ADAMS: ML023510187

Attachment

TECHNICAL ASSESSMENT SUMMARY FOR GSI-189: "SUSCEPTIBILITY OF ICE CONDENSER AND MARK III CONTAINMENTS TO EARLY FAILURE FROM HYDROGEN COMBUSTION DURING A SEVERE ACCIDENT"

Background

GSI-189: "Susceptibility of Ice Condenser and Mark III Containments to Early Failure from Hydrogen Combustion During a Severe Accident" was proposed in response to SECY-00-0198, "Status Report on Study of Risk-Informed Changes to the Technical Requirements of 10 CFR Part 50 (Option 3) and Recommendations on Risk-Informed Changes to 10 CFR 50.44 (Combustible Gas Control)." This SECY paper explored the means of making 10 CFR 50.44 risk-informed. As a part of this, the paper recommended that safety enhancements that have the potential to pass the back-fit test be assessed for mandatory application through the generic issue program.

In the aftermath of the TMI-2 accident, 10 CFR 50.44, "Standards for Combustible Gas Control System in Light-Water-Cooled Power Reactors," was reevaluated with the intent of providing greater protection in the event of accidents more severe than design basis LOCAs. Specifically when the core is severely damaged, significant quantities of hydrogen gas can be released. This hydrogen is generated by the exothermic chemical reaction of steam with metal (especially the Zircaloy cladding) and would eventually build-up inside the containment building. Pressure suppression containment designs, such as PWR ice condensers and BWR Mark IIIs, exhibit lower containment design pressures and relatively lower containment free volumes. These containments rely on the pressure-suppression capability of a large ice chest (or a pool), where the pressure is a result of steam and/or two phase water from blowdown of the primary (or secondary) system, thus the ability to withstand high internal pressures is not needed.

Consequently, the NRC required PWR ice condensers and BWR Mark IIIs designed containments to be equipped with a supplemental hydrogen control system to deal with large quantities of hydrogen (equivalent to 75% metal-water-reaction of the fuel cladding surrounding the active fuel region) for postulated recoverable degraded core events (i.e., for TMI-like postulated sequences in which the core remains in the reactor pressure vessel (RPV) and coolable). The preferred design was to equip these containments with AC-powered igniters, which are intended to control hydrogen concentrations in the containment atmosphere by initiating local "burns" before a large quantity accumulates. In essence, the igniters prevent the hydrogen (or any other combustible gas) from accumulating in large quantities which could result in a global burn, and may pose a threat to containment integrity.

Safety Significance

For most accident sequences, the hydrogen igniters can deal with the potential threat from combustible gas buildup. The situation of interest for this generic issue only occurs during accident sequences associated with station blackouts, where the igniter systems are not available because they are AC-powered. Thus, this does not affect the frequency of severe accidents, but does affect the likelihood of early containment failure and the potential release of radioactive material to the environment.

Possible Solution

Accordingly, to pursue safety enhancements that would have the potential to pass the back-fit test, GSI-189 addresses the adequacy of power supplied to igniter systems installed in PWR ice condenser and BWR Mark III containments. For station blackout (SBO) events in which neither preferred AC nor backup AC power provided by the emergency diesel generators would be available, the igniters would not be functioning and containment integrity could be challenged. The proposed system enhancement is to provide an additional independent power supply for the igniter systems.

Evaluation Approach

Initiating events, core damage frequencies, and release categories were extracted from existing studies. This technical assessment focused on assessing containment performance for ice condensers and Mark IIIs, i.e., quantifying the reduction in the conditional containment failure probability *with* igniters being available during SBO events. The reduction in probability was converted to a dollar value for averted offsite property damage and public risk, and compared against the overall cost for the implementation and maintenance of the igniter system enhancement to determine if there is a potential cost beneficial back-fit. This is a mitigative fix and as such does not affect the frequency of postulated SBO events. Therefore, the potential benefit of the proposed enhancement does not affect averted on-site costs.

Benefits Analysis:

Ice Condensers:

To carry out an estimate of averted costs in accordance with NUREG/BR-0058 and NUREG/BR-0184, risk results in terms of off-site and on-site person rem, as well as costs, are desired. The results from a Level 3 PRA are needed to perform this assessment. When considering uncertainties in the results, uncertainties in the Level 1, Level 2, and Level 3 analyses should be accounted for. Results of the benefits analysis for ice condensers are provided below, additional details are provided in the first technical evaluation report in ADAMS # ML022880554 which was work performed by Brookhaven National Laboratory.

For the issue of combustible gas control in containment the uncertainties to be considered are:

(1) the uncertainty in the core damage frequency (CDF) contribution from station blackout (SBO),
(2) the uncertainty in the conditional probability of early containment failure (CPEF) due to gas combustion, given station blackout has occurred, and
(3) the uncertainty in the releases and associated consequences.

A number of existing studies have provided estimates for item (1) above; very few have included items (2) and/or (3). To estimate the benefits achieved by enhancing gas control in ice condenser containments to operate under SBO conditions, the key studies that were considered are the NUREG 1150 results for Sequoyah and plant-specific PRA results for the Catawba and McGuire plants.

The NUREG-1150 study for Sequoyah was an integrated (Level 1, Level 2, and Level 3) PRA study of an ice condenser plant. The NUREG-1150 Sequoyah study provides, separately, uncertainty ranges for core damage frequency (Level 1) and containment failure probability

(Level 2). Sequoyah core damage frequency ranges due to station blackout events are presented in Table 5.2 of NUREG-1150 Volume 1. A histogram of early containment failure probability, conditional on loss of offsite power (LOSP) for Sequoyah, is shown in Figure 2.5-2 of NUREG/CR-4551, Vol.5, Rev 1, Part 1. Table 1 below summarizes the values in the reports.

Table 1 Sequoyah uncertainty ranges for internal events

	5th	**mean**	**95th**
SBO CDF frequency from NUREG-1150 (per RY)	5.2E-7	1.46E-5	5.3E-5
CPEF due to LOSP from NUREG/CR-4551, Vol.5	1.3E-4	0.15	0.65

The percentile frequencies from long and short term SBO have been added to approximate a total SBO percentile frequency. More recent work documented in NUREG/CR-6427, "Assessment of the DCH Issue for Plants with Ice Condenser Containments" supports the upper bound uncertainty distribution of the NUREG-1150 CPEF.

The NUREG-1150 results do not present the integrated uncertainty from the SBO core damage frequency distribution convolved with the conditional early containment failure probability distribution. However, Figure 2.5-5 of NUREG/CR-4551, Vol.5, Rev 1, Part 1 provides some insight on the range of the combined uncertainties. That figure, which presents frequency distributions of various accident progression bin (APB) groups, indicates that the 95th percentile of the frequency (i.e., the CDF combined with conditional failure probability) of various scenarios involving early containment failure is no more than one order of magnitude larger than the mean value of the frequency. This data can be used to establish an upper bound of the 95th percentile of the combined uncertainty by arguing, based on the Figure 2.5-5 results, that the additional uncertainty introduced by the CPEF variability will be limited to an increase of 10 times the result obtained with the CDF and CPEF mean value. This is less than a value obtained by using the 95th percentile SBO CDF and the 95th percentile CPEF to calculate benefit, which would obviously represent a more extreme value than the 95th percentile of the combined uncertainty distribution. For the lower bound estimates (i.e., 5th percentile), the benefits from the SBO distribution alone indicates very low values, so a combined lower bound is not warranted.

Regarding recent plant-specific results, Duke Power provided selected results from their latest PRAs for the Catawba and McGuire plants. These results consisted of:

(1) SBO CDF frequencies for internal events (but including tornado), with point estimates, mean, median, 5th and 95th percentiles of CDF provided.
(2) ranges of containment failure probabilities associated with the relevant SBO plant damage states used in the PRA,
(3) early containment failure public health risk results, including person-rem per year, from the studies, and
(4) definitions of the early failure release classes used to obtain the health effects.

With regard to item (3), it was noted that person-rem results for early failures seemed less by a factor between 3 and 4 than those found for NUREG-1150 early failures from comparable scenarios. This difference in health risk was attributed to differences between item (4) above and the release classes from NUREG-1150 for comparable scenarios. The NUREG-1150 release fractions for the important radionuclides are about a factor of 4 higher than the ones used in the Duke PRA. The Duke results were obtained using the MAAP code, while the NUREG-1150 results were obtained with the Source Term Code Package and MELCOR.

Table 2 summarizes the results of the calculations carried out for estimating the benefits of an enhanced combustible gas control system for the ice condenser plants. Results, in terms of averted costs in $k, are shown for three Sequoyah cases, nine Catawba cases and three McGuire cases. The columns in the table are arranged as follows:

Column 1 provides the plant name and the case number.

Column 2 lists the containment failure probabilities used and their source.
N1150 refers to the NUREG-1150 study and the supporting documents.
N/C 6427 refers to the SNL report NUREG/CR-6427.
Duke PRA ranges.

Column 3 indicates the source term used to calculate the consequences.
1150S refers to the NUREG-1150 source terms for Sequoyah, but updated to the values used in NUREG/CR-6349, "Cost-Benefit Considerations in Regulatory Analysis."
Duke source term used in the Duke PRA.
1150S*1.8 and 1150s*2.3 refers to the 1150S values scaled by a factor for differences in population densities between Catawba and Sequoyah, and McGuire and Sequoyah, repectively.

Columns 4 - 7 give averted costs in $k for internal events obtained by combining the SBO frequencies obtained from a point estimate (col 4), the 5th percentile (col 5), the mean (col 6), and the 95th percentile (col 7), each combined with the containment failure probabilities shown in column 2.

Column 8 gives the internal events averted cost estimate approximating the upper bound 95th percentile of the combined SBO CDF and CPEF uncertainty, based on the discussion of Figure 2.5-5 of NUREG/CR-4551, Vol.5, Rev 1, Part 1, provided above.

Column 9 provides the averted cost based on the external events SBO frequency, for which only point estimates exist.

The PRA source of the SBO frequencies for each plant are indicated across the columns.

In Table 2, the following assumptions are applied:
(1) 40 year plant life remaining (assumes 20 year license extension)
(2) 7% discount rate (a 3% discount rate would increase all benefit results by a factor of 1.74)
(3) late containment failure is not averted by the combustible gas control enhancement

Table 2 Averted Costs ($k)

Plant	Case		Source of SBO frequency used					
	Cond Cntmt Failure Prob EF=Early LF=Late NF=No Fail	Source Term	Internal Events					External Events
			Pt Est	Uncertainty			Upper Bound Estimate of 95th combined (Lv1&Lv2) uncertainty	Pt Est
				5th	mean	95th		
Sequoyah			*NUREG-1150*					
1	EF =0.15 (N1150 mn)	1150S (updated)	NA	11	320	1,200	3,200	NA
2	EF =0.65 (N1150 95th)			50	1,400	5,000		
3	EF=0.97 (N/C 6427)			74	2,100	7,500		
Catawba			*Duke PRA Rev 2b*					
1	EF=0.29 LF=0.71 (N/C6427 & Duke PRA range)	Duke	180	11*	220*	750*	2,200*	120
2		1150S	640	40*	790*	2,700*		420
3		1150S*1.8	870	54*	1,100*	3,700*		580
			Duke Rev 2b with RCP seal replaced					
4	same as above	Duke	120	6*	150*	530*	1,500*	NA
5		1150S	420	22*	540*	1,900*		
6		1150S*1.8	570	31*	740*	2,600*		
			Duke Rev 2b w RCP seal replaced & flood wall installed					
7	same as above	Duke	14	2*	31*	100*	310*	NA
8		1150S	52	7*	110*	370*		
9		1150S*1.8	70	9*	150*	500*		
McGuire			*Duke PRA Rev 3*					
1	EF=0.26 LF=0.56 NF=0.18 (Duke PRA range)	Duke	13	2*	32*	110*	320*	98
2		1150S	44	8*	110*	380*		340
3		1150S*2.3	72	13*	180*	600*		540

* includes SBO frequency due to tornado

Plant Cases:

Sequoyah 1
For all the Sequoyah cases the SBO frequencies from the NUREG-1150 studies are used, and the consequences are estimated based on the NUREG-1150 source terms, as updated in NUREG/CR-6349, and updated for inflation and population increase. The first case is calculated using the mean early containment failure probability from NUREG-1150.

Sequoyah 2
Same as Sequoyah 1 but using the 95th percentile of the mean early containment failure probability from NUREG-1150.

Sequoyah 3
Same as Sequoyah 1 but using the early containment failure probability from NUREG/CR-6427.

Catawba 1
SBO frequencies are from Rev 2b of Duke's PRA for Catawba. Note for internal events, the point estimate is strictly internal events, but that the 5th, mean and 95th values include internal events and tornados. The point estimate for tornados is given separately in the PRA and is only about 10% of the mean (which includes internal events and tornados). Therefore the inclusion of the tornado events does not have a big effect. Containment failure probability values are within the range for failure probabilities used in the Duke PRA and the same as those in NUREG/CR-6427 for Catawba. The source term person-rem was extrapolated from the health risk information provided by Duke, with off-site costs scaled from NUREG-1150 off-site cost estimates based on the comparable person-rem ratios.

Catawba 2
Same as Catawba 1 but using the NUREG-1150 source term/consequence results (i.e., those used in Sequoyah cases above). This was done as a sensitivity based on the differences shown in Table 2 above.

Catawba 3
Same as Catawba 2, but since the population around Catawba is larger than that around Sequoyah by a factor of about 1.8, the Sequoyah person rem were increased by that factor.

Catawba 4, 5 & 6
Same as Catawba 1, 2 & 3 respectively, but with the SBO frequencies taking into account RCP seal replacement. The point estimate for tornados is only about 9% of the mean, so again the inclusion of the tornado events does not have a big effect.

Catawba 7, 8 & 9
Same as Catawba 1, 2 & 3 respectively, but with the SBO frequencies taking into account RCP seal replacement and installation of a flood wall. The point estimate for tornados is about 44% of the mean. Therefore here the inclusion of the tornado events does have a large effect.

McGuire 1
SBO frequencies are from Rev 3 of Duke's PRA for McGuire. Note for internal events, the point estimate is strictly internal events, but that the 5th, mean and 95th values include internal events and tornados. The point estimate for tornados is about 51% of the mean. Therefore the

inclusion of the tornado events does have a large effect. Containment failure probability values are within the range for failure probabilities used in the Duke PRA. The source term person-rem was extrapolated from the health risk information provided by Duke, with off-site costs scaled from NUREG-1150 off-site cost estimates based on the comparable person-rem ratios.

McGuire 2
Same as McGuire 1 but using the NUREG-1150 source term/consequence results (i.e., those used in Sequoyah cases above). This was done as a sensitivity based on the differences shown in Table 2 above.

McGuire 3
Same as McGuire 2, but since the population around McGuire is larger than that around Sequoyah by a factor of about 2.3, the Sequoyah person rem were increased by that factor.

Mark IIIs:

To estimate the benefits achieved by enhancing hydrogen control in BWR Mark III containments under SBO conditions, NUREG 1150 results were used for Grand Gulf, and the latest available SPAR models for Grand Gulf and River Bend.

The NUREG-1150 study for Grand Gulf was an integrated (Level 1, Level 2, and Level 3) PRA study and provides, separately, uncertainty ranges for core damage frequency (Level 1) as well as containment failure probability (Level 2). Grand Gulf core damage frequency ranges due to station blackout events are presented in Table 6.2 of NUREG-1150 Volume 1. A histogram of early containment failure probability consequential to SBO for Grand Gulf, is shown in Figure 2.5-2 of NUREG/CR-4551, Vol.6, Rev 1, Part 1. Table 3 below summarizes the values in the reports.

Table 3   Grand Gulf uncertainty ranges for internal events

	5th	**mean**	**95th**
SBO CDF frequency from NUREG-1150 (ry)	1.7E-7	3.9E-6	1.1E-5
CPEF due to SBO from NUREG/CR-4551, Vol.6	~1.E-2	~0.5	~1.0

Considerable information on accident progression and hydrogen deflagration and detonation for Grand Gulf was developed during the NUREG-1150 study and is documented in NUREG-1150 and the supporting documents. Energetic combustion events were reported in NUREG/CR-1150 and the supporting documentation for Grand Gulf (NUREG/CR-4551, Volume 6) to result in early containment failure with a relatively high conditional probability (~0.5). However, in a Mark III containment an unscrubbed release (one which does not pass through the suppression pool) requires failure of the drywell in addition to containment failure.

Before vessel breach the only significant event that was found in NUREG/CR-4551, Volume 6, to cause drywell failure was hydrogen combustion in the wetwell. However, at the time of vessel breach loads from direct containment heating, ex-vessel steam explosions, hydrogen combustion, and RPV blow down contribute to the probability of drywell failure. Accordingly, loads from high pressure vessel breach and hydrogen combustion were determined to be the leading causes of containment and drywell failure.

If the RCS is at high pressure the likelihood of containment failure is relatively independent of whether or not the igniters are operating. In addition, the likelihood of simultaneous failure of containment and drywell is also independent of igniter operation if the RCS is at high pressure.

If the RCS is depressurized at vessel breach the likelihood of containment failure is dependent on whether or not the igniters are operating. If the igniters are not available, the conditional probability of containment failure is approximately 0.5 even with the RCS at low pressure. The likelihood of simultaneous failure of containment and drywell is also about 0.2 at the time of vessel breach. Thus all SBO sequences (without combustible gas control) have a conditional probability of 0.2 of a large release, regardless of the pressure in the RCS.

The potential for containment failure at the time of vessel breach when the RCS is at low pressure and the igniters are operating is not directly assessed in NUREG/CR-4551, Volume 6. However, the conditions prior to vessel breach should be applicable to this situation because the RCS is depressurized and none of the issues associated with high pressure melt ejection would occur. The results prior to vessel breach indicate a conditional probability of containment failure in the range of 0.01 to 0.02 if the igniters are operating.

In summary, for transient sequences with the RCS at high pressure and for all SBO sequences the conditional probability is close to 0.2 that the Mark III containment fails at the same time that the suppression pool is bypassed. However, if the RCS is depressurized and the igniters are operating then the conditional probability is less than 0.1 that the Mark III containment will fail. The IPE database information on the plant damage states (PDSs) for the four domestic Mark III plants was searched to determine the fraction of PDSs that have low RCS pressure. The average across the four plants for PDSs with this attribute is approximately 40 percent, with high RCS pressure making up the remaining 60 percent.

Based on the above discussion, an event tree was constructed and quantified, conditional on an SBO event without a hydrogen control system operating. The late failure split fractions are based on NUREG-4551 Vol. 6 results. A series of benefit calculations was made using the NUREG-1150 SBO frequencies, and the results of the calculations are summarized in Table 5.

To examine the uncertainty in benefits, a sensitivity calculation was made using the 95th percentile for CPEF, which is essentially 1.0, i.e., the containment fails always (Grand Gulf 2 in Table 5). This assumption will increase the benefit from gas control during SBO.

Another sensitivity calculation was made to further increase the benefits by assuming half (rather than 40%) of all sequences are at low pressure, and assuming drywell failure occurs whenever containment fails (Grand Gulf 3 in Table 5). This is quite a conservative case and should provide some reasonable upper bound on the benefit.

To further estimate benefits, as well as, the uncertainty associated with the Level 1 PRA calculations, the latest available 3i SPAR model was used for Grand Gulf, an internal events, Level 1 model, which incorporates uncertainty parameters and can calculate a point estimate, the mean, median and various percentiles associated with the SBO CDF. The model incorporates up to date information on loss of off-site power frequency and emergency diesel generator availability. The NUREG-1150 accident progression was again assumed, and the same sensitivity cases were performed. The results are illustrated in Table 5 (Grand Gulf 4, 5, and 6).

The uncertainty associated with the Level 2 calculations for Grand Gulf cannot be estimated with the SPAR models, since no Level 2 SPAR models incorporating uncertainties are available.

In addition, 3i SPAR model for River Bend was also utilized and benefit results were obtained, again using the NUREG-1150 Grand Gulf accident progression scenario for the Level 2 analysis. For the consequence calculations, the NUREG-1150 Grand Gulf person-rem values for all sequences were increased by a factor of 3.1 to account for the increased population density around River Bend. Benefits were again calculated for the base case of the accident progression using the same split fractions along with two sensitivity cases (River Bend 1, 2, 3, respectively in Table 5). SPAR model SBO frequencies are shown in Table 4.

Table 4 SPAR 3i SBO CDF ranges for internal events

	5th	**mean**	**95th**
Grand Gulf	1.4E-7	2.4E-6	8.2E-6
River Bend	2.7E-8	1.0E-5	2.8E-5

Variation in population density around the plant sites was also surveyed. Based on FSAR projections, Perry has the highest projected year 2000 (50 mile radius) population density, about 7.5 times that of Grand Gulf, which has the lowest. Both Clinton and River Bend have population densities that are about 3.1 times that of Grand Gulf.

Although Perry has the highest population ratio, it also has the lowest SBO frequency. Therefore, since the estimates for River Bend were done with the (high) SPAR 3i model SBO frequencies and by accounting for the increased population density around River Bend (vs. Grand Gulf), the River Bend calculations (River Bend 1, 2, 3, in Table 5) should provide a bound for all four Mark III sites.

Table 5 summarizes the results of the calculations carried out for estimating the benefit of an enhanced combustible gas control system for the BWR Mark III plants.

Table 5					
Plant & Case description		**AVERTED COSTS ($k)**			
		Source of SBO frequency			
		Internal Events			**External Events**
		5th	**mean**	**95th**	
Grand Gulf		*NUREG-1150*			
1	Mean NUREG-1150 CPEF	<1	10	29	NA
2	95th NUREG-1150 CPEF	<1	22	61	
3	95th NUREG-1150 CPEF 50% of sequences at low pressure, drywell always fails if contmnt fails	2	60	170	
		SPAR 3i			
4	Mean NUREG-1150 CPEF	<1	6	22	NA
5	95th NUREG-1150 CPEF	<1	13	45	
6	95th NUREG-1150 CPEF 50% of sequences at low pressure, drywell always fails if contmnt fails	2	36	120	
River Bend		*SPAR 3i*			
1	Mean NUREG-1150 CPEF	<1	57	160	NA
2	95th NUREG-1150 CPEF	<1	120	330	
3	95th NUREG-1150 CPEF 50% of sequences at low pressure, drywell always fails if contmnt fails	<1	320	880	

For all cases the following assumptions are made:
(1) 40 year plant life remaining
(2) 7% discount rate (a 3% discount rate would increase all results by a factor of 1.74)

Cost Analysis:

A cost assessment has been performed to quantify the overall cost for the implementation and maintenance of a range of potential modifications in response to GSI-189 safety concerns. These included reliance on: (1) a pre-staged diesel generator to power the hydrogen igniters; (2) an off-the-shelf portable diesel generator to power the hydrogen igniters; (3) a pre-staged diesel generator to power the igniters and air return fans; and (4) passive autocatalytic recombiners (PARs). The cost analysis is summarized below and the detailed report is the second document in ADAMS # ML022880554 which was work performed by Information Systems Laboratories.

For each modification, estimated implementation and operational (recurring) costs were estimated for both the licensee and the NRC. Licensee implementation costs included allowances for materials and equipment, installation, engineering, worker exposure, emergency procedures, and licensing costs. Licensee operating costs accounted for routine periodic surveillance, maintenance and testing of the independent power source. For the NRC, implementation costs covered rulemaking and reviews of licensee documentation, and NRC operational costs allowed for periodic inspection.

The cost methodology employed is consistent with NRC guidance available in the “Regulatory Analysis Guidelines of the U.S. Nuclear Regulatory Commission,” Revision 3, NUREG-BR-0058, and “The Regulatory Analysis Technical Evaluation Handbook,” NUREG/BR-0184.

Baseline assumptions used throughout this analysis included: (1) all costs expressed in 2002 constant dollars and on a 2002 present worth basis assuming a 7% real discount rate; (2) remaining life of the average affected reactor assumed to be 40 years (20 years remaining on current license plus an additional 20 years for a license renewal term); (3) no incremental downtime (replacement energy costs) required for installation, and; (4) minimal rulemaking costs as it is assumed the rulemaking for GSI-189 can be folded into the current 10 CFR 50.44 rulemaking effort.

In addition, key specifications concerning the physical modifications included: (1) the availability of two diesels at dual unit sites; (2) a separate tank to store the necessary diesel fuel; (3) the powering of one train of igniters to accommodate hydrogen burns and where air return fans are involved, the powering of only one train; (4) control of the backup power supply is assumed to be remote and local, that is, not powered from the control room, however all electrical panels, circuit breakers, and switches will be in-place and operational, and (5) modifications will meet the Category 3 standards and requirements of Regulatory Guide 1.97, Revision 3, unless for certain components, a higher degree will be required.

In addition to the consideration of four different modifications, the cost analysis also accounted for cost differences due to plant variability, sensitivities to key assumptions, and inherent uncertainties.

There are nine domestic PWR plants with an ice condenser containment design; four dual unit sites (McGuire, Catawba, D.C. Cook, and Sequoyah) and one single unit site (Watts Bar). There are four domestic BWR plants with a Mark III containment design at four separate sites (Grand Gulf, Perry, Clinton and River Bend). With respect to plant variability, because of differences in containment design, power requirements, and number of reactors per site, it was determined that no “generic “ plant would be representative of the 13 reactors potentially affected by this issue. Thus, for each of the four modifications, the study developed separate estimates for four classes of plants, namely, (1) three dual-unit PWR McGuire, Catawba, D.C. Cook stations, (2) the dual-unit PWR Sequoyah station; (3) the single-unit PWR Watts Bar plant, and; the four Mark III BWR plants. Cost differences attributable to plant type did not exceed 20% for each of the four modifications evaluated. For example, the “best estimate” for the base case (pre-staged/igniters) ranges from about $265,000 to $320,000 per reactor for the different classes of plants. Similar estimates for Case 2 (portable diesel), Case 3 (pre-staged/igniters/air return fans), and Case 4 (PARs), approximate $195,000 to $240,000, $570,000 to $670,000, and $1,670,000 to $1,750,000, respectively. Given the relatively small cost differences attributable to plant variability among ice condensers, subsequent results reported in this summary statement will do include estimates by type of ice condenser plant in order to allow one to more easily focus on more meaningful cost comparisons.

A sensitivity analysis was performed which allowed for certain key assumptions to vary from those assumed in the base case (pre-staged/igniters). These included: (1) requiring the modification to be qualified for external events; (2) requiring a major rulemaking effort; (3) requiring incremental downtime with corresponding replacement energy cost penalties; and (4) varying the real discount rate from 7% to 3%. External event qualification was the only one that significantly impacted the base case estimate, resulting in almost a doubling of the per reactor “best estimate” cost.

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Finally, for three of the primary modifications examined, an uncertainty analysis was performed using Monte Carlo simulation software. Estimates of the 5^{th} percentile and 95^{th} percentile confidence levels indicate that the uncertainties are skewed toward the higher costs.

The following table shows the “best estimate” and 5^{th} and 95^{th} percentile confidence levels for an *“average”* ice condenser and Mark III containment for the three potential modifications. All cost estimates are on a per reactor basis and include licensee costs and a prorated share of NRC’s costs.

PER REACTOR COST FOR ICE CONDENSER AND MARK III CONTAINMENTS
“BEST ESTIMATE” WITH 5th AND 95^{th} PERCENTILE CONFIDENCE LEVELS
(THOUSANDS OF 2002 DOLLARS)

	ICE CONDENSER			MARK III		
	LOW	BEST EST.	HIGH	LOW	BEST EST.	HIGH
BASE CASE Pre-Staged/Igniters	262	285	464	308	313	459
Sensitivity of Base Case w/ external event qualification		517			555	
Portable/Igniters	185	211	331	222	232	326
Pre-Staged/Igniters & Air Return Fans	506	621	830	N/A	N/A	N/A

Need for Supporting Systems:

As part of the license renewal process, applicants are required to consider severe accident mitigation alternatives (SAMAs) in their environmental assessment. Duke Energy Corporation has submitted an assessment of SAMAs for the Catawba and McGuire ice condenser plants which included consideration of an alternate power supply for the igniter system to address SBO sequences. The staff's review concluded that this alternative appears to be cost beneficial but deferred the decision of implementation to the resolution of this GSI (refer to Draft NUREG-1437, Supplements 8 & 9). However, Duke indicated the availability of the air return fans would be essential to the effective operation of igniters in SBO events; therefore, Duke combined the costs. Clearly, if air return fans as well as igniters are needed, the costs will be substantially higher, i.e., the overall implementation costs are estimated to double. This aspect is only relevant to ice condenser containment designs.

In order to improve our understanding of the role air return fans has on ice condenser containment performance, RES reviewed the technical evaluations associated with the post-TMI hydrogen control requirements and performed updated MELCOR code scoping calculations for the Sequoyah plant. Note that the air return fans were part of the original design of the ice condenser plants to deal with postulated blowdown events in which air is purged from the lower compartments through the ice condenser and into the upper containment volume. This system consists of high capacity fans, e.g., about 40,000 cfm for each independent train and are intended to circulate the upper compartment atmosphere back into the lower compartments.

The post-TMI requirement for ice condensers containments is that a supplemental hydrogen control system be provided so that the consequences of the hydrogen release generated during the more probable degraded core accident sequences do not involve the breach of the containment nor adversely affect the functioning of the essential equipment. Subsequently, a hydrogen igniter system was selected by the industry and was retrofitted inside all ice condenser containments. As a result of the intended performance (i.e., burning lean hydrogen-air mixtures) of this new system, the survivability of essential equipment had to be demonstrated. Therefore, existing engineered safety systems, e.g., containment sprays and air return fans were identified as essential equipment *and* assumed to be available during the more probable degraded core events. SBO was not made a "design basis" for the igniter system because a recoverable degraded core sequence was judged to be sufficiently remote. Primarily, this is a result of the very short time window following the on-set of hydrogen generation in which AC power must be restored to preclude a core melt.

The staff reviewed previous evaluations of hydrogen igniter systems and related combustion issues associated with ice condensers. In support of the Atomic Safety and Licensing Board hearings on hydrogen control for McGuire Units 1 & 2, Duke Power Company assembled a team of highly reputable combustion experts. For combustion issues associated with the ice chest, the experts' response after having toured the McGuire containment was that the geometry and flow conditions inside the ice condenser region are not conducive to producing a transition to detonation. Their view was that for small break LOCA type sequences (such that the lower compartments become steam inerted; combustion is suppressed), the upper plenum igniters would ignite the mixture as it first becomes flammable, then as a richer mixture is vented to the upper plenum, the igniters will produce a horizontal standing flame. If the mixture is further enriched, then the flame will propagate downward into the ice bed until it settles to an equilibrium point where sufficient steam has been condensed. Moreover, even without air return fans or containment sprays, "then the hydrogen stream emerging from the ice condenser will mix slower with the air under the dome, and will be ignited and will burn as a slow-burning diffusion flame." (Reference: Transcript of ASLB Operating License Hearing for McGuire Units 1 & 2, dated February 26, 1981)

Hydrogen combustion testing also supports the view that diffusion flames will tend to develop in the conditions and geometries of concern. During continuous hydrogen injection testing in the various experimental programs, it was observed that diffusion flames would appear, ignited by a very weak flame propagating from the igniter back to the hydrogen source. For example, the larger scaled experiments, such as: Nevada Test Site (NTS) continuous injection tests, and the Mark III Containment Hydrogen Control Owners Group (HCOG), quarter-scaled test program showed that the dominant mode of combustion was diffusion flames.

As part of the on-going effort to risk-inform 10 CFR 50.44, the MELCOR code was used to generate new hydrogen release source terms in which the Sequoyah plant was chosen to represent a typical ice condenser. Thereby building upon that effort, i.e., refining the containment portion of the MELCOR plant deck, containment transient response sensitivity calculations were performed to gain insights during the course of selected postulated SBO events. Lumped parameter codes, such as MELCOR, require the user to make the appropriate input selections to properly consider the different modes of hydrogen combustion.

Additional MELCOR Sequoyah plant calculations were performed for selected SBO core melt sequences. (Although it is recognized that there are limitations of a lumped-parameter code such as MELCOR, which includes limited burn modeling, insights can be gained on the ice condenser containment performance). Parametric code sensitivities were performed to study: (1) variation of combustion limits (deflagration burning), (2) availability of igniters and/or an air return fan, and (3) other relevant code uncertainties. The detailed report is the third document in ADAMS # ML022880554 which was work performed by Sandia National Laboratories.

When igniters are functioning (with or without an air return fan activated), hydrogen accumulation is limited by discrete burning which assures that the resulting pressures do not pose a challenge to containment. When a fan is functioning, there are more burns in the lower containment compartments because more air is re-introduced from the upper containment. However in this case, more ice has melted than in the no-fan case; therefore, the ice chest melt-out would be sooner when a fan is activated. For postulated core melt events, it is beneficial to have the ice maintained as long as possible in the ice chest, to function both as more effective heat sink and for fission product aerosol scrubbing.

In summary, for ice condensers (and Mark IIIs) during postulated SBO events, power to the igniters only is sufficient in controlling hydrogen build-up and delaying early containment failure. Note in hypothetical core melt sequences, even if hydrogen is controlled early in the event, other severe accident processes start to dominate, such as core-concrete interactions (CCI) and would likely be the dominant contributor to late containment failure.

Summary

Ice Condensers

The **benefits** of providing combustible gas control for SBO events at PWR ice condenser plants are highly sensitive to a number of key parameters such as the core damage frequency (CDF), source term, and the conditional early containment failure probability. Data reported in NRC studies and more recent licensee PRA studies suggest that large uncertainties exist relative to these factors. Considering these uncertainties, as well as plant-specific differences, benefits based on *mean* CDF values per reactor are estimated to range from a low of about $30K to a high of $2100K. Further, based on the uncertainties inherent in the analysis, the estimated benefit for the 5% and 95% uncertainty band ranges from $2K to over $3200K per reactor, respectively. Note this upper bound value is estimated to be ten times the mean value to account for level 1 and level 2 uncertainties.

The **costs** of implementing and maintaining backup power to the PWR ice condenser reactors have also been assessed. This analysis calculated total costs to the licensee and the NRC on a per reactor basis for three basic design modifications which involve the use of either a pre-staged or portable diesel generator to power the igniters, or a pre-staged diesel to power both igniters and air return fans. The analysis also considered several sensitivity cases to account for variation in key cost assumptions. Best estimates for this full set of alternatives range from about $195K to $670K per reactor. Further, a 90% confidence *interval* was derived to reflect the uncertainties inherent in the analysis. This broadened the range of costs from about $185K to $830K per reactor.

Mark IIIs

The **benefits** of providing combustible gas control for SBO events at Mark III plants have similar sensitivities as for the ice condensers. However, the uncertainty ranges are much narrower. Benefits based on the mean CDF values per reactor are estimated to range from a low of about $10K to a high of $320K. Further, based on the uncertainties inherent in the analysis, the estimated benefits for the 5% and 95% uncertainty band range from less than $1K to over $880K per reactor, respectively.

The **costs** of implementing and maintaining backup power to the Mark III reactors have also been assessed. This analysis calculated total costs to the licensee and the NRC on a per reactor basis for two basic design modifications which involved the use of either a pre-staged or portable diesel generator to power the igniters. The analysis also considered several sensitivity cases to account for variation in key cost assumptions. Best estimates for this full set of alternatives range from about $235K to $555K per reactor. Further, a 90% confidence interval was derived to reflect the uncertainties inherent in the analysis. This broadened the range from about $225K to about $650K per reactor (because an uncertainty analysis was not performed for the sensitivity with external event qualification, therefore this upper value is a projection).

Recommendation

The results of the cost benefit analysis suggest that there are large uncertainties, particularly on the benefit side with respect to the risk parameters (including phenomenological uncertainties) and plant-specific considerations. While mean values of the cost and benefit results show that the net benefit calculation can be either negative or positive, it is important to recognize: 1) there are significant uncertainties in the averted cost estimates, 2) the potential for large early releases in the absence of igniter function, and 3) the relatively low cost of providing alternate power sources. Thus it is a prudent course of action to pursue an enhancement to the igniter system. Moreover, the cost benefit analysis did not consider potential benefits due to averting some late containment failures and some subset of external initiated SBO events which are difficult to estimate but could provide added benefits. RES also considered qualitative benefits such as defense-in-depth, public confidence and regulatory coherence, and has determined that further regulatory action is justified.

In summary, based on this technical assessment, with due consideration of uncertainties RES concludes that further action to provide back-up power to one train of igniters is warranted for both ice condenser and Mark III plants.

References: Three Technical Evaluation Reports in ADAMS # ML022880554