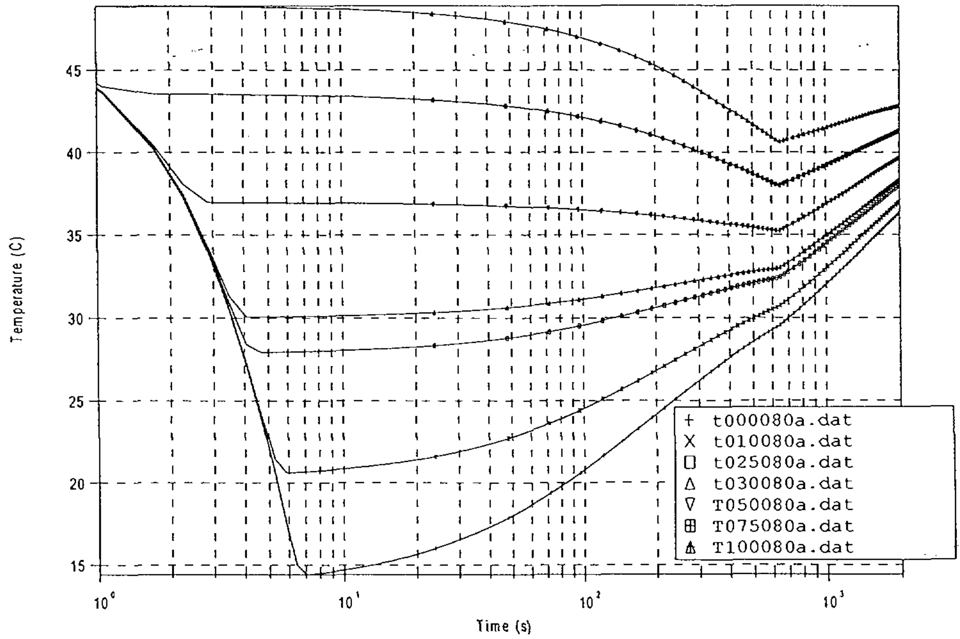

Figure 3. Containment temperature – referent case

The second calculation is performed to check influence of RWST water temperature on containment pressure drop. The calculation is performed for two bounding initial relative humidities, 0% and 100%, to see effect on both, short and long term, depressurization phases. All other conditions are the same as in reference calculation.

The pressure vs. time, for different RWST water temperatures at 0% RH, is shown in Figure 4. The labels used in figures have following meaning: first three numbers are initial relative humidity, last two numbers are RWST temperature. The pressure for 100% initial relative humidity is shown in Figure 5.

In case of 0% initial RH the decrease in RWST temperature has only minor influence on decrease of minimum containment pressure, without influence on time of minimum pressure. In case of 100% initial RH decrease of RWST temperature has significant influence on decrease of minimum containment pressure (heat transfer from containment atmosphere to spray droplets). The time of minimum pressure is again at the time of spray flow termination. For spray temperature equal to containment initial temperature (120 °F), in case of long term cooling, there is no heat transfer (zero temperature difference) and pressure is constant or increasing at very slow rate. The only case (Table 2.) falling below design limit is case 100% initial RH, 40 °F (4.44 °C) RWST temperature (limit is reached 431 s after transient initiation).

Table 2. Minimum pressures, influence of RWST temperature

Case	Min. Pressure (kp/cm^2 gauge)	Time of min pressure (s)
0% RH, 40 °F	-0.0958	7.07
0% RH, 60 °F	-0.0947	7.07
0% RH, 80 °F	-0.0936	7.07
0% RH, 100 °F	-0.0925	7.07
0% RH, 120 °F	-0.0914	7.07
100% RH, 40 °F	-0.1215	641.18
100% RH, 60 °F	-0.0928	641.18
100% RH, 80 °F	-0.0631	640.67
100% RH, 100 °F	-0.0327	641.18
100% RH, 120 °F	-0.0003	N/A

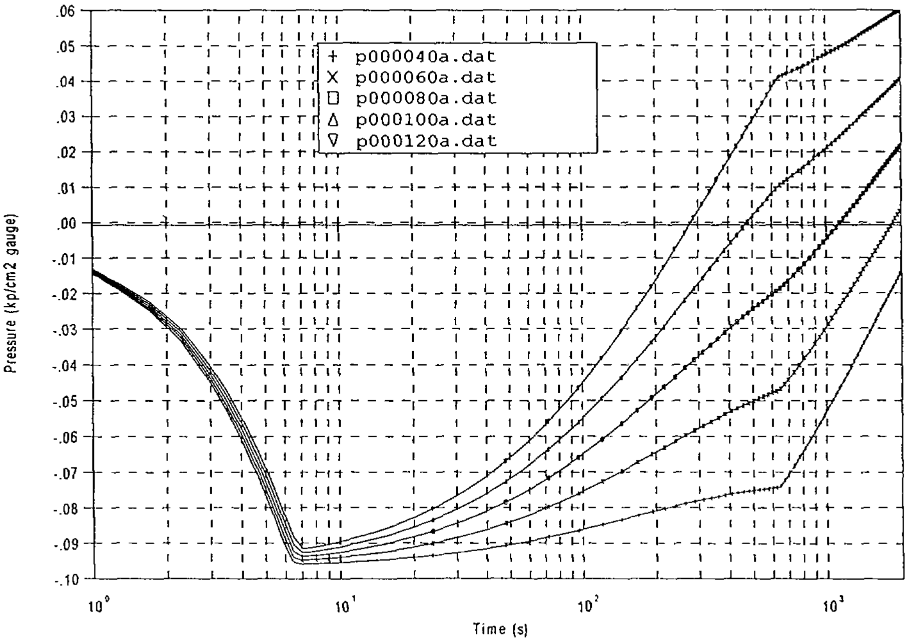

Figure 4. Containment pressure – influence of RWST temperature, 0% RH

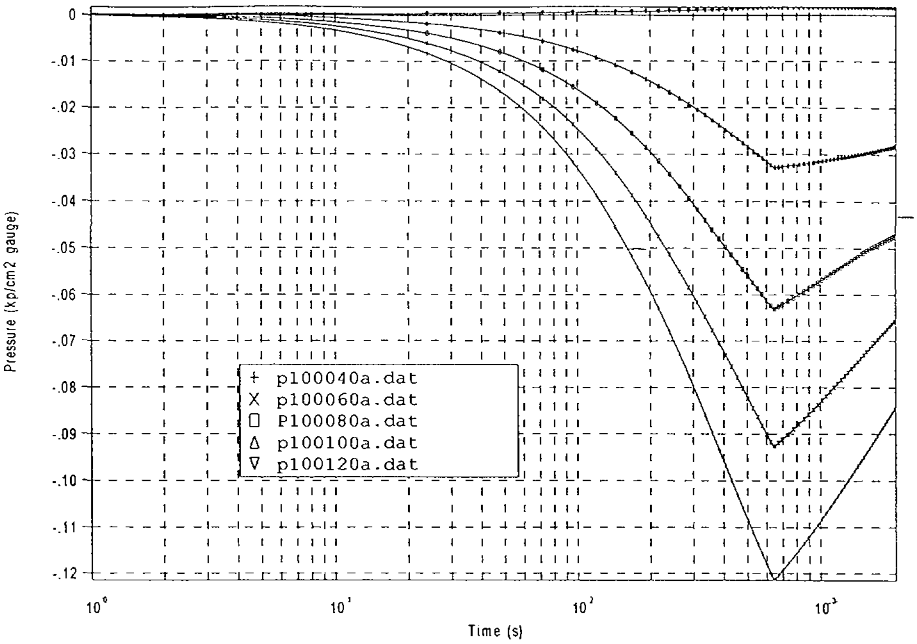

Figure 5. Containment pressure – influence of RWST temperature, 100% RH

The third calculation is performed to check sensitivity on presence of heat structures and initial containment and annulus temperatures. The pressure vs. time, for different cases, is shown in Figure 6. The labels used in figures have following meaning: first three numbers are initial relative humidity, last letter is used to describe analysis assumptions (b- reference conditions, c- annulus temperature increased from 95 °F to 120 °F, e- containment temperature decreased from 120 °F to 95 °F).

The increase of annulus temperature from 95 °F to 120 °F has negligible influence on overall behavior and minimum containment pressure (cases b and c). Decrease of initial containment temperature from 120 °F to 95 °F (cases b and e) results in smaller pressure drop in short term phase (less energy removed from containment atmosphere).

The influence of heat transfer to containment structures has been analyzed at three different initial relative humidities (0%, 30%, 100%). In all cases pressure drop increased without containment heat structures. Influence is negligible at 0% RH, but it is increasing with increased humidity. There is no influence on time of minimum pressure. It can be seen that heat transfer from containment structures to the containment atmosphere is one of the factors causing increase of temperature and pressure after point of minimum pressure, for low initial RHs, and slower decrease during long term phase for higher initial RHs. In the same time heat structures are only factor causing pressure and time increase after end of spray flow (case f for different humidities). Again, in all cases there is margin (Table 3.) to containment negative design pressure.

Table 3. Minimum pressures, presence of HS and temperature sensitivity

Case	Min. Pressure (kp/cm^2 gauge)	Time of min pressure (s)
30% RH, case b	-0.0502	4.07
30% RH, case c	-0.0502	4.07
30% RH, case e	-0.0415	3.47
0% RH, case f	-0.0944	7.07
30% RH, case f	-0.0549	598.67
100% RH, case f	-0.0651	643.58

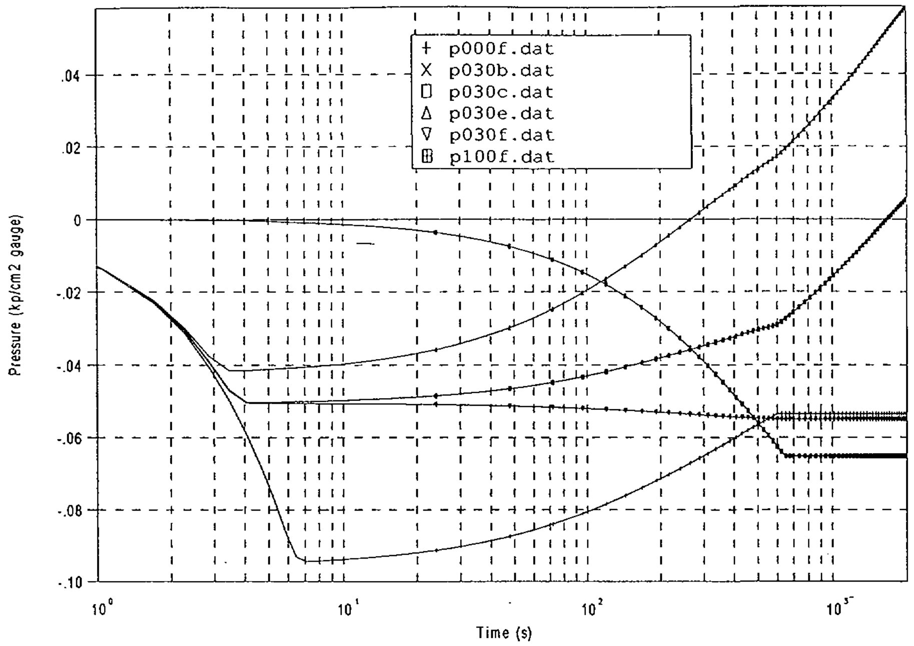

Figure 6. Containment pressure – presence of HS and temperature sensitivity

Finally, the fourth calculation is performed to check sensitivity on change in spray flow rate. The pressure vs. time, for different spray volumetric flow rates, is shown in Figure 7. The labels used in figure have following meaning: first four numbers are volumetric flow rates in gpm (case 030b means 1300 gpm).

The initial RH is 30% in all cases, and all other assumptions are the same like in reference case. The flow rates are chosen based on the following: 1185 gpm is design flow rate, 1300 gpm is conservative value used in USAR analysis, 1800 gpm is spray pump runout flow, and 2370 gpm is two times design flow (in analyzed cases only one train can be actuated according to applicable single failure criteria).

Variation in spray flow has negligible influence on value of minimum containment pressure (at 30% initial RH) and causes decrease of time of minimum pressure with increasing flow rate. The 30% initial RH case is short term cooling dominated case. It is expected to see larger influence for long term cooling dominated cases. In order to check that last two rows are added in Table 4. (minimum pressures at 100% initial RH for 1300 gpm and 2370 gpm spray flows). At 100% RH the pressure drop for 237gpm is increased for about 32% compared to 1300 gpm case, and there is shift in time of minimum pressure for about 20 s toward beginning of transient (earlier generation of $p_{cont}<-0.1$ psig signal). In all analyzed cases there is margin (Table 4.) to containment negative design pressure.

Table 4. Minimum pressures, spray flow sensitivity

Case	Min. Pressure (kp/cm^2 gauge)	Time of min pressure (s)
1185 gpm	-0.0502	4.67
1300 gpm	-0.0502	4.07
1800 gpm	-0.0503	3.47
2370 gpm	-0.0503	2.87
100% RH, 1300 gpm	-0.0597	643.67
100% RH, 2370 gpm	-0.0788	623.87

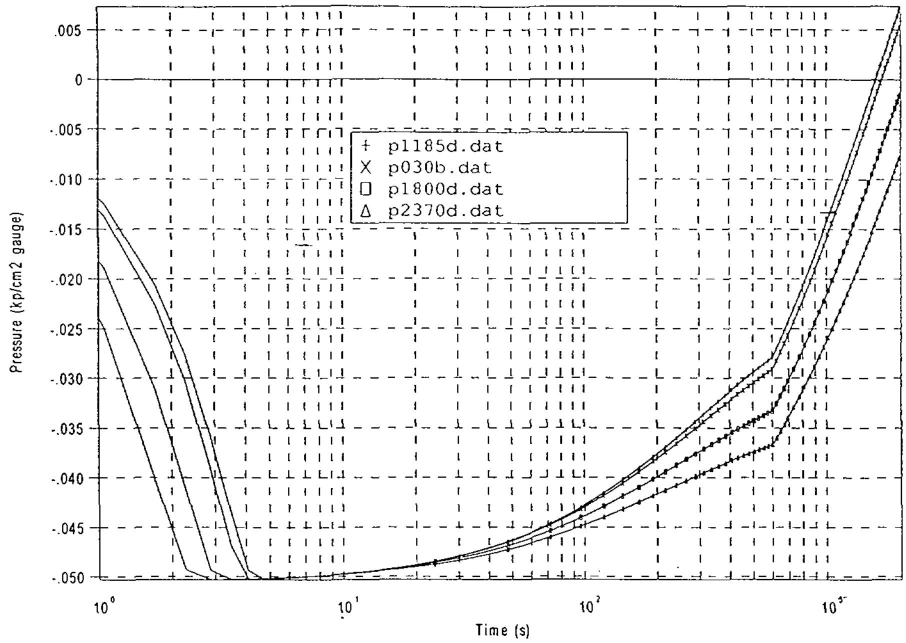

Figure 7. Containment pressure – different spray flows

CONCLUSION

Different aspects of inadvertent actuation of containment spray event were examined including the influence of initial containment humidity, the presence of heat structures and the change of the spray temperature and flow rate. The analyses demonstrate that, in all cases, the sufficient margin to the containment negative pressure design limit (0.1 kp/cm^2) is guaranteed. Even the temperature of 4.44 °C (40 °F) could produce violation of the limit only in case of 100% initial RH in containment.

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