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ACCOUNT FOR FIRE INDUCED LOSS OF ROOM COOLING

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ABSTRACT

A recent fire PRA, which evaluated equipment operability in relation to its ambient temperature, revealed that the operational temperature limit assumed in the internal events PRA was exceeded in selected fire scenarios. For the plant assessed, the environmental qualification (EQ) temperature (between 100°F to 120°F) was adopted as the operational temperature limit for internal events PRA, which was exceeded based on stringent criteria used in the internal events PRA.

Using the HVAC dependency assumptions modeled in the internal events PRA and the EQ temperatures as the equipment failure limits, six fire areas were shown to have significant fire-induced risk largely because of the loss of cooling to certain areas and/or heat addition from a challenging fire. These fire areas included Control Room (122A), Relay Room (100A), 4kV Switchgear Room (64A), 480V Switchgear Room (84A), Electrical Penetration Area (78C), and Auxiliary Equipment Area (84B). This is due to 1) loss of HVAC caused by closing of the fire damper and other isolation mechanisms at the fire location, 2) loss of HVAC caused by closing of the fire damper and other isolation mechanisms outside the fire location, and 3) direct heat addition introduced by the fire. In comparison, it appeared that the fire PRA performed for IPEEE (PSE&G, 1996), and the majority of the IPEEE fire analyses, accounted for heat addition and HVAC loss associated with the fire location. However, potential accident scenarios caused by the fire-induced loss of HVAC outside the fire location were not carefully reviewed.

This paper discusses modeling of the fire-induced loss of HVAC, equipment reliability at elevated temperatures, aggregated failure rates used in the fire PRA, and impact of HVAC failure on mitigation capability. Sensitivity analyses were performed for elevated ambient temperatures and the results show that the CDF/LERF are sensitive to: 1) temperature differences between the actual operating temperature and the temperature at which the base case PRA failure rates were developed, and 2) mission time for the equipment operated at the elevated temperatures[1]. With the mission time set to six hours, assuming a 60°F difference between the actual operating temperature and the temperature at which the PRA failure rates were established (180°F versus 120°F), the CDF and LERF increase by about 3.3% and 2.2%, respectively. Assuming a 100°F difference between the actual operating temperature and the temperature at which the PRA failure rates were established (180°F versus 80°F), the CDF and LERF increase by about 13.5 and 10.3%, respectively.

The sensitivity results indicate that the plant risk might be significantly underestimated if the fire-induced loss of HVAC is not fully accounted for, in particular, if the equipment is exposed to elevated temperatures for an extended period of time, or the differences between the actual operating temperature and the temperature at which the PRA failure rates are based on are large.

Keywords: Fire, Risk, PRA, Loss of HVAC, Room Cooling, Temperature.

1. INTRODUCTION

The recent NRC efforts in developing external events SDP (significance determination process) has a focus area related to the fire-caused loss of room cooling. The *Benchmarking Procedure for SDP Phase II Worksheets for External Events* (NRC, 2004) has a clause specifically asking for modeling approach regarding the fire-induced

[1] The data is not presented in this paper; however, the statement can be inferred from the discussions in Sec. 4.

loss of HVAC. Request for plant specific information number 5 states: "Some fires cause loss of room cooling/HVAC with the subsequent impact on the mitigation capability. Could you identify the major room cooling issues, the heat up time, and the potential recovery action credited by PRA."

In response to the NRC's request, a quick review of the IPEEE was conducted and it appeared that the fire-induced loss of HVAC in areas where fires were not postulated was not discussed in IPEEE. It is unclear regarding the rationale behind the approach. Based on a recent fire PRA that paid specific attention to the room cooling issue, it appeared that the risk contributed by loss of HVAC is significant using the stringent criteria adopted in the internal events PRA.

The assumption that equipment fails the minute ambient temperature exceeds the EQ temperature; i.e., a typical assumption in the internal events PRA, is a reasonable first-order working assumption. When the model results are sensitive to this first-order working assumption, more elaborate and refined assumption is needed. Using the HVAC dependency assumptions modeled in the internal events PRA and the EQ temperature as the equipment failure criteria, six fire areas were deemed to have significant fire-induced risk arising largely from the loss of cooling to a particular area and/or heat addition due to a significant fire. These areas were the Control Room (122A), Relay Room (100A), 4kV Switchgear Room (64A), 480V Switchgear Room (84A), Electrical Penetration Area (78C) area and Auxiliary equipment area (84B). Therefore, the first-order assumption regarding equipment operability in relation to the ambient temperature requires refinement.

Evaluation of data presented in NUMARC 87-00 (NUMARC, 1991) and information presented in the EPRI Fire Modeling Guide (EPRI, 2002), a conclusion could be reached that, in many cases, safety related equipment operation might continue when temperatures are well above the EQ temperature. The operational temperature limit assumed for the fire PRA could be changed to 180^{o}F from 120^{o}F, for instance. One of the reasons could be the reliance on the temperature margins between the operation limit and design limit and between the design limit and ultimate failures.

For Salem PRA, with the 180^{o}F temperature limitation, unless heat is added, ventilation and cooling are not needed for equipment to operate during accident mitigation as room temperatures would stabilize below 180^{o}F or require many hours for such temperature to be achieved. This period of many hours would allow plenty of time for ad hoc means of recovery. This permitted a significant relaxation of the HVAC dependency assumptions and/or times to equipment damage. Furthermore, in the event of a rapid room heat-up due to the direct effects of a fire, equipment would not fail until room temperature exceeds 180^{o}F (60^{o}F higher than previous assumption) allowing more time for fire detection and suppression. With the temperature limit raised to 180^{o}F, it appeared that neglecting fire-induced loss of HVAC might be justified.

The elevated operation temperature most likely will lead to the degradation of equipment reliability due to operation at temperatures well above the normal or EQ value. Therefore, accelerated thermal aging needs to be modeled for numerous pieces of safety related equipment called upon to operate at significantly higher ambient temperatures than those normally experienced during the operating life of the equipment upon which the unreliability parameters used in the PSA had been derived. The failure rates could be significantly higher than for equipment operating below their respective EQ limits. The equipment reliability used in fire PRA should consider the temperature at which the data was collected, the temperature for which the data is used, and the duration during which the equipment is exposed at high temperatures (the HVAC could be restored after the fire).

2. SIGNIFIANCE OF HVAC ASSUMPTION

In a recent fire PRA which initially used the HVAC dependency assumptions modeled in the internal events PRA and the EQ temperature as the equipment failure criteria, six fire areas were deemed to have significant fire-induced risk arising largely from the loss of cooling to a particular area and/or heat addition due to a significant fire. These areas were the Control Room (122A), Relay Room (100A), 4kV Switchgear Room (64A), 480V Switchgear Room (84A), Electrical Penetration Area (78C) area and Auxiliary equipment area (84B). The ambient temperature rise is sufficient to exceed the EQ temperature causing the modeled equipment to fail based on the equipment failure criteria.

Fire causing the ambient temperature to exceed the EQ temperature is largely due to, loss of HVAC, closing of damper, and addition of heat from the fire. The first two causes are similar to SBO.

When the equipment dependency on ambient temperature is removed (i.e., equipment does not require HVAC support), the calculated plant risks are significantly reduced. Results in the Table 1 demonstrate this point[2].

Table 1. HVAC Dependency Impact on Fire Risk

Fire Area	CDF with HVAC dependency	CDF without HVAC dependency	LERF with HVAC dependency	LERF without HVAC dependency

[2] The CDF and LERF listed in table were draft values. Final, refined CDF and LERF are significantly lower after incorporating many other modifications.

64A	3.13E-5/year	5.60E-6/year	1.14E-5/year	1.40E-6/year
84A	4.45E-4/year	9.02E-5/year	9.84E-5/year	2.03E-5/year

Two observations can be derived from the above table:

- The HVAC dependency assumption can have a meaningful impact in certain postulated fire scenarios. Both fire areas 64A and 84A show significant reduction in CDF and LERF when the HVAC dependency is removed from the model.
- The severity of the impact from the HVAC dependency assumption varies from area to area. In this case, fire area 64A is more sensitive to the dependency assumption.

It is evident from the above table that fire-induced loss of HVAC can have a significant impact on plant risk. Ambient temperature rise and equipment failure criteria associated with ambient temperature need to be carefully evaluated in a fire PRA.

Two factors contributed to the significant impact of loss of HVAC to the plant risk.

1. The assumption that equipment cannot operate if ambient temperature exceeds the EQ limits.
2. The significant and steep ambient temperature rise

The assumption related to the EQ temperature is the result of a modeling convenience using a first-order approximation. The significant and steep ambient temperature rise came from fire and PRA modeling limitation (EPRI, 2002) and a desire to be on the conservative side. These two assumption combined significantly amplified the effect of loss of HVAC on plant risk.

The impact of the loss of HVAC is further magnified due to a PRA modeling limitation carried over from the internal events PRA. The limitation is the assumption that equipment seizes to operate the moment the EQ temperature is exceeded. With few exceptions, internal events PRA does not consider time dependencies. This limitation combined with the steep temperature rise prevented certain mitigation actions to be properly credited.

For a fire area with manually activated suppression system, its treatment has a significant impact on the fire risk profile. If the room temperature exceeds the EQ limit before the first fire responding personnel can manually activate the fire suppression system, the typical PRA approach precludes the benefit of the suppression system. With the approach adopted for the fire PRA, excluding the manual actuation (both the first responder and full fire fighting team) increases the relevant sequence risk by a factor of 70.

3. EQUIPMENT FAILURE CRITERIA ASSOCIATED WITH AMBIENT TEMPERATURE

The assumption that the equipment seizes to operate the moment the EQ temperature is exceeded significantly overestimates the importance of the EQ temperature. For all practical purposes, the EQ temperature is the suggested operating temperature range for an optimal equipment performance. Equipment operated within the EQ temperature range ensures the nameplate reliability. It is generally assumed that equipment operated beyond the EQ temperature can have a less than optimum performance. For significant deviation from the EQ temperature range, the equipment performance can be degraded or the nameplate reliability can be questionable.

The assumption that equipment seizes to operate the moment the EQ temperature is exceeded significantly discounts the operation margins in the design and the EQ temperature calculations. For both equipment and EQ temperature, there is a margin between the operation limit and design limit. There is also a margin between the design temperature limit and ultimate failure temperature.

In response to the SBO coping issue, the NUMARC 87-00 (NUMARC, 1991) documented a comprehensive study regarding equipment operation when the ambient temperature exceeds the EQ limit. NUMARC (1991) documented detailed analyses regarding temperature profiles in dominant areas. Plant specific calculations also estimated temperature profiles for the dominant concerns (PSEG, 2000).

Based on evaluation of the data presented NUMARC (1991), PSEG (2000) and information presented in the EPRI Fire Modeling Guide (EPRI, 2002), it is concluded that in many cases safety related equipment operation can continue when the ambient temperatures are well above the EQ limits.

NUMARC (1991) listed the ambient temperatures for a variety of equipment to operate successfully. These temperatures were derived using a number of approaches. Some temperatures were directly derived from the vendor EQ data and others were analyzed specifically for the NUMARC 87-00. The thermal margin for the listed equipment may vary considerable.

- Mechanical Equipment

Pumps	180^{o}F
Turbines w/Mechanical Governors	180^{o}F
DC Motors	180^{o}F
Fans	180^{o}F

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[3] Results under the columns titled ‘without HVAC’ also contain other insignificant changes.

Blowers	180^{o}F
MOV Actuators	180^{o}F

- Electrical/Electronic Equipment

Cables	185^{o}F
Switches and Relays	185^{o}F
Sensors and Electronic Transmitters	180^{o}F
Electronic Turbines Governors	160^{o}F

These ambient temperatures are significantly higher than typically assumed in the internal events PRA. However, discussions carried out in NUMARC (1991) also suggest that for some equipment the mean time between failures (MTBF) can decrease considerably for significant temperature increases (such as from 120^{o}F to 180^{o}F). There is no sufficient empirical evidence regarding the equipment behavior operating with high ambient temperature.

Based on discussions carried out in NUMARC (1991), two conclusions can be reached:

- PRA equipment can operate successfully when ambient temperature is below 180^{o}F[4] (with the exception of Electronic Turbines Governors.)
- PRA data needs to be re-evaluated in order to take advantage of continued operation of equipment at high ambient temperature.

4. PRA DATA RE-EVALUATION

Based on literature reviews discussed in NUMARC (1991) it can be concluded that the equipment behaves differently when ambient temperatures deviate significantly from the EQ range. It is also self-evident that equipment cannot operate at extremely high ambient temperature. However, these behaviors are equipment specific and temperature dependent. NUMARC (1991) compiled and dissected many postulations regarding how to mathematically model equipment performance under high ambient temperature. PSEG (2000) presented the rationale for the choice of a simplified postulation, i.e., engineering method of the 10K rule. This rule states that a 10K increase in the equipment ambient temperature decreases the equipment MTBF by a factor of 2. This method was used to extrapolate the PRA data to high ambient temperatures to support the firs risk analysis.

The simplified method requires two inputs, baseline temperature and elevated ambient temperatures of interest. Based on NUMARC (1991) and PSEG (2000), and other engineering considerations, the maximum ambient temperature range is between 160oF and 180oF[5]. The baseline temperature (normal operating temperature) ranges from 80oF to 100oF. It might be able to argue that the baseline failure rates are valid up to the EQ temperature limit (e.g., 120oF). Therefore, for most components of interest, the range of temperature rise from the baseline to the maximum ambient temperature would be between 60^{o}F to 100^{o}F. Table 2 contains the revised PRA data using the simplified method[6].

[4] The 180^{o}F is arbitrarily selected based on existing reference [3] analysis.

[5] It is assumed that equipment cannot operate above 180^{o}F ambient temperature.

[6] PSEG (2000) presented rationale regarding (no) modifications of other failure modes.

Table 2. Component Failure Rates at Ambient Temperature 180^oF				
		New Failure Rate (/hr) with different Baseline Temperatures		
Equipment Type	**Baseline Failure Rate (/hr) from PRA**	**T0= 80^{o}F**	**T0 = 100^{o}F**	**T0 = 120^{o}F**
Motor Driven Pumps	1.00E-05	4.70E-04	2.18E-04	1.01E-04
AFW TDP	5.00E-05	2.35E-03	1.09E-03	5.04E-04
AFW TDP-6	6.56E-03	6.56E-03	6.56E-03	6.56E-03
Buses	1.30E-07	6.11E-06	2.83E-06	1.31E-06
Battery Chargers	5.00E-05	2.35E-03	1.09E-03	5.04E-04
Compressors	5.00E-05	2.35E-03	1.09E-03	5.04E-04
Inverters	1.30E-05	6.11E-04	2.83E-04	1.31E-04
Breakers	1.00E-06	4.70E-06	2.18E-06	1.01E-06
Fuses	1.00E-06	4.70E-06	2.18E-06	1.01E-06
Rectifier	1.00E-06	4.70E-05	2.18E-05	1.01E-05
Transformers	1.00E-06	4.70E-05	2.18E-05	1.01E-05
MOVs/ AOVs spuriously operate	1.00E-07	4.70E-06	2.18E-06	1.01E-06

From the data presented in the above table two conclusions can be derived:

- The change in component failure rate is considerable.
- The larger the temperature differences the larger the failure rate changes.

Before the above failure rates are applied, proper mission time to be used is evaluated. Based on an evaluation of fire events data presented in Fire Event Database and Generic Ignition Frequency Model for US nuclear Power Plants (EPRI, 2001) and actual fire loading for the areas of interest, it is judged that six hours duration with high ambient temperature should be used for fire PRA. The remaining mission time can be modeled with baseline ambient temperature.

5. RESULTS

Results of the sensitivity analysis presented in Tables 3, 4, and 5 demonstrate the impact of high ambient temperature to the fire risk profile for selected fire areas. For all these cases, the variable is the temperature change from the baseline to the high ambient temperature. The mission time of 24 hours includes six hours of high ambient temperature environment.

Table 3. Sensitivity Evaluation #1 (baseline temp. 120^{o}F, high temp. 180^{o}F)

Fire Area/Source	**CDF (Base)**	**CDF (New)**	**LERF (Base)**	**LERF (New)**
Control Room (122A)	7.36E-06	7.54E-06	1.27E-06	1.29E-06
Relay Room (100A)	1.06E-06	1.15E-06	1.34E-07	1.41E-07
4kV Switchgear Room (64A)	6.35E-07	6.79E-07	2.73E-08	2.89E-08
480V Switchgear Room (84A)	6.41E-06	6.66E-06	8.58E-07	8.87E-07
Electrical Penetration Area (78C)	4.40E-07	4.41E-07	7.65E-08	7.65E-08
Auxiliary equipment area (84B)	1.63E-06	1.65E-06	2.44E-07	2.45E-07
Total Change	1.75E-05	1.81E-05	2.61E-06	2.67E-06
		+5.90E-07 (3.26%)		+5.90E-08 (2.21%)

Table 4. Sensitivity Evaluation #2 (Baseline temp. 80°F, high temp. 180°F)

Fire Area/Source	CDF (Base)	CDF (New)	LERF (Base)	LERF (New)
Control Room (122A)	7.36E-06	8.25E-06	1.27E-06	1.40E-06
Relay Room (100A)	1.06E-06	1.58E-06	1.34E-07	1.68E-07
4kv Switchgear Room (64A)	6.35E-07	6.94E-07	2.73E-08	2.89E-08
480v Switchgear Room (84A)	6.41E-06	7.56E-06	8.58E-07	9.90E-07
Electrical Penetration Area (78C)	4.40E-07	4.44E-07	7.65E-08	7.67E-08
Auxiliary equipment area (84B)	1.63E-06	1.73E-06	2.44E-07	2.49E-07
Total Change	1.75E-05	2.02E-05	2.61E-06	2.91E-06
		+2.73E-06 (13.49%)		+2.99-07 (10.28%)

Table 5. Sensitivity Evaluation #3 (Baseline temp. 80°F, high temp. 120°F)

Fire Area/Source	CDF(Base)	CDF (New)	LERF (Base)	LERF (New)
Control Room (122A)	7.36E-06	7.43E-06	1.27E-06	1.28E-06
Relay Room (100A)	1.06E-06	1.09E-06	1.34E-07	1.37E-07
4kv Switchgear Room (64A)	6.35E-07	6.76E-07	2.73E-08	2.89E-08
480v Switchgear Room (84A)	6.41E-06	6.53E-06	8.58E-07	8.72E-07
Electrical Penetration Area (78C)	4.40E-07	4.41E-07	7.65E-08	7.65E-08
Auxiliary equipment area (84B)	1.63E-06	1.64E-06	2.44E-07	2.44E-07
Total Change	1.75E-05	1.78E-05	2.61E-06	2.63E-06
		+2.80E-07 1.57%		+2.40E-08 0.91%

6. CONCLUSIONS

Fire-induced loss of HVAC and room heatup need to be specifically evaluated in fire PRAs. Based on the differences between baseline and high ambient temperature, the impact of HVAC loss and heatup impact on fire risk can be significant. In the sensitivity case presented in Table 5.2, the increases in CDF and LERF are over 10% for the six fire areas averaged. For certain areas, such as the relay room in this analysis, the increase in CDF is about 50%. The significant increase in the estimated CDF and LERF and the significant change in fire risk profile requires detailed evaluation.

As demonstrated in the sensitivity analysis, failure to consider the high temperature impact on equipment may result in a possible reduction in the CDF estimate of between 3 to 14 % and the LERF estimate of between 2 and 11% (Tables 5.1 and 5.2). The reduction is significant. If the 180°F is selected as the ambient temperature, the degraded equipment reliability needs to be considered to capture the true fire risk and the associated risk profile. On the other hand, if the EQ temperature (120°F) is the ambient temperature, the maximum difference between the limiting temperature and the reference temperature would be 40°F, and the resulting CDF and LERF increase would be 1.6% and 0.9%, respectively (Table 5.3). This implies that the internal events PRA data is valid for its entire range of application.

As presented in this paper and Wei G. He (2004) the impact on risk from fire induced loss of HVAC and room heat up can be evaluated with reasonable expenditure. Engineering methods can be employed to estimate changes in the PRA data. The revised PRA can then be used to derive new CDF/LERF and the risk profile.

REFERENCES

1. PSE&G, (1996), *Salem Generation Station IPEEE*.
2. NRC, 2004, *Benchmarking Procedure for SDP Phase II Worksheets for External Events*, email attachment.
3. NUMARC, (1991), *Guidelines and Technical Bases for NUMARC Initiatives Addressing Station Blackout at Light Water Reactors*, NUMARC 87-00.
4. EPRI, (2002), *Fire Modeling Guide for Nuclear Power Plant Applications*, Final Technical Report 1002981.
5. PSEG, (2000), *Engineering Calculation S-1-ABV-MDC-1836*.
6. He, Wei G., (2004), *PRA Modeling under Elevated Temperature*, PSAM7 Proceeding.

7. EPRI, (2001), *Fire Event Database and Generic Ignition Frequency Model for US Nuclear Power Plants,* Technical Report 1003111.

