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A Value-Impact Assessment of Alternate Containment Concepts

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Sandia Laboratories

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U. S. Department of Energy

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ABSTRACT

A value-impact assessment is made of alternate containment concepts for commercial light water reactor power plants. Several alternate containment concepts are evaluated and compared considering their potential for reducing public risk and their construction cost. The results and methodology of the Reactor Safety Study (WASH-1400) are used as a basis for determining potential risk reductions that could be realized by alternate containment designs. Among the alternatives considered, filtered atmospheric venting appears to offer the greatest potential for reducing public risk for the least impact.

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EXECUTIVE SUMMARY

This study was performed by Sandia Laboratories at the request of the Office of Nuclear Regulatory Research of the Nuclear Regulatory Commission. The study was done to support a briefing given to the Commission on alternate containment concepts. It was requested that the briefing include concepts "between the present regulations and underground siting that can add to plant safety." The study was performed in a six-week period between April 15, and May 20, 1977. The Commission briefing was given on July 7, 1977.

To complete the study, the relative importance of containment failure modes was determined. It was found that overpressure failure of the containment due to steam and noncondensable gases generated during a core-meltdown accident was the principal contributor to risk. Nine design alternatives reflecting six fundamental concepts for inhibiting overpressure failures were evaluated with potential risk reduction as the figure of merit for assessing relative value. Although combinations of alternatives could have been considered, the objective of the study was to evaluate each alternative on its own merits rather than to identify an optimal design combination. For each alternative, construction costs and impacts on safety and normal plant operations were identified. The results are presented in the form of a qualitative value-impact matrix (see Figure 14). Filtered Atmospheric Venting was judged most favorable based on the value-impact comparison.

To place the results of this study in proper perspective, several points need to be made. The results of this study are based principally on insights from the Reactor Safety Study,* which itself evaluated only two nuclear power plants. Although an effort was made to eliminate considerations reflecting atypical characteristics of these plants, the results of this value-impact assessment must be considered as only indicative of what a much broader study would find. The design alternatives considered herein were judged to be practical, but their feasibility has not been demonstrated. The reductions in relative risk calculated in the study should be considered as only potential gains since other factors which were not dominant in the Reactor Safety Study and therefore, not given detailed consideration, become more important and perhaps could dominate the risk. And finally, this study did not address the broader question of whether any alternate containment design is desirable or justified.

The study was intended to identify the logical alternatives and, among those, to highlight the ones which appear most promising on a value-impact scale.

* Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Reactor Power Plants, U.S. Nuclear Regulatory Commission, WASH-1400 (NUREG 75/014) October 1975.

A VALUE-IMPACT ASSESSMENT OF ALTERNATE CONTAINMENT CONCEPTS

CHAPTER 1. INTRODUCTION

In April 1977, the Nuclear Regulatory Commission requested that Sandia Laboratories perform a value-impact assessment of alternate containment concepts between present designs and underground siting that could add to plant safety. The study was completed in the six-week period between April 15 and May 30, 1977. The results were presented to the Commission in a public meeting on July 7, 1977.

The study was performed in five steps. They were:

1. Determination of the relative importance of containment failure modes,
2. Development of alternate containment concepts,
3. Formulation of design alternatives,
4. Determination of potential value, and
5. Determination of potential impact.

This study used many of the data, methods, and insights from the Reactor Safety Study. An analysis of dominant accident sequences and containment failure modes formed the basis for estimating the risk for each alternate containment concept considered. The Reactor Safety Study determined that accidents which could result in core-meltdown were the major contributors to public risk. The risk associated with the Reactor Safety Study plants is dominated by the few highest probability sequences in the high consequence release categories. The same accident sequences were used in this study; thus, only a few sequences were considered in detail. Given that an accident sequence occurs, the Reactor Safety Study analysis indicated that the resulting level of consequences is dependent upon the mode of containment failure. This provides important insight into the potential for reducing risk to the public. Those alternate containment concepts which most reduce the likelihood of containment failures leading to high consequence releases will be the most effective concepts for reducing public risk.

CHAPTER II. CONTAINMENT FAILURE MODES

The first step in the value-impact assessment was to determine the containment failure modes which made the greatest contributions to public risk. The Reactor Safety Study identified five potential containment failure modes for pressurized water reactors (PWRs) and nine for boiling water reactors (BWRs). They are shown in Table I. To identify those alternate containment concepts which have the most potential for reducing public risk and to evaluate the risk reduction realized, the risks associated with accidents breaching containment in each failure mode were calculated, and the relative importance of each containment failure mode to risk was determined.

TABLE I
Containment Failure Modes

<u>PWR</u>	
<u>Failure Mode</u>	<u>Description</u>
α	- Containment rupture due to a reactor vessel steam explosion
β	- Containment failure resulting from inadequate isolation of containment openings and penetrations
γ	- Containment failure due to hydrogen burning
δ	- Containment failure due to overpressure
ϵ	- Containment vessel melt-through
<u>BWR</u>	
<u>Failure Mode</u>	<u>Description</u>
α	- Containment failure due to steam explosion in vessel
β	- Containment failure due to steam explosion in containment
γ	- Containment failure due to overpressure - release through reactor building
γ'	- Containment failure due to overpressure - release direct to atmosphere
δ	- Containment isolation failure in drywell
ϵ	- Containment isolation failure in wetwell
ζ	- Containment leakage greater than 2400 volume percent per day
η	- Reactor building isolation failure
θ	- Standby gas treatment system failure

The Reactor Safety Study determined a set of dominant accident sequences for both PWRs and BWRs. These were categorized into several release categories, nine categories for the PWR and five categories for the BWR. The categories reflect differing severities of consequences resulting from the accident. The categories and dominant accident sequences are shown in Tables II and III. This study considered the same accident sequences and release categories, but differed slightly from the Reactor Safety Study in that the total probability of each release category was calculated by summing the probabilities of the accident sequences within each category rather than obtaining the total probability by using a Monte Carlo technique. To account for the possibility of an accident having different consequences than those of its assigned release category, both the Reactor Safety Study and this study assumed a 10 percent chance of the accident being in the next higher or lower release category and a 1 percent chance of its being two release categories more or less severe. The contribution of each containment failure mode to the total probability of each release category was calculated and is shown in Tables IV and V.

The expected consequences in terms of early fatalities, latent cancer fatalities, and property damage given that a release occurs were obtained using the consequence model from the Reactor Safety Study. The consequences were calculated for a site whose characteristics correspond to a composite of the reactors located in northeastern U. S. river valleys. The Reactor Safety Study evacuation model was employed for all core melt accidents using an evacuation speed of 1.2 mph. The expected consequences per release for each category are given in Table VI.

The expected value of risk was calculated as follows:

$$\sum_i P(c_i) C_i = \text{expected risk}$$

where

$P(c_i)$ = probability of release category i

C_i = expected consequences given release in category i

i = release category ($i = 1, 2, 3, \dots, 9$ for PWR;

$i = 1, 2, 3, \dots, 5$ for BWR)

The expected value of the risk for each containment failure mode was calculated using the information contained in Tables IV, V, and VI. The results of the calculation are given in Table VII and are shown graphically in Figure 1.

TABLE II

PWR Dominant Accident Sequences
vs. Release Categories*

	RELEASE CATEGORIES								Core Melt	
	1	2	3	4	5	6	7	8	9	
LARGE BRCA A	AB-6 1e10 ⁻¹¹ AP-6 1e10 ⁻¹⁰ ACD-6 1e10 ⁻¹¹ AC-6 1e10 ⁻¹¹	AB-7 1e10 ⁻¹⁰ AB-6 4e10 ⁻¹¹ AMP-7 1e10 ⁻¹¹	AD-7 1e10 ⁻⁹ AP-6 1e10 ⁻⁸ AP-6 1e10 ⁻⁸ AC-6 1e10 ⁻⁹	ACD-6 6e10 ⁻¹¹	AD-6 4e10 ⁻⁹ AP-6 1e10 ⁻⁹	AP-7 1e10 ⁻⁹ AMP-6 1e10 ⁻¹⁰ ADP-6 1e10 ⁻¹⁰	AD-6 1e10 ⁻⁶ AP-6 1e10 ⁻⁶	AC-6 1e10 ⁻⁷	AP-6 1e10 ⁻⁶	
A Probabilities	1e10 ⁻⁹	1e10 ⁻⁸	1e10 ⁻⁷	1e10 ⁻⁸	4e10 ⁻⁸	1e10 ⁻⁷	1e10 ⁻⁶	1e10 ⁻⁵	1e10 ⁻⁶	
SMALL LOCA S ₁	S ₁ B-6 1e10 ⁻¹¹ S ₁ CD-6 1e10 ⁻¹¹ S ₁ P-6 1e10 ⁻¹⁰ S ₁ C-6 1e10 ⁻¹⁰	S ₁ B-7 1e10 ⁻¹⁰ S ₁ CD-6 1e10 ⁻¹⁰ S ₁ P-6 1e10 ⁻¹¹ S ₁ C-6 1e10 ⁻¹⁰	S ₁ B-7 1e10 ⁻¹⁰ S ₁ CD-6 1e10 ⁻¹⁰ S ₁ P-6 1e10 ⁻⁸ S ₁ C-6 1e10 ⁻⁸	S ₁ CD-6 1e10 ⁻¹¹	S ₁ B-6 1e10 ⁻⁹ S ₁ CD-6 1e10 ⁻⁹	S ₁ CD-6 1e10 ⁻¹⁰ S ₁ B-6 1e10 ⁻⁶ S ₁ P-6 1e10 ⁻⁶	S ₁ CD-6 1e10 ⁻⁶ S ₁ B-6 1e10 ⁻⁶ S ₁ P-6 1e10 ⁻⁶	S ₁ CD-6 1e10 ⁻⁶ S ₁ B-6 1e10 ⁻⁶ S ₁ P-6 1e10 ⁻⁶	S ₁ CD-6 1e10 ⁻⁵	S ₁ CD-6 1e10 ⁻⁴
S ₂ Probabilities	1e10 ⁻⁹	1e10 ⁻⁸	1e10 ⁻⁷	1e10 ⁻⁸	1e10 ⁻⁸	1e10 ⁻⁷	1e10 ⁻⁶	1e10 ⁻⁵	1e10 ⁻⁶	
SMALL LOCA S ₂	S ₂ B-6 1e10 ⁻¹⁰ S ₂ P-6 1e10 ⁻⁹ S ₂ CD-6 1e10 ⁻¹⁰ S ₂ C-6 1e10 ⁻¹⁰ S ₂ C-6 1e10 ⁻⁸	S ₂ B-7 1e10 ⁻⁹ S ₂ P-6 1e10 ⁻¹⁰ S ₂ CD-6 1e10 ⁻¹⁰ S ₂ C-6 1e10 ⁻¹⁰ S ₂ C-6 1e10 ⁻⁸	S ₂ B-6 1e10 ⁻⁸ S ₂ P-6 1e10 ⁻⁷ S ₂ CD-6 1e10 ⁻⁶ S ₂ C-6 1e10 ⁻⁶ S ₂ C-6 1e10 ⁻⁸	S ₂ CD-6 1e10 ⁻¹²	S ₂ B-6 1e10 ⁻⁸ S ₂ P-6 1e10 ⁻⁸	S ₂ B-6 1e10 ⁻⁶ S ₂ P-6 1e10 ⁻⁶ S ₂ CD-6 1e10 ⁻⁶ S ₂ P-6 1e10 ⁻⁶	S ₂ B-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴ S ₂ CD-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴	S ₂ B-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴ S ₂ CD-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴	S ₂ B-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴ S ₂ CD-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴	S ₂ B-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴ S ₂ CD-6 1e10 ⁻⁴ S ₂ P-6 1e10 ⁻⁴
S ₂ Probabilities	1e10 ⁻⁷	1e10 ⁻⁷	1e10 ⁻⁶	1e10 ⁻⁷	1e10 ⁻⁷	1e10 ⁻⁶	1e10 ⁻⁵			
REACTOR VESSEL DISRUPTURE - R	RC-6 1e10 ⁻¹²	RC-7 1e10 ⁻¹¹ AP-6 1e10 ⁻¹¹ RC-6 1e10 ⁻¹²	RC-6 1e10 ⁻⁹					RC-6 1e10 ⁻⁷		
R Probabilities	1e10 ⁻¹¹	1e10 ⁻¹⁰	1e10 ⁻⁹	1e10 ⁻¹⁰	1e10 ⁻⁹	1e10 ⁻⁸	1e10 ⁻⁷			
INTERFACING SYSTEMS LOCA (CHECK VALVE) - V		V 4e10 ⁻⁶								
V Probabilities	4e10 ⁻⁷	4e10 ⁻⁶	4e10 ⁻⁷	4e10 ⁻⁸						
TRANSIENT DISRUPT - T	TRB-6 1e10 ⁻⁸	TRB-7 1e10 ⁻⁷ TRB-6 1e10 ⁻⁶	TRB-6 6e10 ⁻⁸ TRB-6 1e10 ⁻⁸ TRB-6 1e10 ⁻⁸		TRB-6 1e10 ⁻¹⁰ TRB-6 1e10 ⁻¹⁰	TRB-6 1e10 ⁻⁷ TRB-6 1e10 ⁻⁷	TRB-6 1e10 ⁻⁶ TRB-6 1e10 ⁻⁶	TRB-6 1e10 ⁻⁶ TRB-6 1e10 ⁻⁶	TRB-6 1e10 ⁻⁶ TRB-6 1e10 ⁻⁶	TRB-6 1e10 ⁻⁶ TRB-6 1e10 ⁻⁶
T Probabilities	1e10 ⁻⁷	1e10 ⁻⁶	4e10 ⁻⁷	1e10 ⁻⁸	1e10 ⁻⁷	1e10 ⁻⁶	1e10 ⁻⁵			
(II) SUMMARY OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORY										
SMALL (500 MVA)	1e10 ⁻⁷	1e10 ⁻⁶	4e10 ⁻⁶	1e10 ⁻⁷	1e10 ⁻⁵	6e10 ⁻⁶	4e10 ⁻⁵	4e10 ⁻⁵	4e10 ⁻⁵	4e10 ⁻⁴
LOCA BOUND (50 MVA)	1e10 ⁻⁸	1e10 ⁻⁷	4e10 ⁻⁷	1e10 ⁻⁸	1e10 ⁻⁷	1e10 ⁻⁶	1e10 ⁻⁵	4e10 ⁻⁶	4e10 ⁻⁶	4e10 ⁻⁵
OFFER BOUND (500 MVA)	4e10 ⁻⁸	1e10 ⁻⁵	4e10 ⁻⁵	1e10 ⁻⁶	4e10 ⁻⁶	1e10 ⁻⁵	1e10 ⁻⁶	1e10 ⁻⁶	1e10 ⁻⁶	4e10 ⁻⁵

Note: The probabilities for each release category for each event tree and the I for all accident sequences are the median values of the dominant accident sequences summed by Monte Carlo simulation plus a 10% contribution from the adjacent release category probability (see Section 4.1).

TABLE III

**BWR Dominant Accident Sequences of Each
Event Tree vs. Release Category***

	Core Melt				No Core Melt
	RELEASE CATEGORIES				
	1	2	3	4	
LARGE LOCA DOMINANT ACCIDENT SEQUENCES (A)	AE-A 2x10 ⁻⁹ AE-B 1x10 ⁻¹⁰ AE-C 1x10 ⁻¹⁰ AE-D 1x10 ⁻¹⁰	AE-E 1x10 ⁻⁸ AE-F 1x10 ⁻⁸ AE-G 2x10 ⁻⁹ AE-H 2x10 ⁻⁹	AE-I 1x10 ⁻⁷ AE-J 1x10 ⁻⁸ AE-K 1x10 ⁻⁸ AE-L 1x10 ⁻⁸	AE-M 6x10 ⁻¹¹ AE-N 7x10 ⁻¹⁰ AE-O 6x10 ⁻¹¹	A 1x10 ⁻⁴
A Probabilities	4x10 ⁻⁹	6x10 ⁻⁸	2x10 ⁻⁷	2x10 ⁻⁸	1x10 ⁻⁴
SMALL LOCA DOMINANT ACCIDENT SEQUENCES (S ₁)	S ₁ -A 2x10 ⁻⁹ S ₁ -B 1x10 ⁻¹⁰ S ₁ -C 4x10 ⁻¹⁰ S ₁ -D 4x10 ⁻¹⁰	S ₁ -E 1x10 ⁻⁸ S ₁ -F 1x10 ⁻⁸ S ₁ -G 2x10 ⁻⁹ S ₁ -H 2x10 ⁻⁹	S ₁ -I 1x10 ⁻⁷ S ₁ -J 1x10 ⁻⁸ S ₁ -K 4x10 ⁻⁸ S ₁ -L 2x10 ⁻⁸	S ₁ -M 2x10 ⁻¹⁰ S ₁ -N 2x10 ⁻¹⁰ S ₁ -O 2x10 ⁻¹⁰	
S ₁ Probabilities	1x10 ⁻⁸	4x10 ⁻⁸	2x10 ⁻⁷	2x10 ⁻⁸	
SMALL LOCA DOMINANT ACCIDENT SEQUENCES (S ₂)	S ₂ -A 2x10 ⁻⁹ S ₂ -B 1x10 ⁻⁹ S ₂ -C 1x10 ⁻⁹ S ₂ -D 2x10 ⁻¹⁰	S ₂ -E 1x10 ⁻⁸ S ₂ -F 4x10 ⁻⁹ S ₂ -G 2x10 ⁻⁸ S ₂ -H 2x10 ⁻⁸	S ₂ -I 4x10 ⁻⁸ S ₂ -J 2x10 ⁻⁸ S ₂ -K 2x10 ⁻⁸ S ₂ -L 2x10 ⁻⁹	S ₂ -M 6x10 ⁻¹¹ S ₂ -N 6x10 ⁻¹⁰ S ₂ -O 6x10 ⁻¹⁰ S ₂ -P 6x10 ⁻¹⁰ S ₂ -Q 2x10 ⁻¹⁰	
S ₂ Probabilities	2x10 ⁻⁸	1x10 ⁻⁷	4x10 ⁻⁷	4x10 ⁻⁸	
TRANSIENT DOMINANT ACCIDENT SEQUENCES (T)	TW-A 2x10 ⁻⁷ TW-B 1x10 ⁻⁷ TW-C 5x10 ⁻⁹	TW-D 1x10 ⁻⁶ TW-E 8x10 ⁻⁸	TW-F 1x10 ⁻⁵ TW-G 1x10 ⁻⁵ TW-H 4x10 ⁻⁷		
T Probabilities	1x10 ⁻⁶	6x10 ⁻⁶	2x10 ⁻⁵	2x10 ⁻⁵	
PRESSURE VESSEL RUPTURE ACCIDENTS (R)		P.V. RUPT. 1x10 ⁻⁶ Oxidizing Atmosphere	P.V. RUPT. 1x10 ⁻⁷ Non- oxidizing Atmosphere		
R Probabilities	2x10 ⁻⁹	2x10 ⁻⁸	1x10 ⁻⁷	1x10 ⁻⁸	
SUMMATION OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORIES					
MEDIAN (50% VALUE)	1x10 ⁻⁶	4x10 ⁻⁶	2x10 ⁻⁵	2x10 ⁻⁶	1x10 ⁻⁴
LOWER BOUND (5% VALUE)	1x10 ⁻⁷	1x10 ⁻⁶	5x10 ⁻⁶	5x10 ⁻⁷	1x10 ⁻⁵
UPPER BOUND (95% VALUE)	8x10 ⁻⁶	3x10 ⁻⁵	8x10 ⁻⁵	1x10 ⁻⁵	1x10 ⁻³

NOTE: The probabilities for each release category for each event tree and the I for all accident sequences are the median values of the dominant accident sequences caused by Monte Carlo simulation plus a 10% contribution from the adjacent release category probability (See Section 4.1).

TABLE IV

Contribution of Containment Failure Modes to Each Release Category - PWR

Release Category	Total Probability	α	β	γ	δ	ϵ	V*	Category 9**
1	7.5×10^{-7}	5.6×10^{-8}	0	7.0×10^{-8}	2.2×10^{-7}	0	4×10^{-7}	0
2	6.9×10^{-6}	3.9×10^{-8}	~0	7.0×10^{-7}	2.2×10^{-6}	0	4×10^{-6}	0
3	3.3×10^{-6}	3.4×10^{-7}	~0	7.0×10^{-8}	2.5×10^{-6}	0	4×10^{-7}	0
4	3.4×10^{-7}	3.4×10^{-8}	4.9×10^{-9}	7.0×10^{-9}	2.5×10^{-7}	6.3×10^{-9}	4×10^{-8}	0
5	4.8×10^{-7}	3.4×10^{-9}	4.9×10^{-8}	0	2.3×10^{-8}	4.0×10^{-7}	0	0
6	4.0×10^{-6}	0	1.3×10^{-8}	0	0	4.0×10^{-6}	0	0
7	3.8×10^{-5}	0	8.0×10^{-8}	0	0	3.4×10^{-5}	0	4×10^{-6}
8	4.4×10^{-5}	0	8.0×10^{-7}	0	0	3.4×10^{-6}	0	4×10^{-5}
9	4.0×10^{-4}	0	8.0×10^{-8}	0	0	3.4×10^{-7}	0	4×10^{-4}

* Check valve rupture in low pressure injection system resulting in a LOCA outside containment without an associated containment failure mode.

** Non-core melt accident with no containment failure.

TABLE V

Contribution of Containment Failure Modes to Each Release Category - BWR

Release Category	Total Probability	α	β	γ	γ'	δ	ϵ	Category 5*
1	8.5×10^{-7}	3.1×10^{-7}	2.4×10^{-9}	2.1×10^{-7}	3.3×10^{-7}	0	0	0
2	5.5×10^{-6}	3.1×10^{-8}	2.4×10^{-8}	2.1×10^{-6}	3.3×10^{-6}	~ 0	0	0
3	2.2×10^{-5}	3.1×10^{-9}	2.4×10^{-9}	2.1×10^{-5}	3.3×10^{-7}	~ 0	0	1×10^{-6}
4	1.2×10^{-5}	0	0	2.1×10^{-6}	3.3×10^{-8}	3.2×10^{-9}	0	1×10^{-5}
5	1.0×10^{-4}	0	0	2.1×10^{-7}	0	~ 0	0	1×10^{-4}

Other containment failure modes did not contribute significantly.

* Non-core melt accident with no containment failure.

TABLE VI
Expected Consequences per Release
Northeast River Valley Composite Site

PWR

<u>Category</u>	<u>Early Fatalities</u>	<u>Latent Cancer Fatalities</u>	<u>* Property Damage (10⁶ \$)</u>
1a (cold)	91	120	2050
1b (hot)	8	114	2270
2	7	67	2440
3	0.4	55	987
4	0	18	335
5	0	6	201
6	0	1	173
7	0	~0	171
8	0	~0	1
9	0	~0	0

BWR

1	7	154	2450
2	~1	100	2970
3	0	51	789
4	0	3	29
5	0	~0	~0

The check valve rupture (V) sequence and overpressure failures (δ) dominate the risk in the PWR with hydrogen burning (γ) and vessel steam explosions (α) contributing a minor portion. For the BWR, overpressure failures (γ and γ') dominate the risk with vessel steam explosions contributing a secondary amount. Melt-through failure contributes significantly to the property damage risk for the PWR; this is a result of the evacuation model used. The cost consists almost totally of the cost of evacuation and emergency relocation of the evacuees, assumed for all core-melt accidents.

The check valve rupture sequence identified in the Reactor Safety Study involved failure of two check valves in the low pressure injection lines resulting in a loss-of-coolant accident outside of the containment. The large contribution of this sequence to risk may well be atypical of most PWRs. In addition, it was believed that regulatory action since the RSS resulted in a decreased likelihood of such an accident. Thus, the containment failure mode considered to be the dominant contributor to risk for both PWRs and BWRs in this study is overpressure failure. It was concluded, therefore, that alternate containment designs that most effectively inhibit containment failure due to overpressure should most effectively reduce public risk.

TABLE VII

Contributions of Containment Failure Modes to Expected Risks

PWR

<u>Containment Failure Modes</u>	<u>Early Fatalities/Yr</u>	<u>Latent Cancer Fatalities/Yr/Yr</u>	<u>Property Damage/Yr</u>
V	4.6×10^{-5}	3.4×10^{-4}	11.0K
δ	2.6×10^{-5}	3.2×10^{-4}	8.4K
γ	8.1×10^{-6}	5.9×10^{-5}	1.9K
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
ϵ	0	6.5×10^{-6}	6.6K
β	~ 0	4.2×10^{-7}	~ 0
Category 3	<u>0</u>	<u>0</u>	<u>0.7K</u>
	8.3×10^{-5}	7.6×10^{-4}	29.2K
Without V:	3.7×10^{-5}	4.1×10^{-4}	18.2K

BWR

α	2.2×10^{-6}	5.1×10^{-5}	0.9K
β	4.1×10^{-6}	2.9×10^{-6}	0.1K
γ	3.6×10^{-6}	1.3×10^{-3}	23.4K
γ'	5.6×10^{-6}	4.0×10^{-4}	10.9K
δ	~ 0	2.9×10^{-8}	~ 0
ϵ	~ 0	~ 0	~ 0
Category 5	<u>0</u>	<u>8.1×10^{-5}</u>	<u>1.1K</u>
	1.1×10^{-5}	1.8×10^{-3}	36.4K

Figure 1. Relative Importance of Containment Failure Modes

CHAPTER III. ALTERNATE CONTAINMENT CONCEPTS AND DESIGNS

Alternate Containment Concepts

To develop the alternate containment designs for use in the value-impact assessment, fundamental concepts that could be employed to yield a reduction in risk were identified. Only PWRs were considered for the rest of the study. Many concepts and alternatives were initially considered; however, the study emphasized those concepts that would inhibit overpressure failures.

The relative contribution to pressure of the gases present in containment at the time of overpressure failure for a typical accident in a PWR is shown in Figure 2. This figure is based on the results of the Reactor Safety Study. The potential overpressure failures which most affect risk result principally from the steam and noncondensable gases generated during the core meltdown accident. The additional heat produced by hydrogen burning, for example, has a minimal effect on risk. Thus, containment design alternatives which only prevented hydrogen burning were not expected to result in significant risk reduction. Six fundamental concepts were selected for evaluation. These are shown in Table VIII.

Figure 2. Relative Contributions to Containment Failure Pressure

TABLE VIII
Alternate Containment Concepts

Increase Containment Design Pressure
Increase Containment Volume
Vent Containment Gases During Core Meltdown Accidents
Condense Containment Steam Generated During Core
Meltdown Accidents
Lower Containment Operating Pressure
Inhibit Accumulation of Noncondensable Gases During Core
Meltdown Accidents

Containment Design Alternatives

For each of these concepts, one or more design alternatives were formulated. For each design alternative, design goals were defined in a manner that would give the design alternative the most favorable value-impact position. The definitions of these conceptual designs were sufficiently detailed to allow a meaningful value-impact assessment to be performed. The design alternatives selected for each concept are described below.

Increase Containment Design Pressure -- Two fundamental methods of increasing the containment design pressure were selected. These involved increasing the strength of the traditional design of surface containment buildings, or burying the containment structure thereby gaining the additional pressure capability resulting from the lithostatic pressure of the soil and moisture overburden. Both shallow and deep underground burial were considered.

Increase Containment Volume -- Only one basic design alternative was developed to achieve increased gas containment capability through increasing the containment free volume. This alternative was based on simply increasing the size of a traditionally designed and constructed containment building.

Vent Containment Gases -- Three fundamental methods were selected for venting containment gases before overpressure failure during a core meltdown accident, thus preventing the uncontrolled atmospheric release of radioactive materials. The first method was to sense pressure buildup during a core meltdown accident and to vent to the atmosphere through a filter thereby reducing the resulting consequences. This alternative was called Filtered Atmospheric Venting. The second method evaluated was similar to the CANDU containment concept. This method was also based on sensing pressure buildup in containment during a core meltdown accident and venting. However, in this case the containment gases would be vented to a standby containment-like structure, one per reactor site, equipped with sprays to condense steam. This alternative was called Compartment Venting. The third method resulted from the observation that much smaller consequences were predicted by the Reactor Safety Study when the molten core melted through the base mat of the

reactor building before overpressure failure of the containment occurred. Thus, a design alternative was considered in which the base mat was thinner than traditional designs. It was hoped that it could be shown that this would result in earlier melt-through of the base mat, thus leading to early pressure release into the ground thereby preventing atmospheric release via containment overpressure failure. This alternative was called Thinned Base Mat.

Condense Steam -- Two design approaches were considered for achieving greater steam condensation during a core-meltdown accident. They were use of an ice condenser and use of a pressure suppression pool. Although ice condensers are used to significantly reduce containment pressure for design basis accidents, this study was interested in the capability of an ice condenser to prevent overpressure failures in a core-meltdown accident. The duration of the study did not allow this to be investigated with sufficient thoroughness to perform a meaningful value-impact assessment. Use of a pressure suppression pool to condense steam was incorporated in the Filtered Atmospheric Venting alternative for both steam condensation and filtration purposes. Thus, no design alternative was included in the final value-impact assessment which exclusively implemented the condensing steam concept.

Lower Containment Operating Pressure -- A design alternative was developed to inhibit the combustion of hydrogen generated during a core melt accident. A containment with a low operating pressure, thus a low oxygen inventory, was included in the value-impact assessment. This design alternative was called Evacuated Containment.

Inhibit Gas Accumulation -- No method of preventing the generation of noncondensable gases or of absorbing generated gases was found during the course of the study which was judged worthy of being included in the final value-impact assessment.

Other -- Throughout the study the subject of double containment repeatedly arose; therefore, it was included as a design alternative. The design goals used were such that the total gas containment capability of both containments was similar to current containments.

This phase of the study resulted in the selection of nine design alternatives for use in the value-impact assessment. These are summarized in Table IX, and the assumed effect on containment failure modes for each alternative are shown in Table X.

TABLE IX
Containment Design Alternatives Used in
Value-Impact Assessment

Stronger Containment
Shallow Underground Siting
Deep Underground Siting
Increased Containment Volume
Filtered Atmospheric Venting
Compartment Venting
Thinned Base Mat
Evacuated Containment
Double Containment

TABLE X
Assumed Effect on Containment Failure Modes for Each Design Alternative

<u>Alternative</u>	<u>Containment Failure Mode</u>				
	<u>VSE</u>	<u>CL</u>	<u>HB</u>	<u>OP</u>	<u>MT</u>
Filtered Atmospheric Venting	U	U	E'	E'	I
Compartment Venting	U	U	E'	E'	I
Deep Underground Siting	E	I	E	E	I
Stronger Containment	U	U	R	R	I
Increased Containment Volume	U	U	R	R	I
Shallow Underground Siting	U	R	R	R	I
Evacuated Containment	U	U	E'	R	I
Double Containment	R	R	U	U	U
Thinned Base Mat	U	U	R	R	I

Legend: VSE = vessel steam explosion

CL = containment leakage

HB = hydrogen burning

OP = overpressure

MT = melt-through of base mat

U = unaffected by design alternative (same as current surface plants)

R = reduced by design alternative (less probable than current surface plants)

E = eliminated by design alternative

E' = eliminated by design alternative unless active components fail

I = increased by design alternative (more probable than current surface plants)

CHAPTER IV. DESIGN ALTERNATIVE DESCRIPTIONS

For each design alternative selected for the value-impact assessment, design goals were established. The design goals were selected to meet two criteria: (1) that they be feasible with current technology, and (2) that they result in the most favorable value-impact position for the design alternative. Each design alternative and its design goals are described below.

Stronger Containment

To increase the pressure capabilities of containment, the study examined the alternative of constructing a stronger containment by increasing the wall thickness. This alternative is illustrated in Figure 3.

Figure 3. Stronger Containment

Accident sequences resulting in overpressure failure can be divided into two categories. First are those loss of coolant accident (LOCA) sequences in which the containment spray systems fail but the emergency core cooling system (ECCS) operates. For these sequences, the containment

pressure builds following a LOCA and may reach several hundred psi. In this case, containment overpressure is expected to precede core melt. In the other case, both the containment heat removal systems and the ECCS fail during injection or recirculation. For these sequences, core melt tends to precede containment overpressure failure. The pressure may rise as high as about 120 psia, but generally melt-through or condensation on cold surfaces will limit the pressure so that overpressure failure is not certain. It is believed to be very difficult to design a containment to withstand the several hundred psi pressures of the first category of accidents. Therefore, the design goal for the stronger containment was to contain the second category of accidents; the design pressure was set at 120 psia estimated to result in an approximate doubling of the thickness of the walls. At this design pressure, the containment should be able to withstand the pressure generated in all dominant overpressure sequences in the Reactor Safety Study except those LOCA sequences in which the containment spray systems fail but the ECCS operates.

Shallow Underground Siting

The shallow underground siting alternative, illustrated in Figure 4, was assumed to involve placing a standard containment under about 30 feet of overburden, thus increasing the pressure capabilities of the structure due to the lithostatic pressure of the overburden. The turbine generator building was assumed to be above grade. Shallow underground siting alternatives are currently under consideration in Germany. Their designs, however, entail a much larger containment volume. This study assumed the same containment volume as a surface plant.

Figure 4. Shallow Underground Siting

Deep Underground Siting

The deep underground siting alternative considered in this study is shown in Figure 5. It was assumed that the top of the containment structure would be at least 100 feet underground with the turbine generator building located at the surface. The pressure capabilities of the containment

would be enhanced by the lithostatic pressure of the overburden although there would still be several access passages to the surface. This alternative would involve construction of a containment similar in size and design requirements to a surface structure with modifications to enable it to withstand the external load exerted by the overburden. All passageways exiting the containment would be sealed during operation, and those passageways to the surface would be sealed at the surface in the event of an accident.

Figure 5. Deep Underground Siting

Increased Containment Volume

Another means of increasing the gas containment capabilities of a PWR containment would involve increasing the containment volume as illustrated in Figure 6. For this alternative, it was assumed that the design pressure would remain at 60 psia and that the volume would be approximately doubled. To accommodate such an increase in volume, it is assumed that the wall thickness would be increased by about one foot. This alternative would be expected to achieve the same benefits discussed in the stronger containment alternative. That is, overpressure failures would not be significantly inhibited for those LOCA accidents in which the containment spray systems fail but the ECCS operates; for other core melt accidents overpressure failure of the containment would not be expected.

Figure 6. Increased Containment Volume

Filtered Atmospheric Venting

The filtered atmospheric venting alternative is illustrated in Figure 7. This alternative assumed use of a pressure suppression pool, envisioned as being placed external to the containment, to reduce the pressure in containment following a core-meltdown accident. Containment gases were assumed to be vented to the atmosphere following filtration by the water in the tank. It is assumed that venting would be achieved automatically upon sensing a pressure which is near but slightly above the containment design pressure (~ 60 psia). The goal would be to assure, for the range of significant meltdown accidents, that the containment design pressure would not be greatly exceeded. It is assumed that relief valves would open under the increased pressure; thus, the containment would remain isolated unless a significant buildup in pressure occurred. Redundant systems and backup manual control would probably be advisable for these valves. The tank would contain enough water to allow condensation of all the steam generated. To ensure that large bubbles do not form, thus reducing the effectiveness of the filter, the steam should probably enter the tank through many small openings. It was assumed that the water would remove almost all of the radioactive contaminants except for the noble gases which would be vented out a stack.

Compartment Venting

This alternative, shown in Figure 8, is similar, in principle, to the vacuum building used in the Canadian CANDU design. For this alternative, a separate, high pressure (60 psia) containment structure was assumed to be constructed, one per reactor site, into which the containment atmosphere would be vented in the event of a core-meltdown accident. As in the filtered atmospheric

venting alternative, venting was assumed to be achieved automatically by opening valves in the connecting piping when containment pressure rises to near design pressure. The auxiliary containment was assumed to be equipped with an elevated water tank which would spray by gravity feed upon sensing a rise in pressure. This spray would condense the incoming steam and allow further pressure reduction in both structures. Spray openings would be sized to spray until the molten core would be expected to have melted through the base mat, thus relieving containment pressure to the ground. The likelihood of overpressure failure would be expected to be greatly reduced.

Figure 7. Filtered Atmospheric Venting

Figure 8. Compartment Venting

Thinned Base Mat

The thinned base mat alternative is illustrated in Figure 9. Current plants have concrete base mats approximately ten feet thick. While no optimal thickness was determined, the concrete under the reactor pressure vessel does not appear to support any loads, so a significant reduction in thickness of the base mat appears feasible. In addition to hastening the melt-through process and thus reducing the overpressure failure probability of selected accident sequences, less noncondensable gases, in particular carbon dioxide and hydrogen, would be expected to be produced from the interaction of the core on the concrete.

Figure 9. Thinned Base Mat

Evacuated Containment

Many plants currently operate at pressures slightly subatmospheric to reduce the normal leakage of gases from the containment. The Surry reactor examined in the Reactor Safety Study operates at about 10 psia. To reduce the likelihood of hydrogen burning, the evacuated containment alternative, shown in Figure 10, was assumed to have about a 5 psia containment, resulting in about 1 psia partial pressure O_2 . Thus, a significant reduction of the chance of hydrogen ignition would be expected. Reduction of the internal pressure to this level should be possible using a steam powered vacuum pump.

Double Containment

The double containment alternative, illustrated in Figure 11, is used frequently in existing containments. The outer wall, however, generally can withstand only minor pressure differentials, its primary function being to protect the inner wall from external missiles. This study examined

strengthening the outer wall such that it would have a gas containment capability equivalent to the inner wall. Thus, failure of the inner wall would not necessarily lead to an escape of radioactivity. In the case of overpressure failure, however, it is likely the outer wall would soon be subjected to pressures similar to those exerted on the inner wall and, as a result, would also fail. To ensure that the concept of double containment was judged on its own merits, the volume within the outer wall was made equivalent to current plants; that is, no benefits resulting from increasing the volume of the containment were allowed. Despite this restriction, it appears that this alternative would offer some benefits in event of internal missiles and could reduce the likelihood of containment isolation failure because of redundant seals on the penetrations.

Figure 10. Evacuated Containment

Figure 11. Double Containment

CHAPTER V. VALUE ASSESSMENT

In considering the value of alternate containment designs, each alternative was considered separately. Combinations of alternatives could have been considered, but the objective was to evaluate each alternative on its own merits rather than to identify an optimal design combination.

Potential risk reduction resulting from implementation of the alternate containment designs was used as the principal measure of value. To determine the potential risk reduction for each alternative, the dominant PWR accident sequences from the Reactor Safety Study were analyzed for each design alternative assuming the design goals had been achieved. The containment failure modes and their probabilities for each sequence were determined, and the probability of each accident sequence was calculated for each alternative. Using these probabilities and the expected values of consequences given a release, the expected values of the risk were obtained as in Chapter II. The results for each alternative are discussed below.

The study concluded that the design alternatives resulting in the most significant potential risk reductions were Filtered Atmospheric Venting, Containment Venting, and Deep Underground Siting. Stronger Containment and Increased Containment Volume resulted in modest potential risk reductions. The remaining design alternatives did not meaningfully reduce the risk.

Filtered Atmospheric Venting

The evaluation of filtered atmospheric venting assumed that the pressures generated following an accident could successfully be relieved through the filtration system. As a result, overpressure failures and hydrogen burning failures would essentially be eliminated, and those sequences which would have caused containment failure by these modes would now cause containment melt-through failures. For purposes of determining potential risk reduction, it was assumed that no overpressure failures or hydrogen burning failures would occur. Since the melt-through sequences result in a much lower release category (category 6 rather than categories 2 or 3), the risks associated with the filtered atmospheric venting alternative would be considerably less. Results of the calculation of the expected values of the risks for this alternative, by containment failure mode, are given in Table XI. As can be seen, the expected values of both early fatalities per year and latent cancer fatalities per year per year could potentially be significantly reduced. The potential property damage risk would be only modestly reduced due to the high cost of evacuation which is assumed to take place for the melt-through accidents. Allowing a failure rate of 0.01 for the venting system did not noticeably affect the risk results.

TABLE XI
Expected Values of Risk for Filtered Atmospheric Venting

Containment Failure Mode	Early Fatalities/Yr	Latent Cancer Fatalities/Yr/Yr	Property Damage/Yr
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
β	~ 0	4.2×10^{-7}	~ 0
γ	0	0	0
δ	0	0	0
ϵ	0	1.5×10^{-5}	7.7K
Category 9	0	0	0.7K
	2.9×10^{-6}	4.3×10^{-5}	9.0K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

* excluding check valve rupture sequence

Compartment Venting

The compartment venting alternative appears to offer a similar potential for reducing the public risk. Rather than some gases escaping through the stack as in the previous alternative, however, all radioactive products are assumed to be retained in the auxiliary and primary containments. Some difference in consequences between these alternatives would result, but this was not pursued in this study. Again, it was assumed overpressure and hydrogen burning failures would essentially be eliminated with a subsequent increase in melt-through failures. Results of the risk calculations, shown in Table XII, are the same as for the previous alternative. A potentially significant reduction in fatality risks appears to exist along with a modest reduction in property damage risk. It may be added that some active components, e.g., valves, must operate for each of these alternatives. Allowing a failure rate of 0.01 for the system did not noticeably affect the risk results.

TABLE XII
Expected Values of Risk for Compartment Venting

Containment Failure Mode	Early Fatalities/Yr	Latent Cancer Fatalities/Yr/Yr	Property Damage/Yr
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
β	~ 0	4.2×10^{-7}	~ 0
γ	0	0	0
δ	0	0	0
ϵ	0	1.5×10^{-5}	7.7K
Category 9	0	0	0.7K
	2.9×10^{-6}	4.3×10^{-5}	9.0K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

*excluding check valve rupture sequences

Deep Underground Siting

The lithostatic pressure of the overburden for the deep underground siting alternative should add approximately 100 psi pressure capability to the containment. As a result, those sequences in which the maximum pressure only slightly exceeds the design pressure of surface containments would probably be contained and would result in melt-through failures. Complete failure of containment as a result of missiles generated by steam explosions would also be unlikely. For those high pressure sequences discussed previously in which the containment spray systems fail, it was assumed that the seals in the access passages would fail under the high pressures (several hundred psi), resulting in a puff release at the surface with consequences similar to normal overpressure failures. These sequences were called containment isolation failures (β) and were assigned to release category 2 or 3 depending on the sequence. While the seals may fail under high pressures, the existence of two sets of seals would significantly reduce the probability of containment isolation failure for reasons other than high pressure. The possibility of the containmant structure failing with subsequent filtration of the release by the overburden was not considered in detail. The results of the risk calculations are shown in Table XIII. The early fatality risk would potentially be reduced significantly. The latent cancer fatality risk would be predicted to be modestly reduced; much of the latent cancer fatality risk arises from the overpressure failure mode which would still remain in the form of high pressure containment isolation failures. The property damage risk would be only slightly reduced as a result of the high evacuation cost. The consequence calculation for the melt-through case was not redone even though the release would be several hundred feet underground. In addition, the influence of impermeable versus permeable rock external to containment was not considered.

TABLE XIII
Expected Values of Risk for Deep Underground Siting

<u>Containment Failure Mode</u>	<u>Early Fatalities/Yr</u>	<u>Latent Cancer Fatalities/Yr/Yr</u>	<u>Property Damage/Yr</u>
α	0	0	0
β	3.6×10^{-6}	1.5×10^{-4}	3.0K
γ	0	0	0
δ	0	0	0
ϵ	0	1.1×10^{-5}	7.1K
Category 9	0	0	0.7K
	3.6×10^{-6}	1.6×10^{-4}	10.8K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

*excluding check valve rupture sequence

Stronger Containment

The stronger containment was assumed to be designed for a pressure of 120 psia. As such, only those LOCA sequences in which the containment spray systems fail but the ECCS operates would be expected to fail the containment by overpressure. All other overpressure and hydrogen burning sequences should be contained and ultimately result in melt-through failures of less consequence. In this alternative and in many of the others, the failure of the containment due to overpressure would be delayed resulting in increased evacuation time and a potential decrease in early fatalities. This delay time, however, has not been considered in the calculations. Results of the calculation of the expected values of the risk for this alternative are given in Table XIV. The potential early fatality risk reduction would be significant whereas the potential reduction in latent cancer fatality and property damage risks would be more modest.

TABLE XIV
Expected Values of Risk for Stronger Containment

<u>Containment Failure Mode</u>	<u>Early Fatalities/Yr</u>	<u>Latent Cancer Fatalities/Yr/Yr</u>	<u>Property Damage/Yr</u>
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
β	~0	4.2×10^{-7}	~0
γ	0	0	0
δ	3.6×10^{-6}	1.5×10^{-4}	3.0K
ϵ	0	1.1×10^{-5}	7.1K
Category 9	0	0	0.7K
	6.5×10^{-6}	1.9×10^{-4}	11.4K
Current Plants ²²	3.7×10^{-5}	4.1×10^{-4}	18.2K

* excluding check valve rupture sequence

Increased Containment

The increased containment volume alternative was assumed to have design goals similar to the stronger containment discussed above. As such, the potential risks calculated for this alternative, shown in Table XV, would be the same as for the stronger containment alternative.

TABLE XV
Expected Values of Risk for Increased Containment Volume

<u>Containment Failure Mode</u>	<u>Early Fatalities/Yr</u>	<u>Latent Cancer Fatalities/Yr/Yr</u>	<u>Property Damage/Yr</u>
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
β	~ 0	4.2×10^{-7}	~ 0
γ	0	0	0
δ	3.6×10^{-6}	1.5×10^{-4}	3.0K
ϵ	0	1.1×10^{-5}	7.1K
Category 9	<u>0</u>	<u>0</u>	<u>0.7K</u>
	6.5×10^{-6}	1.9×10^{-4}	11.4K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

*excluding check valve rupture sequence

Shallow Underground Siting

Placing the reactor slightly below grade, as suggested in the shallow underground siting alternative, would not appear to offer the potential for significant risk reduction, although the proposed 30 feet of overburden would somewhat reduce the risk from overpressure failure. It is not known whether steam explosion generated missiles would penetrate both the containment and the overburden, but no credit for containing steam explosions was assumed in calculating the expected risk. As in the deep underground siting alternative, the possibility of filtration of the release by the overburden following failure of the containment structure was not considered in detail. For this alternative, however, such filtration was expected to be unlikely. Redundant seals should reduce the probability of containment isolation failure. Table XVI presents the results of the calculation of expected risks. Only modest potential reductions in risk are expected for all three types of risk considered.

Evacuated Containment

Evacuating the containment was assumed to successfully reduce the probability of hydrogen burning but was not expected to significantly affect the other containment failure modes. Although reducing the pressure of the containment to around 5 psia would remove much of the air and, hence, the pressure in containment due to this component following accident initiation, air is predicted to contribute little to the pressure at the time of containment failure. As shown in Figure 2, the principal components to the pressure are predicted to be steam and noncondensable gases. As a result, evacuating containment was expected to have a minimal effect on the overpressure failure mode. Although normal leakage from the plant could be somewhat reduced, this was not considered in the probability for containment isolation failure. This alternative also would not be expected to impact the vessel steam explosion probability. Results of the calculation of the expected values of

risk are shown in Table XVII. Only minimal potential reductions in risk are expected to be realized by implementing this alternative.

TABLE XVI
Expected Values of Risk for Shallow Underground Siting

Containment Failure Mode	Early Fatalities/Yr	Latent Cancer Fatalities/Yr/Yr	Property Damage/Yr
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
β	~0	~0	~0
γ	4.4×10^{-6}	3.2×10^{-5}	1.0K
δ	1.5×10^{-5}	2.3×10^{-4}	5.6K
ϵ	0	8.8×10^{-6}	6.9K
Category 9	0	0	0.7K
	2.2×10^{-5}	3.0×10^{-4}	14.7K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

* excluding check valve rupture sequence

TABLE XVII
Expected Values of Risk for Evacuated Containment

Containment Failure Mode	Early Fatalities/Yr	Latent Cancer Fatalities/Yr/Yr	Property Damage/Yr
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
β	0	4.2×10^{-7}	~0
γ	0	0	0
δ	2.3×10^{-5}	2.9×10^{-4}	7.6K
ϵ	0	8.5×10^{-6}	6.8K
Category 9	0	0	0.7K
	2.6×10^{-5}	3.3×10^{-4}	15.7K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

* excluding check valve rupture sequence

Double Containment

Double containment, like the underground siting alternative, would be expected to reduce the containment isolation failure probability as a result of redundant penetrations. As discussed previously, this alternative would appear to offer some increased protection from containment failure due to missiles generated by vessel steam explosions. The reduction in probability of this

containment failure mode is highly uncertain, but this study assumed a reduction by a factor of ten. The results, however, are not very sensitive to this assumption. As can be seen in Table XVIII, the vessel steam explosion failure mode is not predicted to be a large contributor to any of the risks. The double containment alternative would offer almost no potential reduction in risk over current surface plants.

TABLE XVIII
Expected Values of Risk for Double Containment

Containment Failure Mode	Early Fatalities/Yr	Latent Cancer Fatalities/Yr/Yr	Property Damage/Yr
α	1.1×10^{-6}	5.0×10^{-6}	0.1K
β	~ 0	~ 0	~ 0
γ	8.1×10^{-6}	5.9×10^{-5}	1.9K
δ	2.6×10^{-5}	3.2×10^{-4}	8.4K
ϵ	0	6.5×10^{-6}	6.6K
Category θ	<u>0</u>	<u>0</u>	<u>0.7K</u>
	3.5×10^{-5}	3.9×10^{-4}	17.7K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

* excluding check valve rupture sequence

Thinned Base Mat

The final design alternative considered, thinning the base mat, would appear to offer no measurable reduction in risk. For those LOCA sequences in which the containment spray systems fail but the ECCS operates, the containment is predicted to fail by overpressure before core melt begins. This alternative would not affect these sequences. For those sequences in which the core melts but containment heat removal capability is not lost, the sequences already have been categorized as melt-through failures. Thinning the base mat would hasten melt-through in these cases but would not change the basic containment failure mode. While hastening melt-through in these cases may reduce the evacuation time and thereby possibly increase the potential early fatality risk, this possibility was not considered here. For those sequences in which core melt occurs and long-term containment heat removal is lost, the overpressure failure and melt-through failures are predicted to occur on similar time scales, around 20 hours after accident initiation. For these cases, thinning the base mat would be expected to reduce the likelihood of overpressure failures. These sequences, however, involve multiple system failures (emergency coolant injection or recirculation failure in conjunction with containment heat removal system failure) and, as a result, are low probability sequences contributing insignificantly to the risk. Table XIX shows the expected values of the risk for this case. A negligible potential reduction in risk over current plants was calculated. Site dependent properties such as the permeability of the foundation rock were not considered in this analysis, but they would have little influence on this type of an evaluation.

TABLE XIX

Expected Values of Risk for Thinned Base Mat

<u>Containment Failure Mode</u>	<u>Early Fatalities/Yr</u>	<u>Latent Cancer Fatalities/Yr/Yr</u>	<u>Property Damage/Yr</u>
α	2.9×10^{-6}	2.8×10^{-5}	0.6K
β	~ 0	4.2×10^{-7}	~ 0
γ	8.1×10^{-6}	5.9×10^{-5}	1.9K
δ	2.6×10^{-5}	3.2×10^{-4}	8.4K
ϵ	0	6.5×10^{-6}	6.6K
Category 9	0	0	0.7K
	3.7×10^{-5}	4.1×10^{-4}	18.2K
Current Plants*	3.7×10^{-5}	4.1×10^{-4}	18.2K

* excluding check valve rupture

Table XX summarizes the results discussed above. The alternatives fall into three groups for each risk. For early fatalities, the groupings are as follows:

Significant Potential Risk Reduction:	Deep Underground Siting Filtered Atmospheric Venting Compartment Venting
Modest Potential Risk Reduction:	Stronger Containment Increased Containment Volume
Marginal Potential Risk Reduction:	Thinned Base Mat Double Containment Evacuated Containment Shallow Underground Siting

For latent cancer fatalities, the groupings are as follows:

Significant Potential Risk Reduction:	Filtered Atmospheric Venting Compartment Venting
Modest Potential Risk Reduction:	Stronger Containment Increased Containment Volume Deep Underground Siting
Marginal Potential Risk Reduction:	Thinned Base Mat Double Containment Evacuated Containment Shallow Underground Siting

Only deep underground siting changes groups. This is due to the relative contribution to the latent cancer fatality risk of high pressure sequences (those which cause the access passages to fail by overpressure) being greater than their relative contribution to the early fatality risk.

TABLE XX
Relative Risk for Alternate Containment Designs
Normalized to Current Surface Plants

	Early Fatalities		Latent Effects	
	Expected Value	Maximum* Calculated Value	Expected Value	Maximum* Calculated Value
Current Surface Plants	1.00	1.00	1.00	1.00
Thinned Base Mat	1.00	1.00	1.00	1.00
Double Containment	0.91	1.00	0.91	1.00
Evacuated Containment	0.71	0.91	0.83	0.83
Shallow Underground Siting	0.59	0.83	0.71	0.77
Increased Containment Volume	0.18	0.40	0.45	0.56
Stronger Containment	0.18	0.40	0.45	0.56
Deep Underground Siting	0.10	0.30	0.38	0.45
Compartment Venting	0.08	0.29	0.11	0.43
Filtered Atmospheric Venting	0.08	0.29	0.11	0.43

*The maximum calculated value is the value of the consequence that occurs with a probability of 10^{-9} per year.

Complementary Cumulative Distribution Functions

Complementary cumulative distribution functions, showing the probability distribution for various consequences, were constructed for the early fatality risk and the risk from latent cancer fatalities. These are calculated from the conditional probability distribution of the consequences for each release category and the probability of each release category. That is, for a given consequence, C_j , for each release category, i , the consequence model calculates a conditional probability, $P(C_j|i)$. Analysis of the accident sequence probabilities results in the probability of each release category, $P(i)$. To obtain the absolute probability of having a consequence $C \geq C_j$ for a PWR, one performs the following summation:

$$\sum_{i=1}^9 P(C_j|i) P(i) .$$

The complementary cumulative distribution function (CCDF) is the locus of points resulting from considering all C_j . These curves are shown in Figures 12 and 13. The baseline case shown is the CCDF from the Reactor Safety Study with the check valve sequence eliminated. The shaded region depicts the uncertainty band associated with the baseline case. The CCDF's for each group previously discussed are shown. As can be seen, all but one of these curves lies within the predicted

uncertainty band associated with current surface plants. Thus, only the alternatives in this group - deep underground siting, filtered atmospheric venting, and compartment venting - appear to offer the potential for significant reductions in public risk.

Figure 12. Probability Distribution for Early Fatalities per Reactor Year

Figure 13. Probability Distribution for Latent Cancer Fatalities per Reactor Year

CHAPTER VI. IMPACT ASSESSMENT

There are several ways of measuring the impact of alternate designs. This study considered the following:

Impact on construction costs.

Impact of regulatory delay and extended construction schedules.

Impact on normal plant operation.

Deviation from current designs.

It is difficult to quantify all of these factors. Ultimately the impact assessment of alternate designs was based on the factors which could be quantified along with a listing of nonquantifiable factors. It should be noted that those alternatives having the highest cost also had the longest list of non-quantifiable impact factors. While the cost estimates used should be satisfactory for ranking the alternatives, they should not be considered accurate actual cost estimates; the timescales of the study did not permit detailed economic analysis of the alternatives.

Filtered Atmospheric Venting

The filtered atmospheric venting alternative envisioned here was assumed to involve adding a modest-sized water tank external to the existing structure. As such, the impact on the existing containment designs was assumed to be minimal, requiring only the addition of piping equipped with relief valves to channel the containment contents to the tank if the pressure reaches the containment design pressure. The tank itself was not assumed to be elaborate. It could well be possible to use the tank for more than one unit per site. No construction delays or plant reconfiguration are anticipated, and no technological advances would appear necessary. There would, however, be increased maintenance and testing associated with the system. The final assessment of this alternative is that the impacts would be minimal compared to the other alternatives. Assuming a simple tank design, the cost associated with implementing the alternative is estimated to be on the order of a few million dollars per plant.

Compartment Venting

If venting to another compartment were to be implemented, an additional containment structure similar to present containments is assumed to be required at each site. One such structure could potentially serve more than one unit, so one per site may be sufficient. The impact on existing designs would again be expected to be minimal, requiring only additional piping with valves running from the containment to the auxiliary compartment. The additional structure was assumed to cost about the same as existing containments, on the order of \$20 million. It is likely that the

auxiliary containment would have to be completely finished and tested before startup is permitted. To avert a possible extension in construction schedule, additional manpower would be required during construction, especially for a multiple unit site. It is expected, however, that such a delay could be averted. As before, no significant redesign of containment systems or plant configuration would be anticipated and no advanced technological requirements have been identified. Testing and maintenance similar to that for existing containments would probably be required for the auxiliary containment but, once completed, the impacts on normal plant operation are expected to be minimal. Assuming that no extension in construction schedule is required, the cost impacts are estimated to be on the order of \$20 - \$40 million.

Deep Underground Siting

In contrast to the previous alternatives, deep underground siting is expected to result in major impacts on existing designs. The containment is assumed to be covered by about 100 feet of overburden; thus, excavation at least 300 feet below grade would be required. In addition to the increased difficulties of construction, the additional piping and electrical wiring required if the turbine generator were located on the surface would increase the materials cost. The most severe cost impact expected would be the extended construction schedule: a two year extension was used for impact estimates. Such an extension could cost well over \$100 million in increased capital costs and escalation. This cost would be expected to dominate other cost increases. Additional regulatory delays may result, at least for the first plant of this kind. Plant access and personnel mobility may be impaired with potential major impacts on normal plant operation. Finally, the implementation of this alternative would necessitate a complete redesign of plant configuration and probably many plant systems. The impacts of this alternative would be greater than any of the other alternatives considered; in monetary terms alone this alternative was estimated to cost from \$200 - \$400 million per plant depending on the type of underground alternative chosen. A detailed discussion of the impacts of various underground siting concepts such as rock excavation versus cut-and-cover may be found in a recent underground siting study.*

Stronger Containment

The stronger containment alternative was assumed to involve increasing the thickness of the walls. This would entail additional material costs, primarily concrete and steel reinforcement. The structure would require some redesign, particularly in the posttensioning system. The many penetrations and seals could require major modification and may well be more difficult to design since, at present, there are no supports within the wall for the penetrations. Support could be necessary if the thickness of the walls were significantly increased. This design alternative appears to have several advantages. No reconfiguration of the plant would be expected, no technological advances would appear necessary, and little impact on normal plant operation would result. This would also be a completely passive system. Assuming no extension of construction schedules, the cost associated with this alternative was estimated to be modest, on the order of \$15 - \$25 million.

*"Underground Siting of Nuclear Power Plants: Potential Benefits and Penalties," SAND76-0412, NUREG-0255.

Increased Containment Volume

Increasing the containment volume is similar to the stronger containment alternative in many respects. Both would be completely passive with minimal expected technological and operational impacts. The increased wall area would add to the construction cost. In addition, the steel liner would have to be enlarged. While a larger building would be constructed, it was assumed this would not result in increased construction time or regulatory delays. Work could be carried on in other areas while the larger containment is under construction. There may, however, be a complete reconfiguration of the containment internals and a resultant impact on equipment and piping. The cost for this alternative was estimated to be similar to the previous alternative, perhaps around \$20 - \$30 million. The increased cost estimate over the stronger containment alternative was due primarily to the increased liner cost.

Shallow Underground Siting

Many of the impacts identified for deep underground siting would apply, to a lesser extent, to the shallow underground siting alternative. Again, significant excavation to around 200 feet was assumed to be required. A major redesign of plant features may be desirable to minimize the costs of extra piping and wiring. Access and personnel mobility may be more restrictive than for current surface plants, thus impacting the normal operation of the plant. It is expected that conventional construction techniques could be used, but that an extension of the construction schedule of one to two years may be required. Associated with this would be significant capital and escalation costs, perhaps on the order of \$100 million. While not expected to be as costly as the deep underground siting alternative, the increased costs, estimated to be \$100 - \$200 million, would be significant.

Evacuated Containment

Among the least costly alternatives considered was evacuation of the containment. There would be little impact on the plant configuration and no new technological developments. Some aspects of the containment would have to be examined to assure that external pressure requirements were met. The equipment necessary to maintain the vacuum exists and should be available at minimal additional cost with no anticipated construction delays. The greatest impact of this alternative would probably be from an operational viewpoint. This active system would entail increased maintenance and operational costs. In addition, access to the containment may be more limited. There could also be problems with equipment functioning in a reduced pressure environment. From strictly a cost standpoint, however, this alternative should exhibit a minimal impact of perhaps only a few million dollars per plant.

Double Containment

Double containment, as envisioned in this study, would require the construction of another containment wall inside the existing containment structure. This passive system would be expected to require minimal reconfiguration of the plant layout but would probably necessitate a major redesign of the containment and the equipment layout therein. The smaller containment volume may

inhibit mobility within containment and thus adversely affect the normal operation of the plant. While no extended construction schedule would be anticipated, the increased complexity of construction of the double wall and emplacement of the structures therein could add significantly to the cost of construction. It was estimated that this alternative could be implemented at a modest cost of perhaps \$20 - \$30 million.

Thinned Base Mat

The thinned base mat alternative would probably cost less than any of the alternatives considered. This passive system would be expected to impact the plant in very few ways. It may, in fact, cost less to construct than current plants. A new containment foundation design would be necessary but this appears to be the only significant adverse impact of this alternative. Implementation of this alternative would be expected to entail minimal increased cost, perhaps a few million dollars.

Table XXI summarizes the results of the impact portion of this study. Filtered atmospheric venting, evacuated containment, and thinning the base mat would appear to be the least costly alternatives. The underground siting alternatives, both shallow and deep, would entail the most significant cost impacts primarily due to anticipated construction schedule extensions associated with these alternatives.

TABLE XXI

Potential Impacts of Alternate Designs

	<u>Increased Construction Cost</u>	<u>Extended Construction Schedule</u>	<u>Significant Regulatory Delay</u>	<u>Active Components</u>	<u>Significant Design Modifications</u>	<u>Potential Technological Developments</u>	<u>Impact Normal Operations</u>	<u>Potential Multiple Use</u>	<u>Cost Estimate (10⁶ \$)</u>
Filtered Atmospheric Venting	X			X				X	0-10
Compartment Venting	X	Possibly		X				X	20-40
Deep Underground Siting	X	X	X	X	X	X	X		200-400
Stronger Containment	X				Some				15-25
Increased Containment Volume	X				Some				20-30
Shallow Underground Siting	X	X	X		X		X		100-200
Evacuated Containment	X			X			X		0-10
Double Containment	X				X		X		20-30
Thinned Base Mat					X				0-10

CHAPTER VII. CONCLUSIONS

The results of this study are presented in the form of a qualitative value-impact matrix shown in Figure 14. From this matrix it is apparent that, among the alternatives considered, filtered atmospheric venting offers the greatest potential for reducing public risk for the least impact. Compartment venting and deep underground siting offer similar potential for reducing public risk but greater impacts. Evacuated containment and thinned base mat, while being low impact alternatives, offer little potential for reducing public risk. Combinations of alternatives were not considered. Each alternative was evaluated on its own merits rather than attempting to identify an optimal design combination.

Figure 14. Qualitative Value-Impact Matrix

To place these results in proper perspective, several points need to be made. These results are based primarily on risk insights from WASH-1400 which considered only two reactors. Although efforts have been made to eliminate atypical characteristics of these plants, the results of this study should be treated only as indicative of what might be found in a broader study. The basic

premise that overpressure failures dominate risk should, however, be true in general. Although care was taken to define feasible reference designs, the scope of the study did not allow detailed feasibility studies. Before a decision to implement any of these alternatives, detailed studies are recommended of the particular alternatives considered.

The risk reductions presented should be regarded only as potential risk reductions. Eliminating some of these containment failure modes may reduce the probabilities such that other factors, previously determined to be insignificant risk contributors in the Reactor Safety Study and thus not studied in detail, now may become more important and, perhaps, could dominate the risk. Finally, the broader question of whether any alternate containment design to reduce public risk is justified was not addressed. If however, alternate containment designs are seriously considered, it is believed that this study identifies those design alternatives which would most merit further attention.