COST-BENEFIT OF THE BUBBLE TOWER CONCEPT AS A CONTAINMENT PASSIVE SAFETY SYSTEM

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ABSTRACT

Containment system integrity for both PWRs and BWRs can be assured by passive measures highlighted the use of an accessory Bubble Tower. The utilization of the Bubble Tower precludes the possibility of containment overpressurization. From the thermodynamic standpoint, the Bubble Tower is simply water column of about 120 ft. height attached to the containment and connected to the air space above the suppression pool of a BWR, or a PWR In-containment Refueling Water Storage Tank. From the radiological protection standpoint, the Bubble Tower is a water column sufficient to effect decontamination factors of at least 100 for nuclide species other than the noble gases, and with the addition of organic solubilizers sufficient to effect decontamination factors of at least 10 iodides and at least 100 for other nuclide species. When containment steam or noncondensible gas passes through the Bubble Tower, a significant fraction of the radionuclides is absorbed by the water column. When a cost-benefit dose evaluation is performed relative to the utilization of a Bubble Tower, even under conditions where the dollars per man-rem is taken as $1000, the results are favorable. They are substantially more favorable when the dollars per man-rem is taken as $5000 or $10,000 as are the current trends.

DESIGN BASIS ACCIDENT (DBA) AND PASSIVE CONTAINMENT SAFETY SYSTEM MITIGATION

When a postulated loss of coolant accident (LOCA) takes place simultaneously with a station blackout (SBO), but the integrity of the core is maintained (no core melt) for an extended period of time, it has been demonstrated that passive containment cooling system features alone such as natural convection and radiation can reduce reactor decay heat following a design basis accident (DBA), and assure containment integrity (Ref 1, 2, and 3). In this scheme, ambient air enters the annular air space between the containment steel shell and the surrounding concrete shield building through inlets at the shield building lower elevations, is heated by the containment steel shell via natural convection and radiation, rises, and exits the shield building through an opening located above the containment dome. Although this passive air cooling is adequate to reduce reactor decay heat for the New Production Reactor (NPR) and the Advanced Neutron Source (ANS), the high energy released to the containment immediately following a LOCA in power reactors requires additional means of passive cooling during the early phases of a LOCA.

Reference 3 demonstrates that the boiling water reactor's (BWR) suppression pool scheme when supplementing the passive air cooling scheme described in References 1 and 2, can provide sufficient passive containment cooling for CE's System 80+ power reactor. Similarly, according to Reference 3, Westinghouse's AP 600 plant employs water dowsing from the top of the containment steel shell initially until the tank water is exhausted, after which passive air cooling is engendered.

THE BUBBLE TOWER AND CONTAINMENT INTEGRITY DURING A SEVERE ACCIDENT

When a DBA transforms into a severe accident due to significant core melt and/or the failure of safety mitigation systems, containment pressure and temperature can reach levels much beyond design pressure and temperature levels due to hydrogen generation, deflagration, possible steam explosion and direct containment heating. These high containment pressures and temperatures cannot be relieved and cooled by passive containment cooling systems alone. When such conditions prevail, the Bubble Tower will passively relieve containment pressure, and remove in its water column the bulk of the non-noble gas radioactive material including the organic iodides. Thus during a postulated severe accident the Bubble Tower can serve both to relieve containment pressure when the containment pressure exceeds design pressure, and to substantially remove the radionuclides released by virtue of the height of its water column, and the provision of convoluted flow paths and organic solubilizers bo enhance the decontamination factors vis a vis significant contributors to environmental dose.

The Bubble Tower is designed to seismic category I, and meets safety standards of NUREG-0800 (Ref. 4). The prestressed concrete construction follows ACI-439 (Ref. 5) nuclear safety related codes and ANSI/AWWA (Ref. 6) standards for pressurized tanks. In the Bubble Tower water column, organic solubilizers are introduced and maintained to afford a DF of at least 10 for the organic iodide species which have a major role in environmental- impact dose assessment.

The radioactive contaminants in the containment atmosphere may vary from reactor coolant radionuclide inventories (DBA without core melt) to substantial fractions of core inventory which are 10 million times as large as reactor coolant inventories (substantial core melt).

Present thinking per proposed NUREG-1465 (Ref. 7) based on TMI lessons-learned pertaining to the radiocesiums, principally Cs-137, also postuates that the organic iodide chemical constituency in the reactor coolant released to the suppression pool would be 0.25% radioiodine rather than the currently postulated 4% if the reactor coolant chemistry is basic rather than acidic. Adopting this assumption for analysis would have been less stringent, but also less conservative, therefore we assumed a nonbasic chemistry and the constituency of 4% organic iodide in the reactor coolant for the sake of conservatism. Moreover, lessons-learned from the TMI accident dictate that 50% of the radiocesium, Cs-137 and Cs-134, could be released to the containment atmosphere rather than the 1% customarily assumed for all solid fission products as per the earlier TID-14844 document (Ref 8). This paper combined the conservative aspects of TID-14844 and the conservative postulations of proposed NUREG-1465 for its evaluations.

DOSE EVALUATION AND COST BENEFIT

In order to compare the potential worst case effects of boundary site exposure dose to a hypothetical individual in the environment for the cases of having a Bubble Tower and not having a Bubble Tower connected to the containment, the worst case TID-14844 and NUREG-1465 postulations of 100% noble gas, 25% radioiodines, including 4% organic iodide, and 1% solid fission products, other than 50% Cs-137 were used, and assumed to be immediately discharged to the containment atmosphere.

Specification containment leakage of 0.05% of containment air volume was assumed during the first day. Containment spray was operative, and the analytical model, which was time-dependent and followed the activity inventories of an ensemble of some 75 radionuclides, The model took the customary credits for spray removal, plateout, decay factor, and containment airborne leakage per unit time. In addition, exposure doses were converted into $1000 per man-rem and $10,000 per man-rem, and a comparative cost benefit analysis undertaken to determine the cost-effectiveness and utility of the Bubble Tower.

DOSES

The thyroid inhalation dose for 0-2 hours to a hypothetical individual at a representative boundary site was taken as an exposure dose measure for the evaluations. The meteorological dispersion factor X/Q was taken as a representative 5E-4 relative to the boundary site. Also used as a measure was the cumulative effective dose equivalent (CEDE) to a hypothetical individual at the representative boundary site for the first two hours. The CEDE is the cumulative organ dose normalized to whole body dose by the respective organ dose weighting factors. Flow through the Bubble Tower which constitutes a passive safety feature to relieve Containment overpressurization and remove radioactive contamination was parametrically and discretely considered as either 10, 100 or 1000 cfm through a 120 ft high effective water column. The water column has features providing a schedule of decontamination factors (DFs) before release of air to the environment. These are shown in Table 1.

Table 1

BUBBLE TOWER	DECONTAMINATION FACTORS
Noble Gas	1
Elemental Iodine	100
Particulate Iodine	100
Organic Iodine	10
Solid Fission Product	100
SUPPRESSION POOL	**DECONTAMINATION FACTOR:**
Noble Gas	2
Elemental Iodine	10
Particulate Iodine	10
Organic Iodine	5
Solid Fission Product	10

The calculated contribution of airborne design release through the Bubble Tower even at 1000 cfm contributes about 52% to the boundary site thyroid inhalation dose limitation of 300 rem for as given in 10 CFR 100 (Ref. 9).

COST BENEFIT

The utility of a protection scheme such as the Bubble Tower can be evaluated through cost-benefit analysis when one translates man-rem exposure to a common denominator such as dollars. In 1971, the Otway paper (Ref. 10) was published which listed dollar values for the man-rem from $10 to $998. The U.S. Atomic Energy Commission reviewed papers of this nature and surmised that a conservative estimation of dollars per man-rm would be $1000. Current thinking among diverse sources as Brookhaven National ALARA center, the Pacific Rim nuclear power plant operators, and others has been to operators and others has been to raise the dollar figure per man-rem to as high as $10,000, and we will utilize both values in our analysis.

All of our cost benefit analyses initiate from the point of an incident having occurred which threatens to transform the accident into a severe accident. The question we sought to answer was thus: What is the cost differential between preserving containment integrity by utilizing a passive feature such as the Bubble Tower and virtually precluding overpressurization, versus not using the Bubble Tower and substantially increasing the chance of overpressurization and not preserving containment integrity?

The cost-benefit evaluations require the consideration of all pertinent cost factor contributors, and associated probabilities or weighting factors such as:

- Modes of exposure dose, whole body dose, thyroid dose, etc., converted to dollars
- Organ weighting factors associated with inhalation exposure dose
- Probabilities of transforming from an incident to a severe accident with loss of containment integrity both with and without the Bubble Tower
- Contributory costs such as the fixed cost of the Bubble Tower, the cost of plant downtime with and without the Bubble Tower, and the probable cost of permanent plant shutdown in case of a severe accident

In our analysis of man-rem exposure, it was necessary to consider virtually all modes of exposure dose such as gamma cloud submersion dose, beta cloud skin dose, and organ inhalation dose. The latter was a summation of weighted organ inhalation dose from thyroid through bone surface through lung inhalation dose, etc., normalized to total body or whole body dose in man-rem and translated into dollars using the $1000 or $10,000 per man-rem figure. The summation of dollars was then translated into probable dollars by multiplying by the estimated probabilities of occurrence. The baseline for the analysis was that the incident had occurred but had not yet been transformed into a severe accident where the containment integrity was threatened. The question we sought to answer was: What is the cost differential between preserving containment integrity by utilizing a passive feature such as the Bubble Tower and precluding overpressurization, versus not preserving containment integrity by not using such a passive feature? The cost benefit analysis turned out to be clearly favorably disposed towards having a Bubble Tower from a dollars standpoint. Considering the cost of installing the Bubble Tower and the dollar equivalent of inhalation man-rem exposure at the boundary site by way of release or leakage of containment atmosphere airborne contamination to the environment, the cost benefit for the case of having a Bubble Tower is more favorable than the case of not having a Bubble Tower by a factor of about 14 at 10 cfm, by a factor of about 15 at 100 cfm, and by a factor of about 185 for 1000 cfm even for the assumption of 1000 dollars per man-rem. See Table 5 for cost benefit work sheet evaluation.

From the standpoint of exposure dose, the Bubble Tower was substantially more favorable than the case of having no Bubble Tower. In fact the conclusion could be reached that the Bubble Tower in all cases up to 1000 cfm design venting of the containment atmosphere would pass the exposure dose strictures of 10 CFR 100 relative to the thyroid while the total effective dose equivalent or TEDE, which includes the cumulative organ dose equivalent or CEDE would stabilize at less than 42 rem while the thyroid and TEDE dose would be substantially larger and increase with increasing vent rates; if there were no Bubble Tower, for example, in the case of 1000 cfm release rates, the thyroid dose and the TEDE would reach respectively 96,200 rem and 37,200 rem during the first two hours. See Tables 2 and 3.

Table 2

TWO-HOUR INTEGRATED BOUNDARY SITE THYROID INHALATION DOSE (REM)

LEAKAGE AND/OR FLOW	CONTAINMENT SPEC LEAKAGE EXCEEDED	CONTAINMENT SPEC LEAKAGE +BUBBLE TOWER FLOW
@ 10 cfm	972 rem	77.6 rem
@ 100 cfm	9710 rem	86.3 rem
@ 1000 cfm	96200 rem	172.8 rem

* Criterion of 300 Rem thyroid dose to hypothetical person at boundary site is cited as limitation in 10 CFR 100 for first two hours after occurrence of accident.

** Containment Spec Leakage is taken as 0.05% the first day, and its contributory boundary site dose is 76.6 rem.

Table 3

TWO-HOUR INTEGRATED BOUNDARY SITE TOTAL EFFECTIVE DOSE EQUIVALENT (TEDE) WHICH INCLUDES CEDE INHALATION DOSE FOR ALL ORGANS (REM)*

LEAKAGE AND/OR FLOW	CONTAINMENT SPEC LEAKAGE EXCEEDED	CONTAINMENT SPEC LEAKAGE + BUBBLE TOWER FLOW
@ 10 cfm	379 rem	34.5 rem
@ 100 cfm	3790 rem	35.1 rem
@ 1000 cfm	37200 rem	41.0 rem

* No criterion given for TEDE to hypothetical person at boundary site in 10 CFR 100. Organ weighting factors were used for this analysis, and CEDE was added to whole body cloud submersion dose.

** Containment Spec Leakage taken as 0.05% the first day, and its contributory boundary site dose is 34.5 rem.

SUMMARY AND CONCLUSIONS

1. The passive feature such as the Bubble Tower can preclude containment overpressurization ensuant from a severe accident and at the same time provide acceptable environmental protection contra radioactive airborne emissions.

2. The Bubble Tower can be operative in the range up to 10,000 cfm and still be within the acceptability limits of 10 CFR 100 respecting thyroid dose for the first two hours after the accident.

3. The Bubble Tower can be operative in the range up to 10,000 cfm and still minimize the total effective dose equivalent (TEDE) to less than 45 rem for the first two hours after the accident.

4. The containment with the Bubble Tower has a very favorable cost edge over the containment without the Bubble Tower relative to the equivalent cost of man-rems, operational downtime cost, fixed cost for building the Bubble Tower, etc.

5. The containment with the Bubble Tower has a very favorable environmental edge over the containment without the Bubble Tower relative to exposure dose during the first two hours after the incipience of the accident particularly in the realm of thyroid dose and total effective dose equivalent (TEDE).

Table 4

COST-BENEFIT EVALUATION OF THE BUBBLE TOWER FOR $1000 AND $10,000 PER MAN-REM

COST (DOLLARS)*

Leakage and/or Flow to Environment	WITH BUBBLE TOWER		WITHOUT BUBBLE TOWER	
	@$1000 per man-rem	@$10,000 per man-rem	@$1000 per man-rem	@$10,000 per man-rem
@ 10 cfm	4.03E+7	4.35E+7	1.02E+8	4.77E+8
@ 100 cfm	4.04E+7	4.35E+7	6.29E+8	5.75E+9
@ 1000 cfm	4.04E+7	4.41E+7	7.50E+9	7.45E+10

* Cost takes into account the probability of containment leakage exceeding spec. and the probable loss of containment integrity both with and without the Bubble Tower, and the man-rem exposure consequences of excessive leakage and loss of containment integrity translated into dollars. Cost also includes the cost of Bubble Tower downtime and installation, and the cost of downtime or inoperability for a plant without the Bubble Tower safeguard.

When the Bubble Tower is available, the costs are relatively fixed since the cost of man-rem exposure is not a significant cost factor; the contrary is true when the Bubble Tower is not available.

Table 5

COST-BENEFIT WORK SHEET EVALUATION

	@ 10 cfm		**@ 100 cfm**		**@ 1000 cfm**	
	BUBBLE TOWER	**NO BUBBLE TOWER**	**BUBBLE TOWER**	**NO BUBBLE TOWER**	**BUBBLE TOWER**	**NO BUBBLE TOWER**
PROBABILITY OF CONTAINMENT LEAKAGE BEYOND SPEC (After DBA initiates)	0.01	0.1	0.01	0.1	0.01	0.1
PROBABILITY OF CONTAINMENT BREACHMENT (After DBA initiates)	1.0E-4	0.01	1.0E-4	0.01	1.0E-4	0.01
EXPOSURE (MAN-REM) per 1000 person	34.5	379	35.1	3790	41	37200
EXPOSURE DOLLARS per 1000 persons						
@ $1000 per MAN-REM	3.45E+7	3.79E+8	3.51E+7	3.79E+9	4.10E+7	3.72E+10
@ $10,000 per MAN-REM	3.45E+8	3.79E+9	3.51E+8	3.79E+10	4.10E+8	3.72E+11
PROBABLE EXPOSURE DOLLARS per 1000 persons						
LEAKAGE BEYOND SPEC						
@ $1000 per MAN-REM	3.45E+5	3.79E+7	3.51E+7	3.79E+8	4.10E+5	3.72E+9
@ $10,000 per MAN-REM	3.45E+6	3.79E+8	3.51E+8	3.79E+9	4.10E+6	3.72E+10
CONTAINMENT BREACH						
@ $1000 per MAN-REM	3.45E+3	3.79E+6	3.51E+3	1.90E+8	4.10E+3	3.72E+9
@ $10,000 per MAN-REM	3.45E+4	3.79E+7	3.51E+4	1.90E+9	4.10E+4	3.72E+10
TOTAL PROBABLE EXPOSURES DOLLARS per 1000 persons						
@ $1000 per MAN-REM	3.48E+5	4.17E+7	3.55E+5	5.69E+8	4.14E+5	7.44E+9
@ $10,000 per MAN-REM	3.48E+6	4.17E+8	3.55E+6	5.69E+9	4.14E+6	7.44E+10
PLANT PROBABLE DOLLAR LOSS	3.00E+7	6.00E+7	3.00E+7	6.00E+7	3.00E+7	6.00E+7
COST OF BUBBLE TOWER	1.00E+7		1.00E+7		1.00E+7	
TOTALS						
@ $1000 per MAN-REM	4.03E+7	1.02E+8	4.04E+7	6.29E+8	4.04E+7	7.50E+9
@ $10,000 per MAN-REM	4.35E+7	4.77E+8	4.35E+7	5.75E+9	4.41E+7	7.45E+10

REFERENCES

1. *Passive Cooling Containment study* – John J. Shin, R.C. Iotti, and R.F. Wright
ASME PVP Conference Transactions PVP-Vol 252, July 1993

2. *NPR and ANS Containment Study using Passive Cooling Techniques* – J.J. Shln, R.C. Iotti, and R.F. Wright
8th KAIF/KNS/OKAEA Conference Proceedings Seoul, Korea, April 1993

3. *Universal Passive Containment Protection* – R.C. Iotti, M.J. Parnes, J.J. Shin, and R.F. Wright
24th Structural Mechanics in Reactor Technology (SMIRT) Karlsruhe, Germany, August 1993

4. *NUREG-0800*

5. *ACI-349*

6. *ANSI/AWWA P110*

7. *NUREG-1465* – Accident Source Terms for Light-Water Nuclear Power Plants. L. Soffer et al (6/1992)

8. *TID-14844* – Calculation of Distance Factors for Power and Test Reactor Sites. March 25, 1962

9. *10 CFR 100* – Reactor Site Criteria (spec. 10 CFR 100.11)

10. *The Quantification of Social Values* – Harry J. Otway Presented at Symposium entitled: "Risk Versus Benefit Analysis: Solution or Dream?" Nov. 11, 1971, Los Alamos Scientific Laboratory

Figure 1

COMBINED PASSIVE SAFETY