



The Evaluation of Risk Impact for Design Candidates Using PSA Model

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ABSTRACT

Level 3 PSA sensitivity study is performed to gain an insight on the risk impact for the containment design alternatives. Potential radiological consequences that take into account the approximate source terms are evaluated. The resulting CCDFs (Complementary Cumulative Distribution Functions) for individual dose at the site boundary are compared with the Korean ALWR off-site release goal and the release frequency goal for EPRI ALWR emergency plan simplification.

1. Introduction

Containment for nuclear power plants should maintain its integrity during the accident progression to mitigate the severity of accident and to provide the leaktightness which minimizes the radioactive release to environment. The Korean ALWR under consideration adopts a dual containment. Different from the nuclear plants with a single containment, the leaked radioactive nuclides from the inner containment wall are not released directly to the environment but collected in annulus space where a subatmospheric pressure is maintained. And they are finally vented to atmosphere via an appropriate filtering system.

PSA can be used during the design process to assure the top level quantitative design goals for safety and to provide an acceptable and optimized design option. In this paper, the risk impacts of single and dual containment design alternatives are examined. The offsite release frequencies according to radial distances from reactor are calculated taking most of severe accidents into consideration. The reference plant in this assessment is based on the Korean ALWR design.

2. Description of Containment Design Candidates

Most of operating PWRs in Korea, including KSNP (Korean Standard Nuclear Plant), has a single containment shell configuration; prestressed concrete with a steel liner plate. A steel-lined containment with proper radiological protection design has been accepted by the regulatory body to meet the regulatory requirements for offsite radioactive release limits under design basis conditions.

A dual concrete containment configuration with a secondary (outer) reinforced concrete containment shell enclosing the primary (inner) prestressed concrete containment shell is chosen for the Korean ALWR. This is to further minimize and control the radioactive release to the environment. Special safeguards ventilation system equipped with filter units is provided in the annular space between the primary and secondary containment to collect,

filter, control, and monitor any radioactive leakage from the primary containment. The secondary concrete containment also provides an additional protection to the primary containment from external loads and hazards such as wind, typhoon, tornado, explosion, and other impact.

In case of a steel-lined primary concrete containment, the steel liner functions as the leak-tight barrier against the release of radioactive fission products into the environment. The prestressed concrete shell, in conjunction with conventional reinforcing steel is relied upon to resist all the design loads. The steel liner is not used as a strength element to resist design loads.

3. Risk Evaluation for Design Candidates

PSA(Probabilistic Safety Assessment) is an important tool at the design stage to gain an insight of the relative weakness in the plant and to support the choice of design option including redundancy and diversity of the safety system. Probabilistic safety goal provides a means to evaluate the quantitative results of PSA. In EPRI Utility Requirement Document, LRF(Large Release Frequency) target was set up at a frequency lower than $10^{-6}/RY$ and whose consequences of 25 rem individual effective dose at the site boundary[1]. And the release frequency target for the EPRI ALWR emergency plan simplification was set up as a cumulative frequency of less than $10^{-6}/RY$ for sequences resulting in greater than 1 rem over 24 hours at the site boundary [2]. The same quantitative goals are selected for Korean ALWR design [3].

In this paper, the two containment types, the single containment shell and the dual containment design chosen for Korean ALWR have been examined from the viewpoint of offsite release risk. The result of the risk assessment for two containment design alternatives were reviewed against the above safety goal.

3.1 Methodology & Assumptions

The dose evaluation uses the MACCS code [4] to estimate the risk impact of the postulated accidental releases. MACCS code performs plume dispersion analyses based on the yearly meteorological data to estimate the air and ground-level concentrations of the released nuclides. Multiple dispersion analyses allow the application of statistical analysis to the full range of results, based on the probability of the meteorological sequences that caused those results. This accounts for the possibility of an accident occurring at any time during the year. The air and ground concentrations per nuclide are then converted to exposure dose for the following pathways: cloudshine, groundshine, and inhalation. Statistical evaluation is applied to the multiple dispersion analysis results so that the consequences are presented in terms of the mean value as CCDFs[5].

The release categories determined via the containment response analyses are the primary inputs to the consequence analyses (calculation of the offsite releases). Each release category is defined in terms of its isotopic content; its magnitude and energy; the time, duration and location of the release; and the occurrence frequency for the release. For each release category, the MACCS computer code was used to calculate the CCDF for effective dose equivalent at distances of 500 meters and 800 meters from the reactor. This CCDF curve represents the frequency with which a given effective dose equivalent would be exceeded at a radius from the reactor. In each calculation, a meteorological sequence is selected from a set of meteorological data, and the downwind effective dose equivalent at a distance is calculated for a period of 24 hours following the release. The frequency for the dose is calculated by multiplying the conditional probability of the meteorological sequence by the occurrence frequency of the release category being evaluated. The [dose, frequency]

couplet is saved, and after a large number of equivalent sampled dose calculations are performed for the release category of concern, the resulting set of [dose, frequency] couplets are used to generate the CCDF for the specific release category. After the CCDFs were generated for all release categories, the CCDFs were numerically summed to generate a total CCDF.

The meteorological reference file contains hourly weather condition data for the plant site. The reference site weather data of EPRI URD was used to estimate off-site dose. The emergency plans and population data was not required for the dose calculation at the site boundary. The ORIGEN code was used to calculate the core inventory of radioisotopes. The calculation was based on a core with a discharge burnup of 54,000 MWD/MTU. The standard values in the MACCS user's manual were used for other input parameters.

3.2 Source Terms

The level 2 PSA result of Korean ALWR is used for source term consideration. From the level 2 PSA of at-power internal event, internal fire, and flood, the release categories are selected. For each release category, MAAP 4[6] run was made to obtain the source term. In turn, the MAAP calculated source term was inputted to the offsite dose evaluation. MAAP analysis result for the single and dual containment is presented in Table 1 and Table 2. Three cases are considered in this study; single containment with steel liner, dual containment without considering hold-up within annulus, and dual containment with hold-up. The internal event and external event accident sequences to be considered are the same for all three cases. Only the difference in three cases is the release fraction of fission products.

- *Case 1 : single containment with steel-liner*

The release fraction for the intact containment category is assumed that fission products are released directly into the atmosphere from the containment with a leakage rate of 0.2 vol%/day. Since in performing the level 2 PSA for Korean ALWR, the release frequency and category is evaluated at the inner containment, the release frequency is the same as the other cases. The release fraction of containment failure events (early and late) includes leak fraction before the containment rupture is occurred. The source term for this case is presented in Table 1.

- *Case 2 : double containment without considering hold-up within annulus*

The fission products for the release categories of an intact containment with successful operation of the APS (annulus purge system) are considered to leak at a design leakage rate from the inner containment. The design basis leakage of 0.5 vol%/day is chosen for the Korean ALWR. The APS filtering is considered as the only removal mechanism. The removal calculation through APS is performed with the assumption of 10% bypass and 85.5% removal for fission products except for noble gases. Noble gases are assumed to be bypassed 100%. In other words, it is assumed that noble gases are leaked to the environment in proportion to the design leak rate. The release fractions and frequencies of containment failure/ bypass category are the same as the other options. The source term for this case is presented in Table 2.

- *Case 3 : double containment with considering hold-up within annulus*

In order to consider the hold-up effect for the double containment, in addition to the removal mechanisms for fission products due to the APS filtering, the noble gases decay during the holdup within annulus building is credited. The difference with the case 2 above

is for the sequences with the intact inner containment. The leakage rate of the noble gases from the annulus building to the atmosphere is reduced by 50% due to the radioactive decay. This roughly assumed that the decay corresponds to a hold up time of a day.

4. Results & Discussions

The offsite release goal for Korean ALWR design is as follows.

" In the event of a severe accident, the dose beyond a site boundary from the reactor shall not exceed 1 rem. The mean frequency of occurrence for higher offsite doses shall be less than once per million reactor years." The CCDFs were generated by a series of dose calculations for the containment designs. Table 3 presents the point estimate values for the 3 cases. Figure 1 presents the 1 rem exceeding frequencies according to the distances from the reactor. The offsite release design goal is met both for the dual containment option with 0.5 vol%/day leakage rate and single containment option with 0.2 vol%/day leakage rate.

The single containment option was shown the smallest exceedance frequency. As shown in Table 1 and 2, the release frequency of the intact containment sequences is about 90% of the total release frequency. For the intact containment sequences, the release depends on the design leak rate. Hence, the frequency exceeding the limit of 1 rem strongly depends on the design leak rate. Because the design leak rate for the single containment is 0.2 vol%/day, it has smaller exceedance frequency than the dual containment with 0.5 vol%/day.

5. Conclusions

The risk impact of two containment design alternatives, single with liner plate and dual, are examined. The off-site release frequencies according to the radial distances from reactor are calculated for each case. The release height and the release energy are conservatively assumed. The calculations show that the site boundary of 500 m is sufficient to meet the design goal for the single containment with the lower leak rate as well as the dual containment with higher leak rate. For the dual containment with the higher leak rate, however, the results are sensitive to the degree to which the holdup effect of noble gases in annulus area is credited. The behavior of short-lived radionuclides is strongly influenced by the holdup time. When one assumes that 50% of the total noble gases leaked to the annulus area decays out during the holdup, the result of dual containment at 0.5 vol%/day leak rate is comparable with that of single containment at 0.2 vol%/day leak rate. To assess the impact of dual containment on the risk more realistically, it is recommended to evaluate the holdup time and the exact operation mode of the annulus purge system.

6. References

1. EPRI-URD, Vol.II, Rev. 7, 1995, Chap. 1A: PSA Key Assumptions & Groundrules, Section 5.1
2. EPRI-URD, Vol.III, Rev. 7, 1995, Chap. 1, Section 2.6.5.
3. Korean Utility Requirements Document, 1998, Chap. 1A:PSA Key Assumptions & Groundrules. Section 5.1
4. D.I.Chanin.et al., 1990, MELCOR Accident Consequence Code System(MACCS) User's Guide, NUREG/CR-4691,Vol.1
5. J.W Hickman, et al., 1983, PRA Procedures Guide, NUREG/CR-2300, Vol.2
6. MAAP4 User's Manual, 1994, EPRI, RP-3131-02

Table I. Source Term for single containment with steel-liner (0.2 vol%/day)

Containment Failure Mode	Release Category	Release Frequency (Y ⁻¹)			Release Start-time (sec)	Release Duration (sec)	Release Fraction								
		Internal Earth	Internal Fire	Internal Flood			Inert	I	Cs	Tc	Sr	Ru	La	Ce	Ba
Intact Containment (93%)	RC 1	3.98E-07	1.69E-08	4.73E-09	3079	86410	7.84E-04	7.21E-07	7.21E-07	1.09E-06	8.60E-09	1.94E-07	1.73E-10	1.30E-12	4.99E-08
	RC 2	5.65E-10	2.83E-11	7.91E-12	3079	36410	7.84E-04	7.21E-07	7.21E-07	1.09E-06	8.60E-09	1.94E-07	1.73E-10	1.30E-12	4.99E-08
	RC 3	5.68E-07	2.22E-08	5.78E-09	8392	86410	1.19E-03	6.30E-07	6.32E-07	7.39E-07	1.70E-08	2.29E-07	6.04E-10	4.75E-12	6.32E-08
	RC 4	1.15E-07	2.87E-08	7.98E-09	5432	86430	1.81E-03	5.39E-06	6.12E-06	2.77E-05	7.87E-08	3.88E-06	1.62E-09	1.99E-11	4.52E-07
Early Containment Failure (0.5%)	RC 5	2.78E-12	3.97E-12	8.62E-13	8402	9698	1.22E-04	6.47E-07	6.48E-07	7.58E-07	4.39E-08	4.08E-07	1.40E-09	8.24E-12	1.29E-07
					18100	76701	7.78E-04	4.20E-04	5.24E-04	2.41E-04	9.25E-04	9.22E-05	3.12E-05	8.54E-08	1.81E-03
	RC 6	2.59E-09	7.82E-10	2.17E-10	5456	86400	7.49E-01	7.46E-03	7.46E-03	1.81E-02	6.78E-04	1.74E-03	8.46E-06	1.60E-07	1.13E-03
	RC 7	1.10E-09	2.71E-11	8.21E-12	8402	9698	1.22E-04	6.47E-07	6.48E-07	7.58E-07	4.39E-08	4.08E-07	1.40E-09	8.24E-12	1.29E-07
					18100	76701	9.90E-01	1.62E-03	1.98E-03	8.14E-04	2.40E-03	2.32E-04	8.08E-05	2.18E-07	4.64E-03
	RC 8	8.89E-10	2.28E-10	6.21E-11	5456	86400	9.46E-01	2.52E-02	2.69E-02	5.06E-02	1.52E-03	8.32E-03	2.54E-05	3.63E-07	4.29E-03
Latent Containment Failure (21%)	RC 9	1.46E-11	6.97E-13	1.86E-13	8399	77903	1.70E-03	2.68E-05	2.49E-05	3.22E-05	9.07E-07	1.04E-05	3.15E-08	2.35E-10	3.44E-06
					86360	8420	1.57E-01	1.55E-05	1.80E-05	2.99E-05	6.40E-07	7.35E-06	2.70E-08	1.67E-10	2.60E-06
	RC 10	2.73E-10	1.79E-11	4.82E-12	8402	78240	1.12E-03	6.57E-07	6.61E-07	7.78E-07	5.98E-08	4.58E-07	2.03E-09	1.04E-11	1.60E-03
					86620	8160	1.15E-01	5.62E-07	3.40E-06	8.08E-07	8.00E-11	0.00E-01	3.00E-12	1.00E-14	1.00E-10
	RC 11	4.72E-09	9.10E-10	2.39E-10	5456	86430	1.89E-03	5.47E-06	6.25E-06	1.15E-05	1.94E-07	2.86E-06	9.67E-09	4.89E-11	7.33E-07
	RC 12	4.72E-09	9.10E-10	2.39E-10	5456	86480	1.85E-03	5.95E-06	6.92E-06	1.30E-05	2.94E-08	2.79E-06	1.52E-09	1.11E-11	3.82E-07
	RC 13	1.24E-10	3.29E-11	9.05E-12	5483	86401	1.96E-03	1.21E-05	1.27E-05	2.51E-05	1.87E-07	3.54E-06	5.64E-09	6.62E-11	8.31E-07
					8379	77901	1.70E-03	2.69E-05	2.69E-05	3.28E-05	9.07E-07	1.04E-05	3.15E-08	2.35E-10	3.44E-06
					85360	8420	8.11E-01	2.95E-04	5.43E-04	1.72E-04	3.30E-05	3.97E-05	1.38E-07	9.19E-10	1.42E-05
					8379	78290	5.39E-02	4.31E-05	4.61E-05	6.30E-05	1.60E-06	1.99E-05	6.31E-08	4.31E-10	6.40E-06
				86620	8110	7.71E-01	6.90E-05	1.11E-04	4.79E-05	1.84E-06	2.07E-05	7.82E-08	4.74E-10	7.40E-06	
	RC 16	4.72E-09	9.10E-10	2.38E-10	5456	86400	1.85E-03	5.51E-06	6.10E-06	1.07E-05	2.90E-07	2.67E-06	8.20E-09	4.63E-11	7.31E-07
	RC 17	4.72E-09	9.10E-10	2.39E-10	5456	86480	2.01E-03	7.71E-06	8.93E-06	1.47E-05	1.46E-07	3.34E-06	4.85E-09	4.18E-11	7.61E-07
Basemat mch-through (0.3%)	RC 19	4.67E-09	6.04E-10	1.64E-10	5456	86401	1.96E-03	1.19E-05	1.23E-05	2.42E-05	2.84E-07	3.87E-06	9.41E-09	1.00E-10	1.17E-06
Containment Failure Before Reupter (1.8%)	RC 20	1.83E-08	1.41E-09	2.12E-09	4697	86430	1.86E-03	5.71E-06	5.70E-06	4.76E-06	1.09E-07	8.07E-07	4.11E-09	8.05E-11	3.48E-07
Containment Isolation Failure (0.6%)	RC 21	2.29E-09	1.58E-10	4.68E-11	2175	86430	4.09E-01	1.03E-02	1.02E-02	9.61E-03	7.10E-04	1.55E-03	1.60E-05	4.85E-07	7.67E-04
	RC 22	1.44E-12	9.98E-14	2.94E-14	2210	86410	8.64E-01	1.72E-01	1.76E-01	1.72E-01	1.03E-03	1.40E-02	5.03E-04	1.65E-05	1.15E-02
	RC 23	4.11E-09	0.00E+00	0.00E+00	1983	86440	0.00E+00	3.70E-01	3.67E-01	5.08E-01	3.24E-02	1.14E-01	8.64E-04	1.61E-05	8.33E-02
SGTR Bypass (1.5%)	RC 24	1.62E-08	9.36E-10	2.60E-10	10490	86430	8.98E-01	3.24E-01	3.25E-01	1.67E-01	4.68E-03	4.70E-02	2.56E-04	6.00E-07	1.98E-02

Table 2. Source Term for Double containment (0.5 vol%/day, No considering Holdup)

Containment Failure Mode	Release Category	Release Frequency(R/Y)			Release Start-time (sec)	Release Duration (sec)	Release Fraction								
		Internal Event	External Event (Fire)	External Event (Flooding)			Inert	I	CS	TE	SR	RU	LA	CE	BA
Intact Containment (93.4%)	RC 1	3.38E-07	1.69E-08	4.73E-09	3079	86410	1.95E-03	2.74E-07	2.74E-07	4.15E-07	4.19E-09	8.42E-08	1.06E-10	7.06E-13	2.48E-08
	RC 2	5.65E-10	2.83E-11	7.91E-12	3079	86410	1.95E-03	1.89E-06	1.89E-06	2.86E-06	2.89E-08	5.81E-07	7.29E-10	4.87E-12	1.71E-07
	RC 3	5.68E-07	2.22E-08	5.78E-09	8392	86410	2.92E-03	1.90E-07	1.92E-07	1.94E-07	3.59E-08	1.80E-07	1.27E-09	5.47E-12	8.53E-08
	RC 4	1.11E-07	2.87E-08	7.98E-09	5432	86430	4.54E-03	1.13E-05	1.38E-05	5.32E-05	3.07E-07	1.36E-05	3.61E-08	2.09E-10	1.71E-06
Early Containment Failure (0.5%)	RC 5	2.78E-12	3.97E-12	8.62E-13	8402	86400	7.81E-01	3.99E-04	5.01E-04	3.43E-04	9.23E-04	6.25E-04	3.46E-05	1.07E-07	2.19E-03
	RC 6	2.98E-09	7.82E-10	2.17E-10	5456	86400	7.49E-01	7.46E-03	7.40E-03	1.81E-02	6.76E-04	1.74E-03	8.46E-06	1.60E-07	1.13E-03
	RC 7	1.08E-09	2.71E-11	8.21E-12	8402	86400	9.97E-01	1.90E-03	2.03E-03	1.07E-03	2.63E-03	1.69E-03	9.90E-05	2.98E-07	6.06E-03
	RC 8	8.88E-10	2.28E-10	6.21E-11	5456	86400	9.11E-01	1.88E-02	2.01E-02	6.18E-02	4.05E-03	8.01E-03	5.24E-05	8.88E-07	6.68E-03
Latent Containment Failure (2.0%)	RC 9	1.46E-11	6.97E-13	1.86E-13	8379	86400	1.62E-01	7.70E-05	8.28E-05	9.15E-05	8.15E-06	3.41E-05	2.42E-07	1.78E-09	1.97E-05
	RC 10	2.73E-10	1.79E-11	4.82E-12	8402	86400	9.95E-02	4.11E-06	7.06E-06	2.32E-06	6.22E-08	5.91E-07	2.53E-09	1.51E-11	2.45E-07
	RC 11	4.77E-09	9.10E-10	2.38E-10	5456	86400	4.40E-03	1.45E-05	1.65E-05	4.41E-05	5.22E-07	7.81E-06	1.98E-08	2.07E-10	2.13E-06
	RC 12	4.77E-09	9.10E-10	2.38E-10	5456	86480	4.36E-03	2.16E-05	2.38E-05	4.78E-05	4.14E-07	8.31E-06	9.85E-08	4.83E-10	1.84E-06
	RC 13	1.24E-10	3.29E-11	9.05E-12	5483	86400	4.51E-03	1.70E-05	1.77E-05	5.86E-05	2.85E-06	1.86E-05	1.35E-07	1.72E-09	6.83E-06
	RC 14	1.81E-11	9.54E-13	2.49E-13	8379	86400	8.14E-01	2.65E-04	3.99E-04	2.70E-04	8.84E-06	7.93E-05	3.47E-07	2.04E-09	2.91E-05
	RC 15	4.32E-11	2.18E-12	5.77E-13	8379	86400	8.25E-01	4.24E-04	5.62E-04	1.39E-04	8.81E-06	7.43E-05	3.40E-07	1.95E-09	2.83E-05
	RC 16	4.77E-09	9.10E-10	2.38E-10	5456	86400	4.46E-03	2.09E-05	2.16E-05	4.58E-05	2.19E-06	8.03E-06	2.99E-08	4.37E-10	3.98E-06
RC 17	4.77E-09	9.10E-10	2.38E-10	5456	86400	4.36E-03	2.14E-05	2.34E-05	5.31E-05	1.25E-06	9.83E-06	1.84E-07	8.25E-10	3.24E-06	
Basemat melt-through (0.5%)	RC 19	4.67E-09	6.04E-10	1.64E-10	5456	86400	8.89E-01	3.84E-04	7.92E-04	2.00E-03	4.06E-08	4.80E-08	2.87E-09	1.88E-09	2.56E-07
Containment Failure Before Rupture (1.8%)	RC 20	1.83E-08	1.41E-09	2.12E-09	4697	86430	6.74E-01	4.64E-02	4.85E-02	4.20E-02	4.94E-03	1.38E-02	5.13E-05	8.87E-07	7.98E-03
Containment Isolation Failure (0.6%)	RC 21	2.29E-09	1.58E-10	4.68E-11	2175	86430	8.03E-01	4.32E-03	4.32E-03	1.32E-02	4.72E-04	3.46E-03	1.08E-05	2.81E-07	7.03E-04
	RC 22	1.44E-12	9.96E-14	2.94E-14	2210	86410	8.11E-01	1.59E-01	1.60E-01	1.47E-01	9.65E-03	2.85E-02	1.96E-04	4.83E-06	1.33E-02
	RC 23	4.31E-09	0.00E+00	0.00E+00	1983	86440	1.00E+00	3.70E-01	3.67E-01	5.06E-01	5.24E-02	1.14E-01	8.64E-04	1.61E-05	8.33E-02
SGTR Bypass (1.5%)	RC 24	1.63E-08	9.36E-10	2.60E-10	10490	86430	8.46E-01	2.60E-01	2.61E-01	1.46E-01	2.44E-02	4.35E-02	4.79E-04	7.76E-06	4.40E-02

Table. 3 1 rem Exceeding Frequency Evaluation Results

Case	Events	1 rem Exceeding Frequency (/RY)			
		500 m	(%)	800 m	(%)
Case 1	Internal Event	5.44E-7	89.7	4.74E-7	89.9
	Fire + Flooding	6.25E-8	10.3	5.34E-8	10.1
	TOTAL	6.07E-7	100	5.27E-7	100
Case 2	Internal Event	7.56E-7	90.8	6.60E-7	90.5
	Fire + Flooding	7.63E-8	9.2	6.90E-8	9.5
	TOTAL	8.32E-7	100	7.29E-7	100
Case 3	Internal Event	5.86E-7	89.9	5.31E-7	89.7
	Fire + Flooding	6.58E-8	10.1	6.09E-8	10.3
	TOTAL	6.52E-7	100	5.92E-7	100

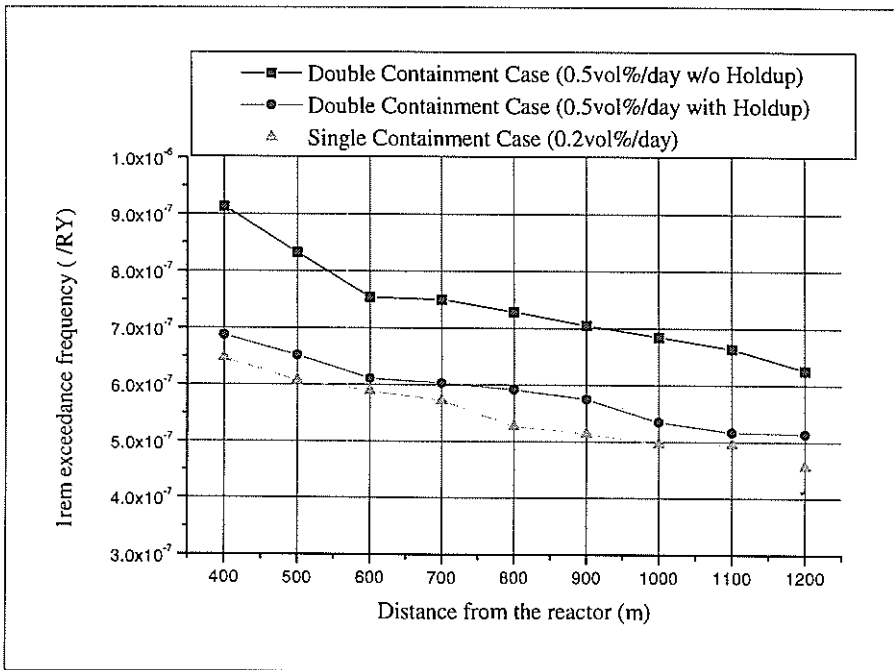


Fig. 1 1 rem Exceeding Frequency Distributions for Containment Options