

On The Issue of Integrated Risk – A PRA Practitioners Perspective

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Abstract – *The issue of integrated risk was raised by the NRC staff in the course of developing a risk informed technology neutral framework for licensing new reactors. This issue was framed in the context of proposals to design and license so-called modular reactor plants in which a number of small reactors are combined to produce electric power capacities comparable to that of current generation large reactor plants, e.g. 1300Mwt. In the NRC staff and ACRS deliberations on this issue various options were devised and proposed based on past interpretations of the NRC safety goal policy statement. It is the opinion of the author that some of the conclusions that have been made in the discussion of this issue both for existing multi-unit sites and proposed modular reactors have not adequately considered the risk of multi-reactor accidents on the same site. Such accidents have been largely ignored in Probabilistic Risk Assessments that support most of the risk informed applications. In this paper, the author will develop somewhat different conclusions about the integrated risk issue including a somewhat different interpretation of the NRC safety goal policy statement.*

I. INTRODUCTION

The current fleet of operating reactors includes some sites with a single reactor, and many others with two or as many as three reactor units. The multi-unit sites include those with essentially separate facilities as well as several that employ highly integrated and shared support systems. Some have the capability to cross connect the emergency core cooling systems and others have shared control rooms. In the future, there is a potential of building more reactor units on these same sites. Some of these may be modular reactor plants with a collection of upwards of 4 to 8 reactor modules that share some supporting and auxiliary systems and structures.

The purpose of this paper is to review some of the technical issues associated with the risks of multiple reactor sites in applying the NRC safety goals and in advancing risk informed regulation. One particular issue, the treatment of the risks of accidents involving more than one reactor core, is identified as being given inadequate consideration in the current discussion on integrated risk.

I.A. Review of Recent NRC and ACRS Policy Discussions

The NRC Safety Goals and associated Quantitative Health Objectives include the following criteria for acceptable levels of risk to individuals who live near nuclear power plants¹:

“The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1%) of the sum of prompt fatality risks resulting from other accident to which members of the U.S. population are generally exposed.”

“The risk to the population in the area of nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1%) of the sum of cancer fatality risks resulting from all other causes.”

The concept of what is meant by the term “plant” referred to here is open to interpretation. By looking at titles of Safety Analysis Reports for Multi-unit facilities such as Byron, Braidwood, Sequoyah, and South Texas, it would appear that the authors of these reports have equated the term “plant” with a facility having multiple reactor units. As noted in SECY 05-0006² the NRC staff has often applied to term plant to individual reactor units on a site, but acknowledged that the definition of plant vs. site was open to interpretation²:

“Traditionally, it has been the staff’s practice in making risk-informed decisions to consider risk on a per plant basis. This has been considered reasonable because of the limited number of plants on a site (maximum 3) and because of the low risk generally posed by currently operating plants, as indicated by staff and industry studies (e.g., NUREG-1150, Individual Plant Examination Program). However, it is recognized that the population around a site is exposed to the hazard of everything that is on that site. In promulgating the Safety Goal Policy in 1986 both the term “plant” and “site” were used. Whether this was intended to address integrated risk or not is not clear, but is a consideration with respect to how to treat integrated risk.

Nevertheless, with the potential for modular reactors in the future it is appropriate to consider when and how (if at all) integrated risk should be addressed,

since the number of reactors on a site could be significantly more than three.”

Hence, the staff seems justified in ignoring integrated risk for current sites, but seems to realize it may become an issue with future modular reactor facilities based on the number of reactor units. In SECY 05-006, the staff proposed that the integrated risk from modular reactor designs be more explicitly considered in the development of a technology neutral framework for new reactors:

“For modular reactor designs, the staff has developed a proposed position (i.e., Option 3 discussed in Attachment 2) and has incorporated it into the framework. Specifically, the integrated risk from multiple reactor modules (where several small reactors are used to generate the electrical output of one large reactor) will be considered in risk-informed licensing decisions as follows:

- *The integrated risk will assess accident prevention for modular reactor designs, independent of reactor power level.*

- *The integrated risk will account for the effect of reactor power level in assessing accident mitigation for modular reactor designs.”*

The other options considered by the staff included maintaining the status quo in Option 1 and a partial approach to integrated risk in Option 2 in which the core damage frequency goal for existing plants is divided into sub-goals for each reactor module in a modular plant while ignoring the fact that the consequences of core damage from small cores would be less than those from large cores. In their review of this issue, the ACRS came to the following observations and conclusions³:

“1. The Quantitative Health Objectives (QHOs) apply to the site as a whole. The sum of the contributions from each reactor on the site to acute and latent fatalities should be bounded by the QHOs.

2. The Committee has not reached consensus on the approach that should be taken to determine the core damage frequency (CDF) goal. Two views are presented in the discussion below.”

II. OPEN QUESTIONS ON INTEGRATED RISK

At this juncture the author wishes to point out that it is not clear exactly what the staff has in mind for Option 3 as how integrated risk should be taken into account. The focus on metrics for prevention and mitigation is difficult for this author to understand in light of some points that are to be made in this paper. What the ACRS has in mind is easier to understand, but there are still open questions in interpreting their views on the matter. The open questions raised by both positions include the following:

1. Were the original safety goal QHOs intended to apply to the entire site or to individual reactors for the currently licensed reactors?
2. How are the risks from accidents involving more than one reactor on the same site to be taken into account?
3. How are the risks from currently licensed reactors and proposed new reactors, modular or otherwise to be combined if the safety goal is to be applied to the site?
4. How can PRA results that have been limited to scenarios involving single reactor accidents be used to justify the current single reactor treatment of the safety goal?

II.A. Safety Goal QHOs for the Reactor or Site?

This author can only speculate about the intent of the safety goal QHOs as to whether they were intended to apply to the site as a whole or to individual reactors. However, simple logic would indicate that the QHOs should in fact be applied to the entire site, as indicated in the previous NRC staff quotes. The population living in the vicinity of a reactor site is exposed to the sum of the risks from all the different types of accidents from all the reactors that could occur on that site. This includes the separate contributions from each reactor in the case of single independent reactor accidents as well as accidents involving damage to and resulting source term from more than one reactor. Moreover, if new reactor units are added to a given site, modular or otherwise, the individual risks from reactor accidents near the site will increase, and hence should be taken into account when applying the QHOs.

The NRC staff has justified the historical treatment of QHOs as being applied to individual reactor risk metrics based on a line of argument that seems reasonable, but unconvincing. The ACRS statement seems to reinforce the idea that QHOs should be applied to the site. However it is not clear that either the NRC staff or the ACRS positions have adequately considered the risk contribution from multiple reactor accidents. Most of the technical dialogue on this topic seems to be focused on how to manipulate the results from separate PRAs on each reactor. The ACRS statement talks about summing the risks from each reactor before applying the QHOs but does not mention the role multiple reactor accidents on the same site. The NRC staff acknowledges such multi-reactor accidents in the technical discussion of the issue, but the argument for justifying single reactor treatment of the QHOs for current plants does not appear to account for this contribution to risk.

The NRC acknowledgement of different types of accidents is noted in the following statement from the issue paper²:

“It should also be noted that in assessing the risk from plants consisting of multiple reactor modules, the event sequences that contribute to risk will generally fall into two basic categories (1) those that affect each reactor module individually and (2) those that can affect two or more modules simultaneously (e.g., seismic events). Accordingly, the overall risk from a plant comprised of multiple reactor modules consists of the sum of the risk from both categories, and may be lower than the sum of the risk from all modules if they were treated separately, particularly if some systems are shared among reactor modules. This would be due to the fact that the risk from event sequences that affect all reactor modules simultaneously may not be equal among the reactor modules.”

The above statement accounts for multiple reactor accidents, but this definition is true for existing multi-reactor sites as well as those where future modular reactors might be built. Hence, it does not appear that such accidents were taken into account in the justification for why the QHOs could be applied to single reactor PRA results for the existing fleet of plants. In addition, it is not clear whether multi-reactor accidents were considered in the statement about how the results might be combined.

As noted by the NRC staff, It has been common practice in the application of the safety goals to consider the assessment of risk and the evaluation of the acceptability of the level of risk on an individual reactor basis. This practice is fundamental to the logic that has been used to derive relationships between the QHOs and the surrogate risk metrics of core damage frequency and large early release frequency. This logic is supported by a body of work in the application of PRA in which only single reactor accidents were considered. Indeed, there are no requirements in the current PRA standards or procedures in the currently available PRA procedure guides to account for the possibility for multiple reactor accidents.

II.B. How are multi-reactor accidents to be taken into account?

Our current state of knowledge about the risks from accidents is derived from PRAs. For the most part PRAs on multi-unit sites have been performed on individual reactors separately. In fact, some multi-unit sites have performed a PRA only for one of the sited reactors, arguing that symmetry considerations justify a single reactor PRA. In order to meet expectations for PRA quality, as defined in the various PRA standards, such PRAs must address certain multi-unit dependencies in the modeling of risks that involve damage to a single reactor. The capability to use equipment from one reactor to back up failures on another is typically considered, however

the probability that resources are consumed by concurrent reactor accidents is almost always ignored.

There have been few PRAs investigate the potential for event sequences that may involve accidents on two or more reactors concurrently. One example is the original Seabrook PRA which included a limited investigation of such sequences in the context of a full scope Level 3 PRA for sequences initiated from full power operation. Full scope means that initiating events caused by a full spectrum of internal and external hazards were included. Results and insights from that study are presented in Section III. As will be seen, the risks from accidents involving two or more reactors on the same site cannot be dismissed and must be taken into account even if the degree of shared systems is minimized.

II.C. QHO Contributions from Existing and New Reactors?

It is likely that most if not all of the next fleet of new reactors will be built on one or more of the existing licensed reactor sites in view of the additional costs and effort that will be required to approve new sites. When a new reactor is added to an existing site, modular or otherwise, the risks to individuals surrounding the site will increase, all other factors being equal. It seems reasonable to assume that safety goal QHOs should be applied to the site as a whole in this instance as well. Indeed, there may event sequences that could impact a combination of a new and an existing reactor or reactors that would need to be considered. If an accident were to occur on one of the sited reactors initially, there would be at a minimum control room habitability issues to contend with on the other reactors. It may be difficult to support the argument that design basis events for each reactor can be established independently.

II.D. Role of single Reactor PRAs?

In the view of the author, the body of work involving PRAs that assume core damage can only occur on one reactor at a time cannot be used as a basis to justify why QHOs have been applied thus far to each reactor independently. The reasons for this view will be evident from the information presented in the next section.

III. INTEGRATED RISK RESULTS FOR SEABROOK

III.A Overview

The first PRA results for Seabrook Station were published in 1983 prior to the cancellation of Unit 2 and prior to the issuance of an operating license for Unit 1⁴. The project specification called for a state-of-the art PRA which was eventually used to address emergency planning issues that delayed the licensing of that plant. It

was a Level 3 PRA of accidents initiated from full power and full treatment of internal and external hazards such as fires, floods, and seismic events. The PRA included a Level 3 quantification of the integrated risk from operation of both units.

A conceptual presentation of the integrated risk profile for a two unit station is provided in Figure 1 in the form complementary cumulative distribution function (CCDF) curves. Since the completion of the Reactor Safety Study⁵, the CCDF curve has been used to express the results of a Level 3 PRA. Each curve is in turn the sum of a set of curves for different accident sequences grouped into release categories. To produce these curves uncertainties in the estimation of event sequence frequencies, source terms, and consequences are taken into account. Single curves represent mean frequency values. For generality, the reactor units are not assumed to be identical in this figure, as they were at Seabrook. The combined risk of a two unit station is the sum of three curves; one for each of the single reactor accident cases, and one for the case of multi-unit accidents.

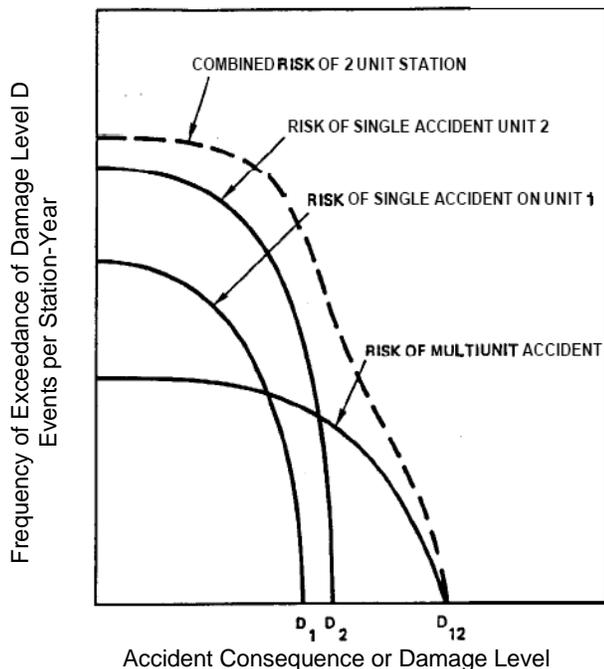


Figure 1 Integrated Risk of Two Unit Station

Since the original PRA for Seabrook was published there have been a number of updates to support the Individual Plant Examination (IPE) and the IPE for external events, and more recent updates to support various risk informed applications. The CDF results for the more recent updates are substantially lower than those developed in Reference 4 to account for risk management actions, design changes, modeling enhancements, and updates to incorporate various generic and plant specific data. However, some of the insights derived from the

original PRA are still valid when viewing the results from a relative perspective. Note that the updated PRA results did not include and integrated multi-unit risk assessment because Unit 2 was cancelled before the updates were performed.

There are a variety of initiating events such as certain loss of offsite power events, loss of service water events, and seismic events that lead to concurrent event sequences on two or more reactor units on a site. The question of multiple concurrent reactor accidents is not one of possibility but rather one of probability. The probability is significantly influenced by the use of shared and dependent systems, if this is a factor, as well as common cause failures in redundant systems the multi-unit sites. It was determined in the Seabrook PRA that multi-unit accident sequences made a significant contribution to multi-unit risk in comparison with the linear combination of single reactor accidents at each unit.

Unlike some existing multi-unit sites which have a more integrated and interdependent design of the plant support systems, the multi-unit plant originally designed for Seabrook included two essentially independent reactor units. While each unit had its own set of emergency diesel-generators and service water pumps, there was some small degree of shared equipment in the service water and circulating water intake structures and in electrical switchyard.

There are several key inter-unit dependencies at Seabrook Station that were found to influence the development of an integral risk statement.

These include:

- The sharing of some systems and hardware between Unit 1 and Unit 2. The most important examples are the offsite electric power system and the tunnels that supply service water and circulating water to both units.
- The added redundancy of equipment and manpower at the station to support either unit in the event that unit develops a problem.
- The planned overlap of the initial stage of Unit 1 operation and the later stage of Unit 2 construction.
- The physical proximity of the two units, separated by some 500 feet, to certain external hazards (e.g., earthquakes and external floods).
- The potential for common cause failures of systems or components at both units due to causes other than external hazards (e.g., design errors, maintenance errors repeated on both units). This potential influences the likelihood of concurrent accidents on both units.

Each of the above factors has an influence on the likelihood of potential accidents at the station and the list includes factors having positive as well as negative effects. The possibility of multiple reactor accidents at the same time or different times in the same year also affects

the magnitude of consequences to be factored into the risk curves for the combined two reactor unit station.

III. B Treatment of Dual Reactor Initiating Events and Event Sequences

The PRA was first completed for Unit 1 and then information from the Unit 1 PRA was used to construct a simplified model for the integrated risk from the two unit station to cover the time period both units were in operation. The subsequent extension of the PRA to include events initiated during low power and shutdown modes occurred after Unit 2 was cancelled.

Table 1 Classification of Initiating Events for Integrated Risk Model

Category	Initiating Events
Events Impacting Both Units	<ul style="list-style-type: none"> • Loss of Offsite Power • Seismic Events • Tornado and Wind • External Flooding • Truck Crash in Switchyard
Events Impacting Both Units under certain conditions	<ul style="list-style-type: none"> • Loss of Condenser Vacuum • Loss of Service Water • Turbine Missile
Events impacting each unit independently	<ul style="list-style-type: none"> • Loss of Coolant • General Transients • Loss of Component Cooling • Loss of one DC bus • Internal fires • Internal floods • Aircraft crashes

The first step in completed in the integrated station risk model was to review the list of initiating events to identify those that would have the potential to impact both units concurrently. The list of initiating events from the single unit PRA was divided into three categories: those that would definitely impact both units; those that would impact both units under certain conditions; and those that would be expected to occur independently: The results of this evaluation are shown in Table 1.

The next step was to construct a plant model to develop the event sequences for initiating events that impact both units. An important aspect of this model is the treatment of common cause failures on redundant components in both units. In the case of seismic events, the usual conservative model was applied in which it is assumed that seismic failure of a given component represents the common cause failure of all the similar components using that same fragility curve. In the case of loss of offsite power events and truck crash into the transmission lines, a special model was developed that distinguished between common cause failures that impact both diesel generator units at one reactor unit, from

common cause failures that impact all 4 diesel-generators at the two unit station. In the dataset that was used to derive the diesel generator beta factors a total of 8 common cause events were found to be applicable to the Seabrook design. One of these events was judged to impact all 4 emergency diesel-generators, while the remaining 7 were found to impact two diesel generators on a given unit. Hence, an effort was made to refine the common cause treatment of emergency diesel generators so as not to mask the ability to distinguish between single and multiple reactor accidents. Unfortunately, the methods available did not permit that refinement in the case of seismic induced failures.

III.C Results for Integrated Core Damage Frequency

The results from the Level 1 part of the assessment are shown in Table 2. The results obtained for the calculation of core damage frequency provided some surprising results. It was not expected that multiple reactor accidents would have a significant frequency because the reactor units designed for Seabrook did not have a significant degree of shared systems. The initiating events found to be common to both reactors would be present at essentially any site. Nonetheless the frequency of events involving damage to both reactors was found to be less than an order of magnitude less frequent than the single reactor CDF value. Due to the relatively high contribution from dual reactor core damage scenarios, the total frequency of core damage at the two unit station was found to significantly less than that found by simply doubling the single reactor CDF result.

Table 2 Level 1 Results from Integrated PRA

Risk Metric	Mean Value
Single Reactor Unit CDF	2.3×10^{-4} /reactor-year
Two Unit Station CDF	
- Core damage to one reactor	4.0×10^{-4} /station-year
- Core damage to both reactors	3.2×10^{-5} /station-year
- Total	4.3×10^{-4} /station-year

Note that when presenting results for an integrated PRA for a multi-reactor site, the frequency basis needs to be defined carefully. In view of the contribution from multiple reactor accidents, it is not useful to measure frequencies on the traditional reactor year basis. Event sequence frequency results are most conveniently expressed on a per site year basis. Only the events that are assumed to occur on each unit independently, or single unit results, make sense in terms of per reactor year units. To combine all the results, the site year metric is most convenient.

One of the reasons for the relatively high contributions from dual reactor accidents was the fact that

at Seabrook, the single reactor results were dominated by the same list of initiating events that were found to impact both units. Loss of offsite power was the dominant initiating event in the single reactor PRA results. If the single reactor CDF result had been dominated by independent events such as loss of coolant accidents, the relative contribution from dual unit events would have been much less.

It is also necessary to define what is meant by the term “core damage frequency” in the context of integrated risk. The frequency of core damage at the two unit station planned for Seabrook, a value of 4.3×10^{-4} per station year is the frequency of an accident involving damage to one or both cores. There is another metric, which is the frequency of core damage on one and only one core, which has a different value of 4.0×10^{-4} per station year. Hence the whole concept of surrogate risk metrics for integrated risk needs to be considered very carefully.

The major contributions to dual reactor unit core damage frequency are listed in Table 3. The results are seen to be dominated by seismic events, although loss of offsite power and external flooding also make significant contributions. The assumption that all seismic induced failures are common cause with respect to all redundant components at both units, which has an unknown degree of conservatism, is important to note when interpreting these results. However, even if this assumption were relaxed, the frequency of dual unit core damage events would still be significant, and certainly too high to be dismissed.

Table 3 Major Contributors to Frequency of Core Damage to Both Units

Initiating Event	Frequency of Core Damage on Both Units (Events/station-year)
Seismic Events	2.8×10^{-5}
Loss of Offsite Power	2.8×10^{-6}
Truck Crash into Transmission Lines	1.0×10^{-7}
External Flooding	1.6×10^{-6}
Total	3.2×10^{-5}

III.D Treatment of Damage States and Releases

The next steps to the development of the integrated risk model for Seabrook was the completion of the Level 2 and Level 3 models for both the single and multiple reactor accidents. If there were an accident involving core damage on more than one unit at a given site, the consequences from the damage from each reactor would in general be different as the same plant damage states and release categories resulting from the core damage would not necessarily be the same. In the specific case of Seabrook, the damage states and release categories in

the case of a dual unit accident were found to be highly correlated for several reasons.

The most important damage states from the standpoint of determining the risk of early health effects for the initiating events that impact both units involve the failure to isolate containment penetrations. Two release categories were found to dominate early health effect risk for both the single unit and dual unit accident cases. One category denoted as S2V involves failure to isolate small penetrations and another S6V denotes failure to isolate large penetrations.

In the case of sequences involving station blackout following a loss of offsite power, truck crash in the switchyard, or seismic induced loss of offsite power, the probability of failure to isolate small penetrations is high due to motor operated valves which fail open so that the probability of release category S2V is high for these sequences. There are also some seismic event sequences in which seismic induced failures lead to failure to isolate the large containment purge penetrations in the event these are open at the time of the initiating event, resulting in release category S6V. Both of these categories would satisfy the current criteria for constituting a large early release as each has the potential to produce health effects from prompt radiation syndrome.

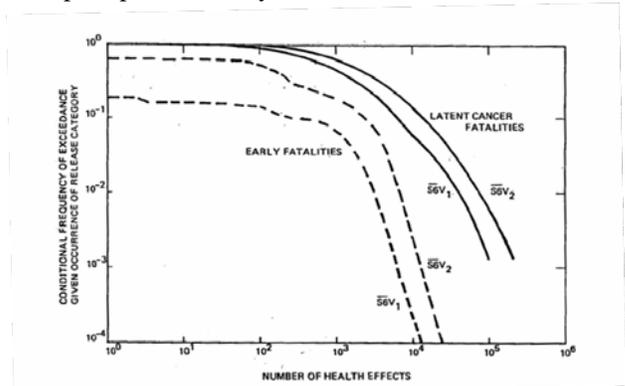


Figure 2 Conditional Risk Curves for Early and Latent Fatalities for Single (S6V₁) and Double (S6V₂) Core Melts with Large Isolation Failure

The conditional risk curves for release categories S6V and S2V are shown in Figures 2 and 3, respectively. These are the same as the CCDF curves in Figure 1 except that the occurrence of the release is assumed. The curves reflect the variability and uncertainty in the source term and meteorological conditions at the time of the release. The consequences from single reactor accidents are presented with the subscript 1 and those from dual unit releases are shown with the subscript of 2. The conditional risk curves for both the latent cancer fatalities and early fatalities due to prompt radiation syndrome are shown in the Figures.

As seen in these figures the results for dual unit releases are much different than a simple scaling of the

single unit results. Importantly, the probability of 1 or more early fatalities is seen to increase by a factor of roughly 5 when comparing results for single and dual unit releases for release Category S6V in Figure 2. This reflects the non-linear relationship between source terms, which are a factor of two different between single and double reactor releases. The increase in probability of a given number of fatalities reflects the fact that for the single reactor accidents doses within a significant fraction of the surrounding population are high but below the thresholds for prompt radiation fatality, but when the source terms go up by a factor of 2 they exceed these thresholds. The results for the latent cancer risk, however do not show this behavior because there are no thresholds assumed in the linear dose response models used for latent health effects. Hence, for the latent health effect models, the dual unit risk curve is approximately a factor of 2 to the right of the single reactor curve.

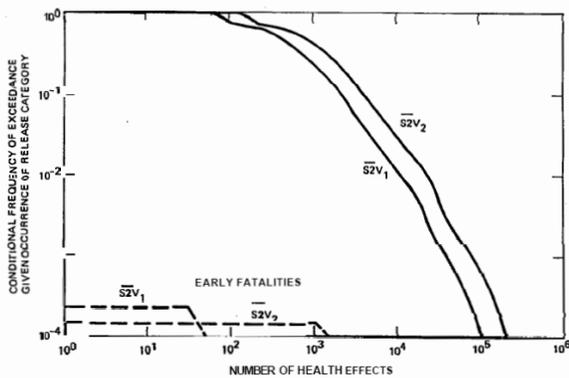


Figure 3 Conditional Risk Curves for Early and Latent Fatalities for Single (S2V₁) and Double (S2V₂) Core Melts with Small Isolation Failure

The results in Figure 3 are somewhat more complex because there are only unusual meteorological conditions in which small isolation failures were found to produce doses high enough to exceed prompt radiation death thresholds. It is interesting to note that the upper tails of the early fatality risk curves increase by more than an order of magnitude when the source term is increased to reflect damage to both cores. The latent cancer behavior for S2V is similar to that for S6V.

The total integrated risk for the two unit station is presented in Figures 4 and 5 for early fatality risk, and latent cancer risk respectively. The separate contributions from single reactor accidents and dual unit accidents from each of the dominant release categories are shown. Fortunately, the frequencies of release category S6V₂ is sufficiently small that it does not make a significant contribution to the overall profile for early fatality risk. However release category S2V₂ does in fact make a significant contribution to the overall early fatality risk

profile, and in fact tends to dominate the risk curve in the low frequency-high consequence end of the profile.

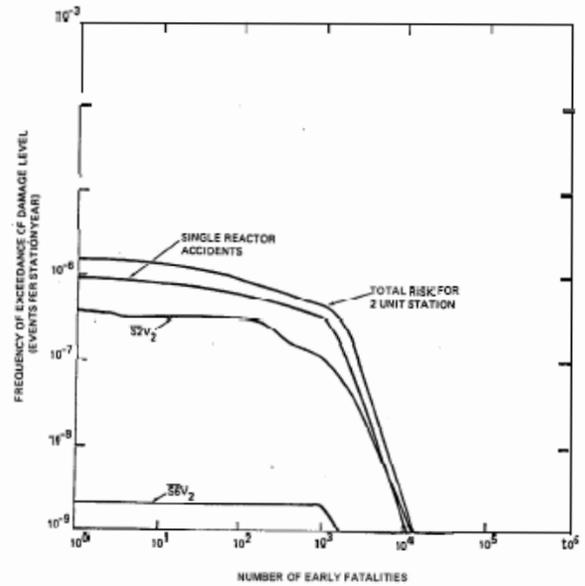


Figure 3 Risk Curve (CCDF) for Early Fatalities for Two Unit Reactor Station.

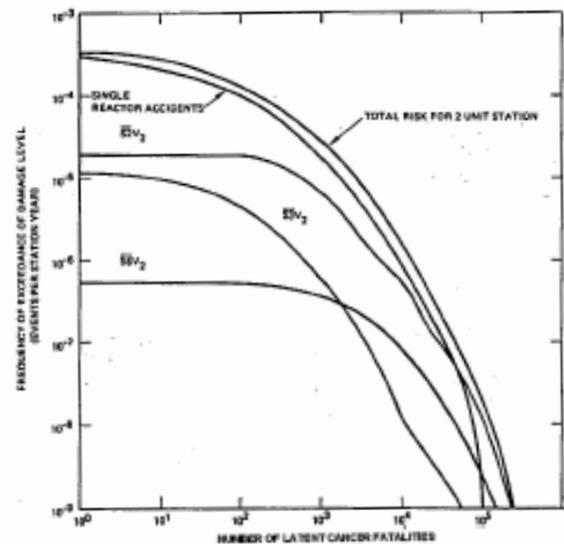


Figure 4 Risk Curve (CCDF) for Latent Cancer Fatalities for Two Unit Reactor Station

The results for latent cancer fatality risk include a third release category for dual unit events, S3V which involves late containment failures due to overpressurization and since it is late does not contribute to early health effect risk. The three dual unit release categories combine to dominate the integrated risk curves at exceedance frequencies below about 10^{-7} per station

year, while in the higher frequency ranges, the single reactor events dominate.

In reviewing these results that were developed more than 20 years ago, the following observations and conclusions regarding the results obtained for Seabrook are offered:

- The development of an integrated risk profile for a multiple reactor station cannot be developed by manipulating risk metrics such as CDF or LERF derived from PRAs of single unit accidents.
- For an integrated risk assessment of a site with two or more reactors, the frequency basis should be on a per site year basis; frequencies per reactor year are problematic for being able to combine contributions from single and multiple reactor accidents.
- The models used to develop event sequences for multiple reactor accidents at Seabrook were simplified in relation to those for single reactor events.
- The degree of independence between the reactor units designed for Seabrook was very high, and likely as high as it gets. There are other sites in which there are more shared equipment and interdependencies suggesting even higher relative contributions of multiple reactor accidents.
- Due to the collective lack of experience in performing integrated PRAs the numbers developed at Seabrook need to be taken with a grain of salt. The relative contributions of multi-unit accidents initiated by seismic events may have been somewhat overstated due to some of the modeling simplifications. The results could be much different if updated using up to date models and data. Nonetheless the results that were obtained make a strong case that multiple reactor accidents are significant contributions to risk even for independent reactor units on the same site and must be taken into account in developing the integrated risk of multi-reactor site.
- Keep in mind that these multi-unit risk insights are not currently relevant for Seabrook as only one reactor unit was completed and put into operation there.

III. CONCLUSIONS

From this PRA practitioner's perspective, the following conclusions have been reached:

- Recent NRC staff and ACRS discussions on the integrated risk issue have been severely handicapped due to the use of concepts and

terminology that have been historically defined and applied while investigating risks one reactor at a time. Risk metrics such as CDF need to be redefined to make sense for multi-reactor sites.

- The evidence presented in this paper based on work performed more than 20 years ago at Seabrook indicates that the frequency of multiple concurrent reactor accidents on the same site is significant and needs to be taken into account when addressing the integrated risk issue.
- Due to the non-linear relationships between source terms and early health effect predictions, simple manipulation of risk metrics defined for single reactor accidents will not suffice. The consequences of a dual unit reactor accident can be much greater than the linear combination of single reactor consequences.
- Application of QHOs should be applied to the entire site. All the risk contributions from the reactors on the site need to be considered including the contributions from multiple reactor accidents and both new and existing reactor units.
- The links that have been established between the surrogate risk metrics of CDF and LERF and the safety goal QHOs are only valid for the case of single reactor accidents. These established links are based on a body of work from PRAs that have generally neglected multiple unit accidents.
- PRA methods and associated standards should be enhanced to consider appropriate treatment for multi-unit accidents to support PRA applications for multi-unit sites for which QHOs need to be applied.
- The above conclusions apply to existing multi-unit sites as well as future modular reactor plants.

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