PEER REVIEW-
BCL Report on the Radionuclide Release
Under Specific BWR Accident Conditions.

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NOTE: The transcripts can be misleading because they are twice removed from the meeting, once because they are written and again because of the time between the meeting and the transcript. At best, the transcript gives general indications of issues.

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MR. POWERS: I want to begin by just reminding you how the VANESA code fits into this overall calculational scheme for the source term.

VANESA is the model that we are using to calculate the fission product release from source term that comes about because of the melt interactions in the reactor cavity region.

Before we can do calculations with VANESA model, we need information from several of the other codes used in the overall calculation procedure.

(Slide.)

There are, of course, accident and plant specifications that are the definition of the problem. The things that most concern us in VANESA about these are the reactor cavity geometry and the concrete composition.

We also get from the MARCH code and the CORSOR code what the coremelt looks like as far as its initial mass and its initial temperature when it comes down into the reactor cavity.

We also get the melt composition with respect to the fission products and whether the zirconium has been completely oxidized or not, whether we have metallic zirconium coming in from the reactor activity.

The information from these accident and plant specifications and the outputs from the MARCH code and the CORSOR code are then fit into the CORCON code, which models melt interactions with concrete in the reactor cavity.

We use this code primarily to determine what the melt temperature is during the course of this interaction, what the gas generation rate is due to the molten core debris attacking the concrete. We get CO_2 and H_2O release rates. We also get the geometric surface area of the melt as it erodes through the base mass, but the surface area keeps changing on us.

Finally, we get the rate at which concrete gets melted and incorporated into the core debris melt. It's quite an important quantity for us, because it tends to dilute the melt and thereby compress the vaporization of fission products, accentuate the vaporization of nonradioactive materials.

Information is then fed into VANESA model. VANESA itself calculates large input quantities. Here's the mass rate at which aerosols are generated.

Here's the aerosol composition, aerosol particle size, and some of the material properties, notably the density.

We also take information on the gas generation, do chemical calculations to get the gas flux out of melt and the composition of that gas with respect to hydrogen and carbon monoxide, as well as CO_2 and H_2O.

(Slide.)

Obviously, the calculations of VANESA are only as good as the information it gets from these other sources. One would like to know how that information -- how sensitive VANESA is to that information from other sources. One would like to know how well the VANESA code compares to some experimental data and how sensitive it is to the model of the melt-concrete interactions.

It's the discussion of these quantities that I am going to concentrate on in this morning's talk.

(Slide.)

What I want to show you are a series of calculations -- comparison calculations that we have made with VANESA code. Calculations we do with VANESA are for the Surry plant.

Two conditions: One where all of the zirconium has

been oxidized to zirconium dioxide in the initial melt; one in which only half of the zirconium has been oxidized with zirconium dioxide.

At the time of the reactor safety study, I think there was general perception that zircaloy reactions would be complete. I think our modern perception is, certainly the results that we are getting in as interim source term study, that zirconium has not been completely reactive.

We became concerned about this because zirconium is quite a reactive metal, and it will tend to reduce fission products and enhance the volatility.

(Slide.)

What I showed here is a plot of the aerosol generation rate predicted by the VANESA code as a function of time for the two situations. Surry has none of the zirconium present at the metal for the Surry plant. But you see, in the calculations, the melt initially comes down quite hot, compacts the base mat, and gets partially quenched. Quenching causes the aerosol generation rate to drop quite dramatically.

Then, as the decay heat and the heat of oxidizing any metallic zirconium overcomes this quenching, temperatures rise, we get the melt flipping from the metallic phase being less than in the oxide phase, to the other way around. So, we get a peak in the aerosol generation rate.

Then, as the melt continues to cool and the gas

evolution rate drops, aerosol production rate drops, what you see is that between the no-zirconium case and the half-zirconium case there is some difference in the aerosol generation in the early time. Eventually, all the zirconium gets oxidized, and the two calculations proceed in the same fashion. There's not what I would call an order of magnitude difference in those two calculations.

We concluded from that whether the zirconium was oxidized or not was not an enormously sensitive variable in our calculation.

MR. HILLIARD: This is Hilliard from Hanford Engineering Development Laboratories.

Is that due to hydrogen production, the difference in those two curves?

MR. POWERS: Hydrogen, in the general reducing quality of gases coming through the melt, makes the biggest single difference.

In the zirconium there, nearly all the water gets reduced to hydrogen, nearly all.

When the zirconium is not present, then it's like 80 percent reduction of the water vapor coming into the concrete that's turned into hydrogen. It makes a different oxygen potential. We get different volatilities.

We get some differences in the speciation of the aerosol that's coming in there.

MR. KRESS: Kress, Oak Ridge.

Dana, you indicated part of that curve was a result of the flipping over of the layers. But you get temperatures out of the CORCON code.

MR. POWERS: Yes.

MR. KRESS: Does the CORCON code recognize this flipping over and its possible effect --

MR. POWERS: Yes, it does. And it has quite an effect on the temperature when it does the flipping. You are losing a heat transfer mechanism, particularly in the oxide phase.

MR. COOPER: Cooper, Harvard.

With the very active bubbling, would that not serve to keep it really rather well mixed?

MR. POWERS: What we have observed experimentally is even at the very highest gas evolution rates during the initial deposition here is that stratification occurs. We get a metallic and oxidic phase, some mixing in the inter-facial layers.

But basically, you have two distinct phases, both of which are reasonably well mixed. That is a strictly experimental observation that we have made and fairly large-scale tests.

Now, when you use tests in which you are using simulant melts, like thermitic melts, where you would have

iron and aluminum oxide, in that case you start off with metallic phase, more dense, and you don't get this flipping phenomenon.

When we use corium melt, we start off with the oxidic phase, more dense than the metallic phase. In that case, what we have observed experimentally is, starting off with the oxide ph. se, interacting at the bottom, as the interaction proceeds we get into a sandwich kind of structure, with the oxide on the bottom -- heavy oxide on the bottom, metallic phase in between, light oxide on top.

We've never been able to sustain a corium test long enough to go -- completely switched. But I think that's merely a matter of time and duration of the test.

MR. REYNOLDS: Reynolds, University of Virginia.

I had a question about the -- you're assuming it is all liquid, and you could have the melt falling into water down there, for example, and it will solidify, and then it will maybe eventually melt, or you may have some solid mixed with -- well, with concrete, which melts at a much lower temperature.

Could you have solids there? Could they remain solid for a long period of time?

MR. POWERS: You're absolutely correct. And I'll show you some calculations that show you even the initial melting temperatures that we have used in some cases are

sufficiently low that you would expect a lot of solidification. You can't model that with the CORCON code. So, we've ignored it; we've said it's really a liquid, just has a low temperature. It's an uncertainty area. We have been doing experiments specifically in that area, of looking at what happens if this core debris is solvent, rather than coming down as a complete liquid.

Two observations I will make: One is that hot, solid core debris attacks concrete, and it attacks it just about as vigorously as does liquid core debris if the temperatures were the same -- in other words, extrapolating the line, you really can't tell the difference.

The other observation is when we have done laboratory experiments and doped solid UO_2-zirconium mixtures with fission products, put them into liquid concrete, we've found fission products partition into the liquid phase with the solid largely as you would predict, based on structural considerations. Those that adopt cubic structures in the solid phase tend to stay in the solid UO_2. Those that don't tend to go into the partition preferentially, into liquid concrete. How much effect that has on our release calculations, I can't really tell you. What I can tell you is that the amount of aerosol generation we get at these relatively low temperatures is predicted by VANESA as low.

Consequently, it is not going to be a real dramatic

effect either way. It does not really matter if we drop this generation rate, which is, here, sitting in 5 grams a second down to one gram a second.

Okay?

When we get the very high-generation rates that really have the biggest impact on the containment behavior, we get those only at very high temperatures -- when the core debris will be liquid.

(Slide.)

What I would like to do now is to compare the calculations we got with the VANESA code to a correlation of experimental data that we have developed sometime ago for the Zion-Indian Point study. What this is is a completely empirical correlation of aerosol generation rate data that we collected in experiments of two general categories: one category of experiments with relatively small-scale corium melt interacting with concrete. Corium melt would be about 3 kilograms interacting over a four-inch-diameter circle of concrete; and some very large-scale experiments where we were pouring 200 kilogram melts of stainless steel onto 15-inch-diameter concrete cavities.

(Slide.)

The general form of the empirical correlation is shown here. Aerosol concentrations measured in these experiments were found to have a temperature dependence -- essentially an exponential fashion -- and to depend on the superficial velocity of the gas through the melt, and what we modeled as essentially a linear fashion.

With this correlation -- that's all it is, is an empirical correlation -- we found most of our experimental data to be fit this way, with uncertainties of like plus or minus 25 percent or so.

MR. SILBERBERG: What kind of distribution do you

think you have on this?

MR. POWERS: This, in fact -- this slide was made up sometime ago, Mel. It says 2 micrometers. When we went back and recalculated for Albuquerque atmosphere, we found the size was really 1.3 micrometers, and the geometric standard deviations, if you fit the data to a log normal distribution, varied between about 2 and 2.3.

MR. COOPER: Particle size presumably is diameter. Is it aerodynamic diameter, and is it by mass, mass median aerodynamic --

MR. POWERS: Classic cascade factor. You can see what this correlation allows us to do. We can get from the CORCON code melt temperatures and calculate superficial gas velocities, just as we did for the VANESA code.

We can effectively decouple the CORCON code from our comparison, and compare it with just what VANESA calculates to this empirical model.

MR. REYNOLDS: Can you repeat what this is for, what kind of aerosols experiment it was for?

MR. POWERS: It was for core debris interacting with concrete. The experiments were two types. Large scale, 200 kg, stainless steel melt going on to large concrete crucibles; and small experiments, 30 kg, corium composition melts going into relatively small concrete.

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(Slide.)

What I show here is exactly the same calculations as before with the calculation that we get from the empirical correlation shown as the green dotted line. What you see is early in the calculation the empirical correlation is exactly bracketed by the VANESA calculations. Even late in the accident, where there is some disagreement between the two there is no more than a factor of two difference in the predictions, which would get from the empirical correlation and the more mechanistic model. The biggest difference is a curve very late in time, which is really beyond where an experimental data would be collected. Experimental data tend to be concentrated in this phase of the interaction.

Even out here at very late times, where aerosol generation rates are slow, we don't have a very big difference. This is the difference between 9 grams per second being generated and about 5 grams being generated per second.

What this tells me is that at least the VANESA model is not orders of magnitude in the amount of aerosol generation range predicted; that it seemed to agree with the

empirical experimental data rather well.

Another comparison that is quite interesting to make is then to compare what we calculate now with either the empirical model or the VANESA model with what one would get from the reactor safety study model.

(Slide.)

The reactor safety study model for the aerosol source term during melt/concrete interactions was really concentrated on just fission product release. They didn't have descriptions of the nonradioactive contributor to this aerosol, which makes up most of the aerosol. So in absolute value, one really cannot compare the reactor safety study model to these more mechanistic and modalistic models. One can compare the timing and the timing that chosen in the reactor safety study was to have aerosol interactions taking place, first, on an exponentially decaying release rate, and then they got rid of everything in the last half-hour.

So their source term cut-off stopped at about two hours into the interaction, whereas we predict much more protracted aerosol generation rate.

The differences between what were calculated by the reactor safety study model and what we would calculate now also extend into the fission product releases for individual isotopes.

(Slide.)

Here I have for those same calculational accidents that I showed before, compared the amount of tellurium retained in the melt as a function of time of the melt/concrete interaction. My zero times here on all these plots respond to when melt comes out of the reactor vessel into the reactor cavity.

In the reactor safety study, they assumed all the tellurium would be released so at the end of two hours everything is gone, nothing is retained in the melt.

The VANESA model, on the other hand, calculates that there is some release of tellurium but that it would take essentially infinite time to release all of the tellurium out of the melt.

For this particular calculation, we started off with just a little less than six kg of tellurium and after about seven hours we still had about four kg still in the melt, and based on the curvature here, it's going to be a long time before release is significantly more.

(Slide.)

On the other hand, for other isotopes, the VANESA model predicts less release than the reactor safety study, but much more release.

Here I have compared the percent of strontium and barium released as a function of time. The lower curve corresponds to the reactor safety study model, which estimated

that 5 percent of barium and strontium inventories would be released over the course of two hours.

The VANESA model, on the other hand, predicts the barium release comes out to be about 13 percent over the same time period, and then it continues to release at a rather slow rate thereafter.

Strontium release for these calculations was quite high. We initially got about 18 percent release. That went through another release period, topped out about 27 percent of the inventory was released overall, over this time period, seven hours.

MR. SILBERBERG: Dan, mechanistically, what are the differences between the fact that the tellurium would have a very low release compared to the reactor safety study and barium and strontium study comes out high?

MR. POWERS: Two chemical effects are taking place here for barium and strontium. We have the larger number of vapor species that we allow. In the reactor safety study, they considered barium oxide and barium metal. We also considered hydroxides; there's also some strontium mixed compounds.

That is what's doing most of the relief here.

Another chemical effect is that as you create a more and more dilute solution of tellurium in metals, they just become less and less volatile for -- their chemical

activity drops down.

That was an effect that was not recognized at the reactor safety study. They took a boundary approximation of essentially specifying the vapor pressure that persisted for all time. It didn't matter what the dilution was.

MR. REYNOLDS: What about the case with half zirconium not oxidized, versus all of the zirconium oxidized?

MR. POWERS: That factors this calculation here.

MR. REYNOLDS: Is which?

MR. POWERS: This is the half zirconium is present.

MR. REYNOLDS: It seems the zirconium will have a lot of effect on both the barium and the tellurium, and perhaps in opposite directions. If you think about what the Oak Ridge people reported last time, that the tellurium would stay with the zirconium, whereas the barium -- the zirconium should make the barium release higher.

MR. POWERS: We find with tellurium it doesn't make much difference whether we have zirconium present or not. We get just amazingly consistent tellurium release rates. It does make a difference for strontium and barium.

MR. REYNOLDS: Where on that picture is all the zirconium oxidized, then the other half --

MR. POWERS: Right in here.

The other area of sensitivity is the kind of

information we get from the MARCH code. We get from the MARCH code initial melt temperatures and the time at which the melt comes down to the reactor cavity so we can specify the amount of decay heating.

(Slide.)

We had in this last sequence of plans three very interesting problems, because they spanned quite a range, both initial melt temperatures and the time at which we started the molten core/concrete interaction. It varied between a little over an hour to start that up to 30 hours or something like that.

It is a long time. So the amount of decay heat we had was very much less in the TPI sequence and less in this TC sequence.

Initial melt temperatures spanned quite a range. TPI sequence, in fact, had an initial melt sequence specified by MARCH, 1762 Kelvin, which is just sitting out at the liquidis temperature of stainless steel. We couldn't get CORCON to accept such a low melt temperature, just didn't recognize that anything would be molten at that temperature, so we had to do this low-temperature case starting with a melt temperature of 1900° Kelvin.

What I want to do is show you that this kind of information -- what effect it has on predicted VANESA release rates.

(Slide.)

First I show you how the core debris temperature calculated by CORCON varies depending on which of these sequences you are calculating.

Essentially, the TQUV and the TC sequences really behave almost identical. The fact that the TQUV starts at about 400° higher initial melt temperature than does the TC sequence affects things only for a little over an hour. And thereafter, things behave -- one would have a hard time seeing if there was any difference in these two cases.

TPI sequence, where the melt temperature is initially quite low, there is an induction period, runs out to about 6000 seconds, in which there is a difference in the melt temperature.

But eventually, things settle down and it, too, is falling into a consistent temperature range with all the other sequences. Essentially, what's happening is the core debris/concrete interaction is sufficiently vigorous that it's wiping out any of the past history of the core melt behavior that occurs within the vessel.

It can take a little while to do that, but essentially CORCON predicts all sequences kind of become the same as far as gas generation rates and melt temperatures.

MR. SILBERBERG: I guess what that says is -- and that's a pretty long time -- it says that the losses just

really aren't that much greater than the heat source.

MR. POWERS: What happens if you get a balancing act? You have the decay heat as a source; also you have the chemical reaction of the zirconium in here; then you have the concrete decomposition and gas evolution as a loss; and those two things will come into balance to give you a consistent temperature. If you have less decay heat, you get less concrete decomposition.

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(Slide.)

MR. POWERS: Again, by looking at the aerosol generation rate for the TQUV and TC sequences, these are the ones that just seemed amazingly similar. And you can see that the aerosol evolution rate tends to be the same, as well.

They are practically indistinguishable between the TQUV and the TC sequence, both in the amount of mass generated and the actual speciation.

(Slide.)

The TPI sequence, on the other hand, there are some differences, again, in the initial period of time. When melt temperature is much lower than the other two sequences, you get much lower gas evolution rates. We get much lower aerosol evolution rates. But again, after a period of time, we come out here again where it's not over a factor of two

difference in the aerosol evolution as a function of time, out here.

So again, there seems to be a balancing, and we are concluding from this that we are relatively insensitive to the predictions of the MARCH code; that we certainly don't have to have temperatures accurate to more than plus or minus 100°; that the timing at which the melt comes down into the reactor cavity, we don't have to have that especially accurate.

MR. KUHLMAN: Kuhlman from Battelle. What's happening at 24,000 stacking to cause that die in the aerosol generation?

MR. POWERS: We have reached very much the limits beyond which CORCON shouldn't be used, which I think is largely responsible for that drop. We're starting to get cross (crust?) formation and things like that. The heat transfer mechanisms are changing into a regime that CORCON doesn't really bother with.

MR. LEVY: Question. How come you do not see the dip and then the rise back in the aerosol, like you had in the Surry? Can you explain that?

MR. POWERS: You caught me. This is a different plant and different concrete, and it doesn't have that sharp rise that you do for the Surry. Surry has a silicious concrete. This is a high CO_2 concrete here, and we don't get that spike.

The melt temperature stays very consistently high with CO_2 concrete, especially this CO_2, which is very refractory, whereas with the silacious concrete, the fact that you are dissolving and melting concrete itself is cooling the melt and keeping its temperature down. So as you change your heat transfer, and even though the metallic or oxide phases you get pretty fair oscillations in the melt concrete with silacious concrete.

MR. LEVY: So one could argue, probably, the characteristics of the concrete -- they're a mite more sensitive than the MARCH sequences.

MR. POWERS: What you can demonstrate, and we have actually done these calculations recently -- makes a big difference on whether you are in this high CO_2, this 80 percent calcium carbonate concrete, or in a concrete with a significant amount of silicon. That could be like the other situation, I think, of 50 percent calcium carbonate concrete and silacious concrete behave amazingly similar.

But this high CO_2 concrete behaves different. This is a fairly common concrete in the southeastern part of the United States.

MR. COOPER: On page 15 of your status of VANESA validation, you mention that VANESA was sensitive to the CORCON results, and data available in the literature suggest CORCON underpredicts melt temperature. Then you go on to say

that that could be very important for aerosol generation. Now, in your talk, I guess you are saying when you looked into this in more detail, you found the reaching of some sort of temperature equilibrium later on was more important than the initial?

MR. POWERS: Yes. And I will go on and explain that a little further here.

Recall in the sequences that what happened in the melt/concrete interaction is that all sequences seemed to come out to kind of the same thing. There are differences here. They amount to about 50 degrees, as predicted by CORCON. You have to ask the question: What happens if this kind of consistent temperature is off by 100 or 200° here? What happens?

(Slide.)

MR. POWERS: VANESSA is very sensitive here. What I have talked to is an aerosol evolution rate as a function of that kind of equilibrium temperature out there. You can see it's essentially an exponential rate, especially if you get up at temperatures where we are fully liquid.

Al raises a very good point when he says, hey, it's very likely you can precipitate solids out. When you get into these low temperatures where you're precipitating solids we get lower evolution rates not very sensitive to the changes in temperature in this regime here.

Once we're in the melt regime, whatever temperature we get from CORCON makes a big difference on our total evolution rate, has a similar effect on each isotope release rate. There's another effect that is almost of equivalent importance and that is the gas evolution rate we get from CORCON.

(Slide.)

Here's a plot in which plotted release rate as a function of that gas flow rate from melt at about 2200 degrees Kelvin. You can see there's essentially a linear dependenc in this regime. It kind of levels off at either end. So it's very sensitive to what those precise calculations that come from CORCON.

MR. GREEN: George Green, Brookhaven.

Ben, did you say that CORCON overpredicts or under-

predicts melt temperature?

MR. POWERS: It's very tough to say exactly what it does. The one comparison I have seen, it was underpredicting melt temperatures. That's a comparison with the sustained steel melt interacting with the concrete that I was doing the TC and TQ calculations with. In that case, it underpredicted the melt temperature by about a hundred degrees.

MR. GREEN: Would you agree that the correlations in the code would tend or their own merit to indicate that the code is, in fact, overpredicting, or would overpredict, melt temperature just on the basis of the critical examination of the models?

MR. POWERS: I guess I would not comment. I don't know enough to comment on that.

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(Irrelevant)

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MR. POWERS: It might even the understanding of the overall accident. I will agree to that little parochialism up here on the podium in thinking that the world starts at time the vessel break melts through. Perhaps that would be helpful. I think that's what Ken Lee has done in the documenting, reporting the overall accident. He puts these in some

sort of context for you.

MR. LEVY: Could I get you to comment on what would happen to those answers if you had a layer of water on the top of the concrete? The sensitivity of temperature and things of that kind?

MR. POWERS: There are really two things that happen when you put a layer of water over the top of the melt. It's an area where we have limited experimental experience, but it's growing, the experience base. The first is much like the suppression pool problem. You have this water layer you're passing bubbles of vapor and aerosol-laden gas through it. You have a certain amount of that aerosol material gets trapped in the bubbles in the water pool. It may be released later on as the pool boils off, or due to bubbles just breaking at the surface and flipping the material out.

The other effect the water has, of course, is pool melt down. That's an effect that, right now, we cannot meddle with the CORCON code. We are trying to get the CORCON code so it will do exactly that, model a pool layer. We're trying to get the experimental data to back it up. Right now, we can't do that calculation.

MR. CAMPBELL: Campbell, Oak Ridge.

On the previous slide, you made the comment that we get this result like it is a reality. Is there experimental support for that type of curve?

MR. POWERS: Let me show you the experimental support for the one with -- as a function of gas evolution.

(Slide.)

This is a plot of some experimentally measured aerosol concentrations as a function of superficial velocity. At the time, we were looking for essentially a linear relationship between the dots, or the experimental measurements.

You can see what happens is for fairly high superficial gas velocity. There does seem to be a kind of a linear relationship between the velocity of a melt, the gases coming through the melt, and the concentration of aerosols carried out by that gas. Until you get down to relatively low superficial velocities, in that it starts coming into a constant. That's exactly what you'd expect.

There's going to be some evolution rate of aerosols from a melt if there's no sparging at all, just due to convection. For the temperature effect, I don't have a plot with me on that. The data tend to be much spottier. We have either very hot melt or very cold melt and we get, essentially, an exponential relationship-looking sort of thing. But if that area is clear-cut, it's definitely true. You jack the melt temperature up a little bit, it can make a very big effect on the amount of aerosol evolution and change the composition of that evolution.

MR. COOPER: On page 16 of your status of VANESA

validation, you mention proposed tests with molten concrete. Did you mean with molten metal? You want to look at sparging of molten metal?

MR. POWERS: I'm not sure what tests?

MR. COOPER: A series of tests we run with gas sparging through molten concrete to determine the number of aerosol particles --

MR. POWERS: We're definitely looking at concrete there. We're speaking there of a mechanical relationship.

Maybe a little bit of background would help everybody to know what we're talking about here.

(Slide.)

The VANESA model has several mechanisms of aerosol generation considered. The dominant one, the one that attracts a lot of our attention, is what we call the vaporization model. This is just the fact that the melt is very hot. Constituents of the melt have a certain sparging pressure, sparging gas through it. The vapors go into those gas bubbles carried out the vapors there to condense to form aerosol. The other mechanism, the one we call the mechanical mechanism, is due to the fact that when bubbles of gas come to the surface and break, they throw off aerosol-sized particles.

The difference, of course, between these two is the vaporization mechanism produces aerosols having a compos-

ition reflective of vapor pressures at the particular melt temperatures, whereas the mechanical release produces aerosol size having the bulk melt composition. But it's the surface, the top layer, okay?

In the case of melt concrete interactions, that's going to be molten concrete. Very quickly, it's molten concrete. Within minutes it's just a layer of molten concrete fission products partitioned into that molten concrete as those fuels slowly dissolve into it.

MR. COOPER: So that't the top layer?

MR. POWERS: Yes, because it becomes molten concrete. Now, what we had to do on the model was, we had to use data for gas bubbles going through water. There was no reason for us to believe that the size data that we got for water would apply to molten concrete, so we have done the experiments. And I just happened to put the slide in.

(Slide.)

Here are some photographs. These are photographs of aerosol particles produced in exactly that way. Sparge liquid concrete with the gas, an inert gas, and look at the aerosols. You can see what we get little spheres running about a micron in size, almost exactly what we get from the water data; so we feel relatively good about what VANESA did. You can see there are quite a few bubbles.

MR. HENRY: Henry, Falski Associates.

Data on the CORCON that you do for these sequences, does it say the top surface of the pool stay molten through, with the presence of upward radiation, or does it solidify?

MR. POWERS: Let me tell you what I observed in the experiments, Bob. Then, what the code calculates when we have concrete melting and creating a molten layer over the top, it really never crusts. Molten concrete is basically a molten glass and it never really solidifies to form a solid crust, even when it's very cold. It's quite performable and gas bubbles come right up through it and break through the surface for long periods of time.

So what CORCON predicts is probably is not as germaine as how the material itself behaves. Right now, that's an area that's fairly tough to model the amount of radiant heat loss, especially for cavities like zion and what not, which we suspect does stay molten, because the aerosols being produced tend to reflect that radient energy right back.

The gases that are coming off are not transparent to the radiation when they have CO_2. But that too, tends to keep heat into the melt and not let it radiate out into the free environment. Even if those were out there, what would happen, it would radiate up to the concrete, drive that overhead concrete up to its melting point, and set. And, of course, if that overhead concrete is molten, then obviously, the surface of the melt, which is also concrete, would stay molten.

MR. HENRY: I understand that. What is the longest time duration of any of the experiments?

MR. POWERS: Eighty minutes. But more importantly, is what happened after we stopped. Then we would turn off power to the melt and it would cool down and temperatures would drop quite a bit. What you saw was, over the course of twenty or thirty minutes, the surface layer didn't really freeze. It just got more and more viscous. It eventually got so viscous that it behaved like a solid. But it was definitely a glass and not a crystal solid crust.

MR. STRATTON: It seems to me the importance of a layer of water on top of this molten fuel really hasn't been taken into account enough. It seems to me, if there is a good bit of turbulence in the way a bubble is coming through the molten fuel, it's going to open up. The whole thing will be so turbulent that the water will be very effective in cooling the surface of this molten fuel, and it will tend, then, to quench the sparging of the bubbling. Would you comment on the effect of this?

MR. POWERS: We have done a couple of experiments in this area. I think you are entirely right. If you have -- we take a melt, put it onto concrete and pump it full of water, then we get closer to what Bob is talking about. You do get a solid crust over the top, because we haven't had enough time to make this concrete glass. That crust is not gas-imper-

meable. We still get the core debris still attacking. Concrete gases are still coming through, okay?

But I suspect that that crust would interfere in our aerosol production rate, so if nothing else, it ought to stop the mechanical generation. It may even interfere in the vaporization generation because the vapor has to pass through a cold zone. We simply haven't done enough experiments in this area. They are kind of touchy to do because there's another thing that can happen, of course; that the whole system can explode on you. And so, we approach it with a little bit of trepedation.

In the next couple of months we're going to be doing some rather well-instrumented tests specifically in support of CORCON and VANESA to look at this coolant layer problem to see if we can indeed model it, both with aerosol generation and the melt-concrete interaction.

MR. DANA: I was under the impression that, at least the thermal hydraulics of the layer of water, had been looked at in CORCON without worrying about the aerosol?

MR. POWERS: CORCON is definitely setting up to handle the coolant layer. The problem they have is they don't have anything to check the calculation against. There's no good data set.

MR. SILBERBERG: I understand, but we've never been bashful in the past of making a calculation --

(Laughter.)

MR. POWERS: In this case we've learned before this august body: be careful about that.

MR. GREEN: George Green, Brookhaven.

I'd like to address my comment to Bill Stratton and explain something. This coolant layer problem is something that has been looked at in the last couple of months and we expected to find some enhanced mode of boiling, because it would be a new mode of boiling when the glass flops through. And we expected all sorts of things.

One of the things we found, if you got into a certain regime, the temperature that you would account for vapor explosions. Recently, we spent a week talking with Dana on the CORCON group and some others and after my talk about low temperature experiments, they took a high temperature of iron aluminum thermite experiments where they fired it off and after they fired it off -- this is just last week, by the way: Tuesday.

They poured water on it and they got an extraordinary violent vapor explosion. It's one area of core-concrete interaction modelling that may make a second version of this study required once we can get a better understanding of what happens when you drop water on top of molten debris.

(Slide.)

MR. POWERS (?)

I just wanted to conclude this portion of my talk

with saying that it looks to us like the mechanistic modelling, in VANESA at least, is in fairly good agreement with emperical data. We are not off on the wrong tangent on this mechanistic model as far as the overall evolution of aerosols.

We still need to do more checking of particular isotopic releases, and particular. We are very anxious to check the tellurium release predictions. We think VANESA is fairly insensitive to what we get from the MARCH code calculations. We certainly don't need plus or minus five degree numbers. We don't need plus or minus five minute melt injection.

VANESA, of course, is quite sensitive to what we calculate the course of the melt-concrete interactions. Finally, we are getting differences in the VANESA calculations with what our perceptions had been from the reactor safety study and they go in both directions. Some isotopes seem to be released more efficiently and some much less efficiently.

Pages 291 to 302 are about a high pressure ejection of corium from a reactor vessel into a reactor cavity.

MR. CAMPBELL: A very different issue, briefly. Once you have this melt, you have two or three or four layers, depending on just when it is.

MR. POWERS: Three is the most we have ever observed.

MR. CAMPBELL: You may have mortar on top of that.

MR. POWERS: Plus water.

MR. CAMPBELL: The different fission products are in different layers. You're taking that into account as your source term, but you're also taking into account the throwing out of the ones that come from the lower layer, bubble, and go through the higher layer.

So it works both ways.

MR. POWERS: In the VANESA code, we only recognized two layers of melt, and we do take into account of things moving from one layer to the other layer.

MR. CAMPBELL: You take into account scrubbing material back out?

MR. POWERS: That's right.

You're going to have things coming out of the metallic phase and going into the oxidic phase, just moving there. And then the release character is a little different from the oxidic phase than it is from the metallic phase.

Yes? Roger, Oak Ridge?

MR. ROGER: To follow up on this last question, you gave us, earlier, a comparison of your aerosol generation with experimental data. Then you later gave us calculations for various fission product releases.

Do you have any comparison of the experimental release of specific fission products with your calculation?

MR. POWERS: We have a certain amount of data, but we could get done the comparison directly.

We just haven't made the comparison yet.

MR. ROGER: Obviously, you will.

MR. POWERS: Yes.

Qualitatively, we stopped working on the VANESA code when things looked qualitatively right, so I expect the comparison to come out all right. The precise flow in temperatures in the experiments are the biggest problem that we have right now.

MR. ROGER: I am not sure that it necessarily follows that because the basic mass of material, the carrier material, follows, that the specific fission products do, particularly because of the point that Dr. Campbell brought up.

Harking back to the work that was done in melt refining back at Argonne in the '50s, fission products went into slag layers rather definitively by up to an order of magnitude.

So the trace components may not behave like the mass component.

MR. POWERS: That's exactly right. When I said things behave qualitatively, I was speaking on isotopic basis, because the bulk material is right, and I have only shown you comparisons for bulk material. Doesn't mean that specific isotopes will.

We have done some comparisons, and they are reported in the validation study. I have a great deal more material on the high pressure ejection tests, but I think I'll stop here.

If people are interested, I would be glad to talk to them more on the subject.

MR. SILBERBERG: Thank you, Dana.

TEC

TECHNOLOGY for ENERGY CORPORATION

TO: Distribution

FROM: E. P. Stroupe, Director
National IDCOR Program

DATE: November 21, 1984

SUBJECT: Replacement tables for Task 18.1

Attached are two replacement tables. The text has not been adjusted to match the table. It will be modified later.

cb

NUS CORPORATION

910 CLOPPER ROAD
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301-258-6000

CD-CAs-84-147
Project No. 4040
November 15, 1984

Dr. E. Fuller
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Dear Ed,

I enclose revised Tables 2 and 20 of the IDCOR Subtask 18.1 report. These tables present the revised Peach Bottom source terms and the correspondingly revised results of the CRAC2 calculations. The text of the Subtask 18.1 report will be revised to take account of these conclusions. However, I do not expect that the conclusions of the current draft report will change significantly.

Sincerely yours,

Geoff.

G. D. Kaiser, Ph. D.
Manager, Consequence
Assessment Department
Consulting Divison

GDK/bh

Enclosure

cc: M. Fontana (TEC)
Project File

Table 2

PEACH BOTTOM SOURCE TERMS

Accident Sequence	Tr[a] (hr)	Td[b] (hr)	Tw[c] (hr)	h[d] (m)	$\bar{Q}$[e]	Fraction of Core Inventory Released						
						Xe-Kr	I	Cs-Rb	Te-Sb	Ba-Sr	Ru[f]	La[g]
TW (0.1ft^2)	42	80[h]	10(33)[(j)]	10	10^4	1.0	0.19	0.19	0.11	4E-4[(k)]	6E-4	1E-6
TW (1.0ft^2)	37	60[h]	5(28)[(j)]	10	10^4	1.0	0.04	0.04	0.06	8E-5	3E-4	1E-6
TC(V)[(l)]	13	50[h]	4	10	10^4	1.0	0.03	0.03	0.07	5E-5	2E-4	1E-6
TC(V,CRD)[(m)]	2	15[h]	1	10	10^4	1.0	6E-4	6E-4	4E-4	4E-6	1E-5	1E-6
TC(NV)[(n)]	5	50[h]	4	10	10^4	1.0	0.13	0.13	0.11	4E-4	1E-3	1E-6
TC(NV,SPRAY)[(p)]	5	10[h]	4	10	10^4	1.0	0.03	0.03	4E-3	8E-6	3E-4	1E-6
S_1E	23	30[h]	21	10	10^4	1.0	0.04	0.04	0.06	1E-5	2E-5	1E-6
TQVW	19	30[h]	10	10	10^4	1.0	0.05	0.05	0.04	5E-5	2E-5	1E-6

---

[a]Interval between start of hypothetical accident and release of radioactive material to the atmosphere.

[b]Total time during which the major portion of the radioactive material is released to the atmosphere.

[c]Interval between recognition of impending release (decision to initiate public protective measures) and the release of radioactive material to the atmosphere.

[d]Height of release.

[e]Rate of release of heat in calories per second.

[f]Includes Ru, Rh, Co, Mo, Tc.

Table 2 (Continued)

PEACH BOTTOM SOURCE TERMS

[g] Includes Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am, Cm; upper bound

[h] Reduced to 10 hr. in CRAC2 analysis.

[j] TW sequences run with two warning times - long (mechanical failure), short (human error).

[k] 4E - 4 = 4.0×10^{-4}

[l] V - venting is wetwell

[m] CRD - quenching by CRD flow

[n] NV - no venting in wetwell

[p] SPRAY - drywell sprays operating

Table 20

PEACH BOTTOM - AREAS UNDER CONDITIONAL CCDFs

	$TW(0.1ft^2)^a$	$TW(1ft^2)^a$	TC(V)	TC (V,CRD)	TC(NV)	TC (NV,SPRAY)	S_1E	TQVW
Early Fatality[b]	0	0	0	0	0	0	0	0
Early Injury[b]	0.8	0	0	0	6.9	0	0	0
Latent Cancer Fatality[c]	2.1E+3	740	670	25	1.8E+3	540	750	880
Whole Body Man-Rem	3.0E+7[e]	1.1E+7	9.6E+6	3.5E+5	2.5E+7	7.9E+6	1.1E+7	1.3+7
Off-Site Costs ($)[d]	1.1E+9	1.6E+8	1.4E+8	6.8E+6	7.7E+8	1.1E+8	1.6E+8	2.2+8

---

[a] TW results unaffected by different warning times

[b] Using the Peach Bottom daytime or night-time specific evacuation scheme described in Section 5.5.1.2.

[c] Includes thyroid cancer fatalities (about 10% of total). The cancers would appear spread over a period of about 30 years.

[d] 1980 dollars.

[e] $3.0E+7 = 3.0 \times 10^7$.

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CYCLONE DESIGN: SENSITIVITY, ELASTICITY AND ERROR ANALYSES

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(*Received for publication 29 July 1982*)

Abstract—The effectiveness factor, $q = [-\ln(\text{penetration})]/(\text{pressure drop})$, is a useful figure of merit for cyclone design optimization, remaining the same for a system of series/parallel elements as it is for the individual elements, assuming they act independently. The partial derivatives of a function with respect to its variables can be used to determine its sensitivity, the change in the function per unit change in the variable; elasticity, the fractional change in the function per unit fractional change in the variable; and error propagation, the contribution of the variable's variance to the function variance. An analysis of the sensitivity, elasticity and error propagation of each of the independent variables in the cyclone effectiveness factor indicates advantages for designs that use an assembly of high-effectiveness-factor elements, operated at lower flow rates and/or lower pressure drops than for those designs that use a single cyclone.

INTRODUCTION

This article presents an analysis of cyclone performance equations for sensitivity, elasticity and error propagation. Such analyses are useful in exploring optimal and near-optimal designs.

One formulation of the cyclone design problem for a particular application is to minimize penetration within certain constraints, such as total cost or system pressure drop. Penetration is the ratio of the number of particles per unit time flowing from the control device outlet to the number per unit time entering at its inlet. Similarly, penetration can be set at a desired level, and the design adjusted to minimize cost or pressure drop. Formulated in these terms, this is a constrained optimization problem, typically more difficult to solve than the unconstrained problem of maximizing or minimizing some figure of merit. A figure of merit that simplifies the optimization problem and has useful qualities is the "effectiveness factor" (q), the negative logarithm of the penetration, multiplied by the reciprocal of the pressure drop ΔP across the cyclone (Cooper, 1981):

$$q = [-\ln(Pn)]/\Delta P \tag{1}$$

in which the penetration is the penetration of a particular particle size, $Pn(d_p)$. The effectiveness factor is an intensive rather than extensive variable and has units which are the inverse of those of ΔP. It can be viewed as the volume of gas cleaned completely per unit of energy, in units such as $m^3\ J^{-1}$ if ΔP is in $N\ m^{-2}$. A system of several identical devices acting in series and/or in parallel and acting independently would have a system value of q, the system's "effectiveness factor," which would be the same as the value for each individual device, since the devices' pressure drops are additive and their penetrations multiplicative, for each particle size. (See Fig. 1.) This figure of merit has been used in filtration work as a measure of a filter's inherent efficacy for particulate removal in comparison to its pressure drop (U.S. AEC, 1950). The effectiveness factor has recently been applied to cyclones (Cooper, 1981) and to the individual collecting elements in a packed bed (Cooper, 1982a) and a filter (Cooper, 1982b). Other things being equal, it is advantageous in terms of efficiency and/or pressure drop to use a series of high-q devices rather than a

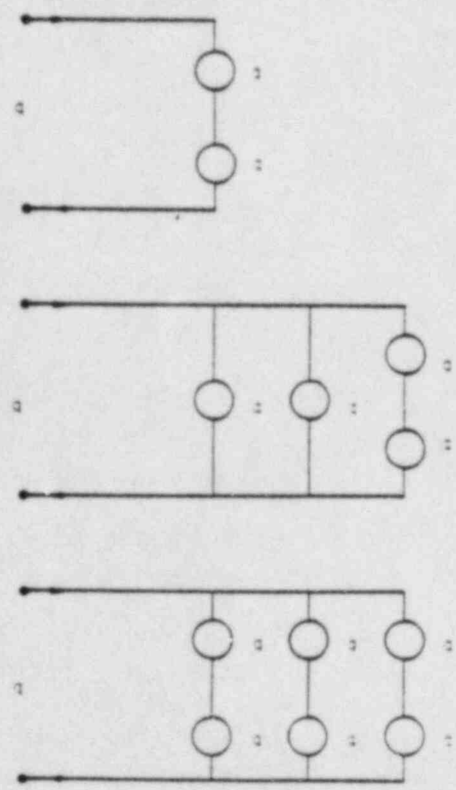

Fig. 1. Effectiveness factors (q) for series/parallel systems.

2

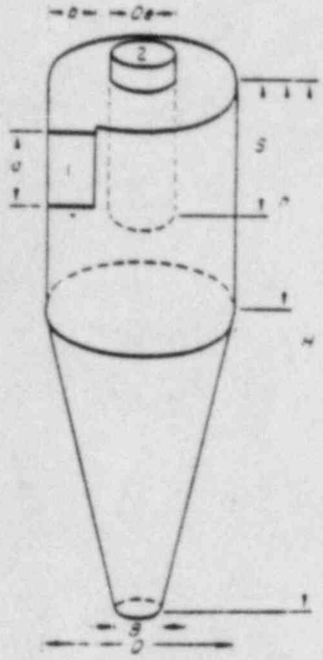

Fig. 2. Cyclone, with dimensions (Leith and Licht, 1972; Leith and Mehta, 1973).

diameter raised to the 0.14 power and is 0.67 for D = 1 m at 283 K; $(1 - n)$ is proportional to the absolute temperature raised to the 0.3 power (Alexander, 1949).

The factor C is a dimensionless combination of cyclone dimension ratios:

$$C = (\pi D'^2/a'b')[2(1 - D_e'^2)(S' - a'/2) + (S' + Z' - h')(1 + d' + d'^2)/3 + (h' - Z'D_e'^2 - S')] \quad (10)$$

in which the primes indicate the quantities have been made dimensionless by dividing them by D: $a' = a/D$, $h' = h/D$, etc. Z' is an estimate of the distance the vortex extends below the gas exit duct (Alexander, 1949):

$$Z' = 2.3D_e'(D^2/ab)^{1/3} \quad (11)$$

and d is the cone diameter at the length Z (Leith, 1979).

These equations describing cyclone penetration made it difficult to infer, without evaluating them, how penetration will vary when one or more of the cyclone dimensions is varied.

The equation for predicting pressure drop chosen by Leith and Mehta (1973) was that developed by Shepherd and Lapple (1940):

$$\Delta P = K(ab/D_e^2)(\rho_g v^2)/2 \quad (12)$$

which Leith and Mehta found to give almost as good agreement with experimental results as did several other more complicated expressions. The value for K is 16 for a cyclone with a standard tangential inlet (Shepherd and Lapple, 1940), so this equation becomes:

$$\Delta P = 8\rho_g Q^2/abD_e^2 \quad (13)$$

showing the strong effect of volume flow rate and cyclone duct exit diameter on pressure drop, along with the influence of the inlet area (ab).

Effectiveness factor: sensitivities, elasticities

The effectiveness factor can be put into a power-law form as

$$q = 2(C\Psi)^{1/(2n+2)}(abD_e^2/8Q^2\rho_g). \quad (14)$$

This form suggests that it will be most convenient to determine elasticity, from which the partial derivatives can be obtained easily, as can their squares. The power-law form exponents for several variables are shown below, for which the Cunningham slip correction has been neglected for particles of the sizes one typically controls by cyclones:

variable	exponent
ρ_p	$1/(2n+2)$
d_p	$2/(2n+2)$
μ_g	$-1/(2n+2)$
ρ_g	-1
Q	$-2+1/(2n+2)$

For a typical value of n, $n = 0.67$, $1/(2n+2) = 0.3$. The exponents show the percentage changes in q expected from a one-per cent change in the variables. As the gas volume rate of flow increases by 1 per cent, the effectiveness factor q will decrease by 1.7 per cent. The decreased penetration is more than offset by increased pressure drop. Thus, there is an inherent advantage in using several cyclones in a parallel arrangement, letting the flow be divided among them. This is the rationale behind the "multiclone". The factors within C cannot have their influences seen so readily, so we performed a series of computer simulations for the conditions shown in Table 1, having chosen particles 5 μm in diameter having the density of water and penetrations near 0.3 for cyclones with D = 1 m.

Table 1 shows the base conditions for three cyclones: one which we "designed" using the optimization procedure of Leith and Mehta (1973) and two standard designs, a high-efficiency design and a general-purpose design taken from the monograph by Leith (1979). The rows list the variables studied: the dimensions of the cyclone, the particle and the gas variables. The last five rows show the derived quantities C, ln Pn, Pn, ΔP and q. The elasticities were calculated by taking the base case values and increasing each in turn by 1 per cent, returning it to its original value after the increase.

Several conclusions can be drawn from the results presented in Table 1:

(1) The cyclone diameter is the variable to which the effectiveness factor is most sensitive.

(2) The ratio D_e/D is one to which the design is also quite sensitive, a characteristic exploited by the Leith–Mehta design.

should be preferable to selecting only a standard design or to calculating an optimal Leith–Mehta design for every series parallel configuration considered.

Acknowledgements—This work has benefited from my discussions with colleagues Dr. David Leith and John A. Dirgo.

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Insufficient attention to these considerations sometimes leads to erroneous conclusions. Thus to explain the shape of the path of a stream of tobacco smoke injected horizontally into a smoke chamber Prosad [84], starting from the assumption that smoke particles settle individually, had to take the absurd value of 24μ for the mean particle radius. In fact the shape of the path was undoubtedly determined by the rate of settling of the stream as a whole because its density exceeded that of air on account of the carbon dioxide contained in it. A striking example of rapid settling of a cloud is furnished by the "fire cloud" which descended with tremendous speed from the volcano Mont Pelée in 1902 and turned the town of Saint Pierre into cinders. Evidently the concentration of the disperse phase (volcanic ash etc.) was so great that the density of the cloud, despite its high temperature, was much higher than that of air.

A very complicated system of movement exists in cumulo-nimbus clouds containing droplets of all sizes from $r = 10\mu$ to $r = 2$–3 mm. In this case, under the influence of the higher temperature of the cloud in comparison with the surrounding air, a rapid rise of the whole cloud takes place at a rate up to 10 m sec^{-1} while the drops of water in it are falling individually at speeds between 0·01 and 8–9 m sec^{-1}. The resultant velocity of some droplets is therefore directed upwards while others move downwards. These phenomena play an essential role in the process of precipitation from clouds (see page 319).

§ 14. THE MOTION OF AN AEROSOL IN A CONFINED SPACE

For aerosols in an enclosure the motion of the particles includes that of the medium caused by convection currents, artificial agitation, etc., as well as their own motion relative to the medium. Just now we are interested only in the latter, and shall examine it for particles settling under gravity. If the particles of an aerosol occupying a space confined by walls settle with a velocity V the medium moves in the reverse direction with a mean velocity φV, where φ is usually a very small fraction of the total volume of the disperse phase. Since the medium is entrained in the vicinity of the particles, then in the spaces between them the velocity of the counterflow is greater then φV. Thus the rate of settling of particles in the present case, unlike the motion of a free cloud, is less than that of isolated particles in an infinite volume by the factor $1 + \varkappa\varphi$ where $\varkappa > 1$.

According to Cunningham [46] still another factor should be taken into account; in the derivation of Stokes' formula one of the boundary conditions is that the velocity of the medium is zero at an infinitely great distance from a particle. When a cloud of particles settles in a confined space, however, the velocity of the medium is zero at a distance ϱ from the centre of a particle, where $2\varrho \approx n^{-1/3}$ is the mean distance between adjacent particles. Thus each particle experiences the same resistance which it would experience at the centre of a closed spherical vessel of radius ϱ. According to Cunningham's calculations this resistance, on a Stokes approximation, is equal to $6\pi r V\eta \times (1 + 1{\cdot}25 r/\varrho)$. Following Oseen, the correction becomes less the greater the Reynolds number $V\varrho\gamma/\eta$. All other authors occupied with this problem have arrived by way of fairly complicated, but not rigorous, considerations at a correction factor of $1 + \varkappa\varphi$ with values of $\varkappa$ equal to 5·5 [85], 7·0 [83] and 4·5 [86]. Rigorous solution of the problem is obviously extremely difficult.

The difference between correction factors of the type $1 + \varkappa\varphi$ (I) and $1 + \varkappa r/\varrho \approx 1 + \varkappa\varphi^{1/3}$ (II) is of importance because at the usual values of φ in aerosols the factor (I) is practically equal to 1 while the factor (II) may be a few per cent greater than 1. For the small values of φ which are of interest this problem has been investigated experimentally only by Kermak [85] who measured the rate of settlement in monodisperse suspensions of various animal erythrocytes with radii 2·4, 3·0, 3·7 and 4·4 μ in water. It turned out that for $\varphi < 0{\cdot}04$–$0{\cdot}08$ the experimental results agree well with a correction factor $1 + \varkappa\varphi$ and $\varkappa$ has values lying in the range 4·8–6·9 for various erythrocytes. Unfortunately the settling rate of isolated particles was not measured in this work but was determined by means of extrapolation.

Thus from the rather scanty data available it may only be said that in the settling of aerosols in a confined space the resistance of the medium at low φ is probably equal to $6\pi r V_s (1 + \varkappa\varphi)$ and $\varkappa$ is close to 5 or 6.

The rate of settling of concentrated suspensions has become important recently in connection with the fluidization of powders (see page 367). In the fluidized state a concentration of particles for which the settling rate is equal to the flow velocity is automatically established. Experiments on fluidization have led to the formula

$$V_s' = V_s(1 - \varphi)^x, \tag{14.1}$$

where V_s' is the settling rate of the entire system of particles and V_s is that of an isolated particle.

For spherical particles Lewis and Bowerman [87] and Richardson and Zaki [88] obtained the same value 4·65 for the coefficient x. An approximate theoretical calculation of the settling rate was made by Richardson and Zaki who started from two models for the distribution of spheres in space; they obtained two curves (V_s', φ) one of which lies about 40 per cent higher and the other 20 per cent lower than the experimental curve.

In conclusion a phenomenon will be mentioned which is familiar to everyone working with aerosols. When concentrated aerosols settle the upper boundary is usually flat and horizontal, a phenomenon which is exhibited both in the laboratory and in natural mists. The explanation is that, for an aerosol density exceeding that of the gas adjoining it, hydrostatic forces counteract any disturbance of the horizontal position of the upper boundary of the aerosol by convection, just as in liquids. Such stabilization of the upper surface will be observed only when the particles move as a whole with the medium, which necessitates a sufficiently high concentration (see preceding section).

The surface of aerosols dispersed in dense gases like chlorine or carbon dioxide etc., is particularly stable [89].

Many theoretical and experimental papers have been devoted lately to the sedimentation of particles in a limited space, or hindered settling. Only equations which refer to very small values of the volume fraction of the disperse phase, φ, (the fraction of the total volume which is filled by the disperse phase) will be given here.

Following Cunningham's idea (see p. 49), but allowing for backwarus flow, Happel [610] and Kuwobara [611] obtained at $\varphi \to 0$ the formula $V_s'/V_s = 1 - \varkappa\varphi^{1/3}$ with $\varkappa = 1{\cdot}5$ [610] and 1·62 [611]. Brinkman [612] deduced the formula $V_s'/V_s = 1 - 2{\cdot}1\,\varphi^{1/3}$ and Hawksiey [613] $V_s'/V_s = 1 - 4{\cdot}5\,\varphi$. Experiments [614] confirmed the expression $V_s'/V_s = 1 - 2{\cdot}1\,\varphi^{1/3}$ for almost isodisperse liquid suspensions. The

results of all other investigations can be expressed by the formula $V_s'/V_s = 1 - \varkappa\varphi \approx (1 + \varkappa\varphi)^{-1}$ with $\varkappa = 4{\cdot}0$ [615, 616], 4·5 [617] and 5·4 [618]. The conclusion (see p. 50) that the velocity of hindered settling at small concentrations depends on φ raised to the first power seems to be confirmed, but no theoretical basis for this is apparent.

The principal difficulty encountered in precision measurements of V_s'/V_s, at small φ, is convection. Wilson [619] using very dilute aqueous suspensions of glass spheres of $r = 1$–$5\,\mu$, found that it was impossible to obtain strictly vertical trajectories of particles at room temperature, although they were realized at 4°C, when the thermal coefficient of water was equal to zero. Only in more concentrated suspensions and aerosols is the downward gradient of concentration high enough to suppress convection. Unfortunately, this is often ignored. It is difficult to combine the two conditions, a high enough weight concentration and a low enough particle concentration, which is necessary for the neglect of coagulation in not very coarse aerosols. It seems, therefore, that much sedimentation analysis of aerosols is erroneous.

§ 15. MOTION OF PARTICLES IN VERTICAL AND HORIZONTAL ELECTRIC FIELDS. PRACTICAL APPLICATIONS

The motion of aerosol particles in an electric field is no different in principle from motion in the earth's gravitational field. The force acting on a particle in an electric field is qE where q is the charge on the particle and E the field strength. The velocity of the particle given by formula (8.2) is

$$V_E = qEB = qE\left(1 + A\,\frac{l}{r}\right)\Big/ 6\pi r\eta. \tag{15.1}$$

The movement of particles in a vertical field is very interesting on account of the practical advantage obtained by the electric field being superimposed upon the earth's gravitational field. The vertical electric field method developed by Millikan [90] and Ehrenhaft [91] is one of the most fruitful methods of studying aerosols and has played a very large role in advancing knowledge in this field.

Aerosol particles are introduced into a chamber formed by two horizontal condenser plates and having side walls of insulating material provided with windows for the observation, illumination and charging of the particles. Observations are made with a horizontal microscope having an eyepiece graticule. The field strength $E = \Pi/h$, where Π is the potential difference and h the distance between the condenser plates. The strength and sense of the electric field can be varied as desired. The rate of fall of a particle V_s is determined first with the field switched off, and then under the simultaneous influence of the electric and gravitational fields, $V_s + V_E$ or $V_s - V_E$ depending on the sense of the electric field. Hence V_E is found. In addition, the field intensity E_g which exactly balances the gravitational force on the particle is sometimes determined

$$E_g = mg/q = \frac{4}{3}\pi r^3 \gamma g/q. \tag{15.2}$$

In some chambers provision is made for varying the pressure between wide limits both above and below atmospheric pressure. The technique of working with the vertical field method has been well set out in the literature [53, 92]; it permits the following problems to be solved.

27.

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ACCIDENT SEQUENCE LIKELIHOOD INFORMATION
FOR NUREG-0956

1. BACKGROUND:

ASEP supports the NRC source term reassessment and severe accident risk reduction work in three areas. First, it provides ASTPO with the accident sequence likelihood information for all the source term accident sequences of the 6 reference plants and a limited rebaseline of sequence likelihood for some of the accident sequences. Second, it provides SARRP Phase I by early 1985 with a detailed rebaseline of sequence likelihood of the ASEP identified dominant accident sequences for the 6 reference plants along with the dominant factors that drive the sequence likelihood. Third, ASEP provides SARRP Phase II by late 1985 with the identification of generic plant groups and the identification and description of the dominant accident sequences by the plant groups.

This paper only identifies the ASTPO needs and the ASEP approach to meet its needs.

2. ASTPO NEEDS:

In November 1983, Bob Bernero, in his memo on "Source Term Report NUREG-0956," requested from DRA the "estimate of the probabilities corresponding to the sequences analyzed in the Battelle reports (BMI-2104)". ASEP was given the task to support NUREG-0956. Conversations were held between ASEP and ASTPO on the precise needs of NUREG-0956 from ASEP. ASTPO did not express the depth and breath of the ASEP input but conveyed that "probability estimate" will play only a minor role in NUREG-0956 since it contains mostly deterministic analyses. Point estimate on the sequence likelihoods was told to be sufficient since the consequence analysis will probably contain no uncertainty analysis. ASEP input was needed by mid January 1984; as of now, the NUREG-0956 schedule has slipped about nine months.

3. SCOPE OF WORK:

ASTPO has identified 19 accident sequences for 6 reference plants for its source term reassessment. The 19 accident sequences consist of both high and low probability sequences. Most of the dominant accident sequences are rebaselined by ASEP. Those that were not rebaselined either required entirely new system models or extensive modification of the original models. Some examples of insights or system changes that were not incorporated in the rebaseline effort are: 1) the modifications of plants in response to ATWS requirements; 2) the possibility that the operator can reach cold shutdown before having to go to the recirculation mode of injection in PWR small LOCA accidents; 3) the possibility that the operator can cool the RCS enough to go to low pressure injection before core melt in PWR small LOCA accidents; 4) the fact that Surry now has an AFWS cross-tie between units; and 5) the fact that the procedures for checking the Sequoyah ice condenser drain plugs have been modified.

The following list contains the ASTPO accident sequences by plants and their status of rebaseline.

PLANT	SEQUENCE	SEQUENCE LIKELIHOOD UPDATE
Grand Gulf	TC	No
	TQUV	Yes
	TPQI	Yes
	S_2E	Yes
Surry	AB	No
	S_3D	Yes
	TMLB'	Yes
	V	Yes
Peach Bottom	TC	No
	TW	Yes
	AE	No
Sequoyah	TMLB'	Yes
	S_2HF	No
	TML	No
Zion[1]	S_2D	Yes
	TMLB'	Yes
Limerick[2]	TC	No
	TQUV	No
	TPE	No

[1]Rebaselined based on Zion review.

[2]Not rebaselined since it is not a RSSMAP and WASH-1400 plant and it is a recent PRA.

4. LIMITATIONS OF REBASELINING OF SEQUENCE LIKELIHOODS:

Due to the time constraint established by ASTPO, the superficial need by NUREG-0956, and the unavailability of the ASEP system models in late 1983 and early 1984, a detailed rebaselining of sequence likelihoods was not performed that would require an extensive re-analysis of the PRA involving modeling and assumption changes, reassessment of data, etc. Therefore, the limited rebaselining information was used from the August 1983 interim report.

The following list of general steps describe the limited rebaseline process.

1. Review the insights collected from recent PRAs, operating experience, TMI fixes or any recent plant fixes, and special safety studies. Determine if the sequence likelihood of the PRA dominant accident sequences should be changed to reflect the new insights.

2. If the insights applied to the dominant accident sequences, apply the quantitative changes to the major cutsets for the failure expressions denoting the sequences. If an insight excludes or includes certain failure modes in the PRA, delete or add cutset expressions by hand representing those failure modes. Subtract out the cutset probabilities for those that are deleted and estimate the additional probability for any cutset expression added to the PRA using generic data for that insight. Adjust the sequence likelihood accordingly to yield a limited rebaselined likelihood for all the PRA dominant accident sequences.

3. Review the PRA non-dominant accident sequences and apply the new insights to them. Determine if they still remain non-dominant. If they become dominant, add them to the list of dominant accident sequences.

In the above rebaselining process, the key steps are ascertaining which insights should be applied to the specific plant of interest and what are the quantifiable changes. ASEP has rebaselined the sequence likelihoods using, for the most part, those insights and quantitative changes agreed to by an author or otherwise knowledgeable person for each PRA. However, additional insights are sometimes listed in the rebaseline tables in the August 1983 interim report. These additional insights could be applicable to the plant of interest but an extensive rebaseline effort is required. While the limited rebaseline effort provides a more current estimate of the likelihoods, the other insights not factored into the limited rebaseline effort could possibly change the sequence likelihoods. Therefore, the sequence likelihoods from the limited rebaselined efforts only present a "better value" and not the "best value" for the sequences of interest. The attached package is a draft input to NUREG-0956.

5. FURTHER ASEP WORK FOR NUREG-0956

The assumptions made on the rebaselined accident sequences will be verified by the utilities. SNL is presently putting together the items for verification. After the verification, the accident sequences will be rebaselined, if necessary, and will be provided in an appendix to NUREG-0956 by August-September 1984.

The verification items for NUREG-0956 will be organized with the items from the ASEP work for SARRP Phase I. Its objective is to determine the current plant risk of the 6 reference plants. ASEP is performing a detailed rebaselining of the selected dominant accident sequences for each of the reference plant using the ASEP generic system models and data. ASEP is performing the initial screening to determine the major contributors that drive sequence likelihoods; the important items (e.g., hardwares, assumptions) for each reference plant will be verified along with the items from the limited rebaseline effort. At the same time frame, the ASEP data base will be reviewed by data analysts for their applicability. ASEP products for SARRP Phase I will be provided by early 1985.

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APPENDIX C
ACCIDENT SEQUENCE LIKELIHOOD INFORMATION

This appendix will serve to give the reader some probabilistic perspective on the sequences analyzed in the source term reassessment studies. Probabilistic information will be given for the nineteen sequences that were analyzed in this document. The sequences were chosen from six reference plants with PRAs and were selected either because they were dominant or because they represented a unique phenomenological situation.

The information compiled in this appendix came from the WASH-1400 PRAs[*1] (Peach Bottom and Surry), the RSSMAP PRAs (Sequoyah[*2] and Grand Gulf[*3]), the Limerick PRA[*4], the Zion PRA[*5], the Review of the Zion PRA[*6], and the PRA rebaselining report produced by the Accident Sequence Evaluation Program[*7]. In many cases the information presented here is based on the analysis in the original PRA, but has been modified (rebaselined) to incorporate some new insights that have been gained since the original PRAs were published. These new insights were not incorporated by modification of the original PRA models but by back-of-the-envelope type calculations.

The original PRA values were modified where possible, but there were several cases in where insights or system changes were not incorporated. The changes that were not incorporated required either an entirely new model or extensive modification of the original model to incorporate them properly. Some examples of insights or system changes that were not incorporated are 1) the modifications of plants in response to the Anticipated Transient Without Scram (ATWS) requirements; 2) the possibility that the operator can reach cold shutdown before having to go to the recirculation mode of injection in Pressurized Water Reactor (PWRs) small Loss of Coolant Accident (LOCA) situations; 3) the possibility that the operator can cool the reactor coolant system enough to go to low pressure injection before core melt in PWR small LOCAs; 4) the fact that Surry now has an auxilliary feedwater cross-tie between units; and 5) the fact that the procedures for checking the Sequoyah ice condenser drain plugs have been modified.

Because all of the numbers presented in this appendix are at least partially based on past PRAs the reader should be careful when comparing the numbers from one plant to the numbers from another. Different PRAs have different analysts, different methods, different levels of detail and different perspectives. The WASH-1400 and RSSMAP PRAs were NRC sponsored while Zion and Limerick were industry sponsored. The RSSMAP models are not as detailed as the WASH-1400, Zion and Limerick models. The WASH-1400 PRAs are ten years old while the Zion PRA represents the state-of-the-art methodology. For these reasons, and others, the reader should not compare the absolute numbers given in this appendix, but instead should compare the contributions of the sequences to the total core melt frequency at the respective plants.

As pointed out in the previous paragraph, each PRA is different. Each of the PRAs handled uncertainties differently. The relevant WASH-1400 PRAs used Monte Carlo simulations to propagate data uncertainties. The RSSMAP PRAs did not consider uncertainties. The Limerick PRA did a brief uncertainty analysis and the Zion PRA did a detailed Bayesian analysis. Because of these differences, the actual uncertainties were not presented along with the sequence description. It should be pointed out here that the uncertainties in sequence frequencies are large, typically on the order of one or two orders of magnitude.

PLANT: Peach Bottom

SEQUENCE: AE

SEQUENCE FREQUENCY: Case A -- 2E-7, Case B -- 2E-8 (From WASH-1400)

INITIATING EVENT FREQUENCY: 1E-4 LLOCAs/year

CORE DAMAGE CONTRIBUTION: < 1%

SEQUENCE DESCRIPTION: This sequence involves a large LOCA followed by a failure of the low pressure injection systems to provide makeup to the reactor.

INITIATING EVENT	A -- Large LOCA
SEQUENCE DISCUSSION	The requirements (amount of coolant makeup) to prevent core uncovery and thus core melt may vary depending on the break size. WASH 1400 evaluated this sequence using two separate sets (cases) of success criteria.
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	Failure of low pressure injection systems: -- Low Pressure Coolant Injection (LPCI). -- Low Pressure Core Spray (LPCS).
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	E -- Case A: 1.5E-3; Case B: 2E-4
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	**Case A** 1. Four of four LPCS pumps OR 2. Two of four LPCS pumps and three of four LPCI pumps. **Case B** 1. Three of four LPCS Pumps, OR 2. Two of four LPCI pumps, OR 3. Two of four LPCS pumps and one of four LPCI pumps.
DOMINANT FACTORS DRIVING SEQUENCE	ASEP did not do an importance evaluation of the Peach Bottom AE sequence.

PLANT: Peach Bottom

SEQUENCE: TC

SEQUENCE FREQUENCY: 7E-6 (From WASH-1400 with some revisions)

INITIATING EVENT FREQUENCY: 7 transients/year

CORE DAMAGE CONTRIBUTION: 30%

SEQUENCE DESCRIPTION: This sequence is initiated by a transient followed by a failure to achieve reactor subcriticality. After failure to achieve subcriticality, the power is expected to equilibrate at 30%. The heat sent to the suppression pool is greater than the residual heat removal capacity. The containment is estimated to fail due to steam over-pressurization at about fifty-eight min. The emergency injection is assumed to fail when the containment fails due to either deformation of the injection lines or cavitation of the pumps.

INITIATING EVENT	T -- Any transient other than a loss of offsite power transient that requires a reactor shutdown.
SEQUENCE DISCUSSION	This sequence makes several assumptions which may not be valid. 1) It is assumed that the failure of three adjacent rods will not shut the reactor down. This may be conservative. 2) It is assumed that the High Pressure Coolant Injection, Low Pressure Coolant Injection or Low Pressure Core Spray pumps will not fail before containment failure. However, it is possible that the pumps could fail prior to containment failure due to lack of net positive suction head or high temperatures. 3) Traditional procedures were assumed. The new emergency procedures may allow the operators to remain within the heat removal capacity of the suppression pool. 4) ATWS 3A implementation was not considered.
SEQUENCE FUNCTIONAL FAILURE	Reactor subcriticality.
SEQUENCE EVENT SYSTEM FAILURES	-- Reactor Protection System (RPS) fails. -- The Standby Liquid Control (SLC) system fails.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	C -- RPS * SLC C -- 1E-6
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	1. RPS succeeds and control rods are inserted into the core OR 2. Recirculation pump trip and manual shutdown of the reactor using SLC or manually driving in control rods.
DOMINANT FACTORS DRIVING SEQUENCE	-- Failure of the operator to initiate SLC or to manually insert the control rods. -- Failure of any three adjacent rods to insert. -- Common mode failure of the RPS logic system resulting from hum[illegible]rrors in testing and maintenance.

PLANT: Peach Bottom

SEQUENCE: TW

SEQUENCE FREQUENCY: 8E-6 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: 7 transients/year

CORE DAMAGE CONTRIBUTION: 30%

SEQUENCE DESCRIPTION: This sequence is initiated by a transient (T) followed by a failure of the Residual Heat Removal (RHR) system to remove heat from the suppression pool (W). If the heat rejection is not initiated within twenty-nine hours the containment is assumed to overpressurize and fail at approximately 132 psi. The rapid depressurization caused by containment failure is assumed to cause the suppression pool water to flash, resulting in cavitation of the low pressure Emergency Core Cooling System pumps due to insufficient net position suction head. Injection is therefore predicted to fail subsequent to containment failure.

INITIATING EVENT	$T = T_1 + T_2 + T_3$ where T_1 -- Transient due to loss of offsite power (0.1). T_2 -- Transient due to automatic trip with interruption of main feedwater (3/yr). T_3 -- Transient due to an automatic trip without interruption of main feedwater (4/yr).
SEQUENCE DISCUSSION	The frequency of this sequence is somewhat subjective. Because of the long time available, the credit given for recovery can vary orders of magnitude depending on what recovery model is used. Most BWRs may also be able to delay containment failure further by opening normal containment vent lines.
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Containment protection from overpressure due to steam. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	W -- Failure to recover the Power Conversion System (PCS) or failure to remove heat from the suppression pool using the pool cooling mode of the RHR system.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	T_1: W -- 8E-6 T_{23}: 1E-6
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	1. One RHR train with flow to the heat exchanger of that train and cooling water operational to that heat exchanger OR 2. PCS.
DOMINANT FACTORS DRIVING SEQUENCE	-- Hardware failures in the output piping and valves of the Emergency Service Water (ESW) system. -- Failure of the operator to start any high pressure ESW pump within twenty-five hours.

PLANT: Grand Gulf

SEQUENCE: T_{23} C

SEQUENCE FREQUENCY: 5E-6 (From Grand Gulf RSSMAP)

INITIATING EVENT FREQUENCY: 7 transients/year

CORE DAMAGE CONTRIBUTION: 23%

SEQUENCE DESCRIPTION: This sequence is initiated by a transient followed by a failure to achieve reactor subcriticality. After the failure to achieve subcriticality the power is expected to equilibrate at 16%. The heat sent to the suppression pool is greater than the residual heat removal capacity. The containment is estimated to fail due to steam over-pressurization at about eighty minutes. The emergency injection is assumed to fail when the containment fails due to either deformation of the injection lines or cavitation of the pumps.

INITIATING EVENT	T_{23} -- Any transient other than a loss of offsite power transient that requires a reactor shutdown.
SEQUENCE DISCUSSION	The sequence description assumes several things, any of which if not true could change the sequence progression. 1) It is assumed that the failure of three adjacent rods will not shut the reactor down. This may be conservative. 2) It is assumed that the pumps will not fail before containment failure. This may not be true; the pumps could fail earlier due to lack of net positive suction head or high temperature. 3) It is assumed that the high pressure core spray can prevent core melt. This may be a non-conservative assumption. Because cold water is put on the top of the core, power instabilities may occur and upward moving steam may prevent water from reaching core hot spots. 4) Traditional procedures are assumed. The new emergency procedures may allow the operation to remain within the heat removal capacity of the suppression pool. 5) The ATWS 3A implementation have not been considered.
SEQUENCE FUNCTIONAL FAILURE	Reactor subcriticality.
SEQUENCE EVENT SYSTEM FAILURES	-- The Reactor Protection System (RPS) fails. -- The Standby Liquid Control (SLC) System fails.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	RPS -- 8E-6 SLC -- 1E-1
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	1. RPS succeeds and control rods are inserted into the core OR 2. Recirculation pump trip and manual shutdown of the reactor using SLC or manually driving in control rods.
DOMINANT FACTORS DRIVING SEQUENCE	-- Failure of the operator to initiate the SLC or to manually insert the control rods. -- Failure of any three adjacent rods to insert. -- Common mode failure of the RPS logic system resulting from human errors in testing and maintenance.

PLANT: Grand Gulf

SEQUENCE: T_{23} PQI

SEQUENCE FREQUENCY: 2E-7 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: 3 transients/year

CORE DAMAGE CONTRIBUTION: < 1%

SEQUENCE DESCRIPTION: This sequence is initiated by a transient requiring primary pressure relief (a loss of feedwater transient -T_2 or a transient in which the feedwater is available and then subsequently fails - T_3Q). At least one safety relief valve fails to close (P). The Power Conversion System (PCS) is not recovered (Q) and the Residual Heat Removal (RHR) system fails to remove heat from the suppression pool. At this point it is assumed that the containment will fail and the injection fails because pipelines have been severed or because injection pumps have cavitated. The core is then assumed to melt.

INITIATING EVENT	$T_{23} = T_2 + T_3Q$ where T_2 -- Transient due to an automatic trip with interruption of main feedwater (3/year). T_3Q -- Transient due to an automatic trip without interruption of main feedwater and independent loss of PCS (4E-2/year).
SEQUENCE DISCUSSION	The frequency of this sequence is somewhat subjective. Because of the large amount of time available, the credit given for recovery can vary orders of magnitude depending on what recovery model is used.
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Containment protection from overpressure due to steam. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	P -- Failure to reclose all safety relief valves. Different type of safety relief valves (Dresser) appear to have a reliability approximated at 1E-2 in place of 1E-1 for the 3 stage target rock safety relief valves according to letter from D.B. Waters (BWR Owners Group) to D.G. Eisenhut (NRC) entitled "BWR Owner's Group Evaluation of NUREG-0737 Requirements II.K.3.16 and II.K.3.18," BWROG-8134, March 31, 1981. Q -- Failure to recover the PCS in about twenty-two hours. I -- Failure to remove heat from the suppression pool using the pool cooling mode of the RHR system.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	P -- 0.01 Q -- 7E-3 I -- 3E-3
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	P -- Closure of all safety relief valves. Q -- Operation of the PCS. I -- One complete train of the RHR system with associated support systems.
DOMINANT FACTORS DRIVING SEQUENCE	-- One of three motor operated valves (MOVs) in RHR train B is closed for maintenance. -- One of three MOVs in RHR train A is closed for maintenance. -- One of two MOVs in the Standby Service Water System (SSWS) train B is closed for maintenance or SSWS train B pump is down for maintenance. -- One of two MOVs in SSWS train A is closed for maintenance or SSWS train A pump is down for maintenance. -- The calculations used to obtain the dominant factors did include rebaseline insights.

PLANT: Grand Gulf

SEQUENCE: S_2E

SEQUENCE FREQUENCY: 8E-9 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: E-2 SLOCAs/year

CORE DAMAGE CONTRIBUTION: < 1%

SEQUENCE DESCRIPTION: This sequence involves either a pipe break or a recirculation pump seal leak inside the drywell (S_2) followed by a loss of all injection (E).

INITIATING EVENT	S_2 -- A small LOCA or a recirculation pump seal leak inside the drywell.
SEQUENCE DISCUSSION	It is assumed in this sequence that if the high pressure injection systems are unavailable the reactor must be depressurized in order to initiate core cooling using the low pressure injection systems.
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	E -- Failure of all injection. (The predominant failure in this event is the independent failure of the high pressure systems and a failure to depressurize the reactor.)
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	E -- 8E-7
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	1. The High Pressure Core Spray train, OR 2. The Reactor Core Isolation Cooling System, OR 3. Any one of the Low Pressure Coolant Injection or Low Pressure Core Spray systems pumps.
DOMINANT FACTORS DRIVING SEQUENCE	-- Failure of operator to allow the Automatic Depressurization System to proceed or to manually depressurize the reactor. -- Hardware or maintenance failure of the HPCS or RCIC system.

PLANT: Grand Gulf

SEQUENCE: T_1QUV

SEQUENCE FREQUENCY: 4E-6 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: 0.1 transients/year

CORE DAMAGE CONTRIBUTION: 17%

SEQUENCE DESCRIPTION: This sequence is initiated by a transients due to a loss of offsite power (T_1) followed by the unavailability of the power conversion system (Q), failure of the high pressure injection systems (U), and failure of the low pressure injection systems (V).

INITIATING EVENT	T_1 -- Reactor shutdown initiated by a loss of offsite power.
SEQUENCE DISCUSSION	There are two TQUV type sequences possible: 1) The early TQUV where High Pressure Core Spray (HPCS) and Reactor Core Isolation Cooling (RCIC) are lost immediately and the low pressure injection systems are lost either due to independent failures of the Low Pressure Coolant Injection (LPCI) and Low Pressure Core Spray (LPCS) systems or because the reactor coolant system is not depressurized. 2) A later TQUV where all AC power is lost causing eventual loss of HPCS and RCIC systems and immediate loss of the low pressure injection systems. The results presented here have been rebaselined with the following changes: a generic frequency of 0.1 instead of 0.2 for T_1; an early norecovery of offsite power of 0.45 rather than 0.2; and the addition of the long term TQUV sequence (see sequence event system unavailabilities).
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	Q -- Failure of the Power Conversion System to provide makeup. U -- Failure of the HPCS or the RCIC systems to provide high pressure makeup to the reactor core. V -- Failure of the LPCS or the LPCI to provide low pressure makeup to the reactor core.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	Q -- 1.0 U (independent failure) -- 2E-3 V (independent failure) -- 4E-3 Diesel unavailability -- 3E-4 Nonrecovery of offsite power one hour -- 0.45 Nonrecovery of offsite power in eight hours -- 0.12 Nonrecovery of diesel in eight hours -- 0.7 UV given no recovery of offsite power or diesels in eight hours -- 1.0 (batteries are assumed to deplete in eight hours)
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	Q -- One complete condensate and feedwater path. U -- Either the HPCS or the RCIC train. V -- Automatic depressurization and any one of the low pressure pumps (LPCI or LPCS).
DOMINANT FACTORS DRIVING SEQUENCE	-- One of six motor operated valves is closed for maintenance or the RCIC pump is down for maintenance. -- Diesel #3 fails to start, diesel #1 fails to start, diesel #2 fails to start. -- Batteries deplete.

PLANT: Limerick

SEQUENCE: TC

SEQUENCE FREQUENCY: Case A -- 1E-7, Case B -- 1E-6 (From Limerick PRA)

INITIATING EVENT FREQUENCY: 6E-5 transients/year

CORE DAMAGE CONTRIBUTION: Case A -- 1%, Case B -- 9%

SEQUENCE DESCRIPTION: This sequence is initiated by a transient followed by a failure to achieve subcriticality. The Limerick PRA included thirty nine sequences that fit this description. The results are presented in two cases: A) those sequences in which core melt is caused by failure to shut the reactor down, and B) those sequences in which the control rods fail to insert, but the reactor is shutdown through alternate methods. Core melt eventually occurs in the Case B sequences due to failure of other systems.

INITIATING EVENT: T -- Any transient after which the control rods fail to insert.

SEQUENCE DISCUSSION: ---

SEQUENCE FUNCTIONAL FAILURE:
Case A: Failure to shut reactor down.
Case B: Failure to maintain reactor inventory after the reactor was shutdown.

SEQUENCE EVENT SYSTEM FAILURES:
Case A: Failure or various combinations of the Reactor Protection, Standby Liquid Control (SLC), Recirculation Pump Trip (RPT), Feedwater (FW), Reactor Core Isolation Cooling (RCIC), and High Pressure Injection (HPCI) systems (see success criteria).
Case B: Failure of injection systems or Residual Heat Removal (RHR) systems after the reactor has been shutdown by alternate means.

SEQUENCE EVENT SYSTEM SUCCESS CRITERIA

Failed Systems or Functions

Transient Initiator	2 SLC PUMP	2 SLC + FW + RCIC	2 SLC + 1 RHR	2 SLC + 2 RHR	2 SLC + FW + HPCI	HPCI LEVEL 8 TRIP	FW RUNBACK	MSIV LEVEL 1 TRIP	RPT
TURBINE TRIP	A	A	A	A	A	N	A	A	N
MSIV CLOSURE	A	A	A	N	A	N	A	A	N
LOSS OF OFFSITE POWER	A	A	A	N	A	N	A	A	A
INADVERTENT OPEN RELIEF VALVE (IORV)	A	A	A	N	A*	N	A	A	A

A: acceptable
N: not acceptable

*Note: The analysis classifies this combination of failed systems for an IORV as being not acceptable. The sequence was determined through analysis to be acceptable too late to be changed in the analysis.

DOMINANT FACTORS DRIVING SEQUENCE: Failure of rods to insert.

PLANT: Limerick

SEQUENCE: TQUV

SEQUENCE FREQUENCY: 1E-5 (From Limerick PRA)

INITIATING EVENT FREQUENCY: T_E -- 5E-2, T_F -- 1.78, T_M -- 3.2, T_T -- 3.98, transients/year

CORE DAMAGE CONTRIBUTION: 86%

SEQUENCE DESCRIPTION: The TQUV sequence for Limerick actually consists of four sequences: TQUV, TQUX, T_EUV and T_EUV all four sequences sequences represent transients followed by a loss of injection. This type of sequence involves a relatively fast core melt in an intact containment at low pressure. The four sequences are described briefly below in the table under sequence discussion.

INITIATING EVENT

$T = T_E + T_F + T_M + T_T$ where T_E -- Loss of Offsite Power.
T_F -- Main Steam Isolation Valve (MSIV) closure and Loss of Feedwater, Offsite Power.
T_M -- Manual Shutdown.
T_T -- Turbine Trip.

SEQUENCE DISCUSSION

TQUV -- A turbine trip (T_T), a manual shutdown (T_M) or a loss of Power Conversion System (PCS), (T_F) transient followed by a failure of or a failure to recover the PCS (Q), failure of high pressure injection (U) and failure of low pressure injection (V).

TQUX -- Same as TQUV except that V becomes X: failure to actuate the Automatic Depressurization System (ADS) in a timely fashion.

T_EUV -- A loss of offsite power transient (T_E) followed by loss of all injection (U and V). This sequence is the most probable of the four types and includes the station blackout sequence.

T_EUX -- T_E followed by loss of high pressure injection (U) and a failure to actuate the ADS in a timely fashion.

All sequences except T_EUV result in early failures of core injection. In T_EUV sequence, the high pressure injection systems (High Pressure Coolant Injection and Reactor Core Isolation Cooling - HPCI and RCIC) can conceivably last for more than four hours. At some time greater than four hours, the batteries will deplete and control of the turbine driven HPCI and RCIC systems will be lost. Failure of HPCI and RCIC is assumed at this time and core melt will eventually occur.

SEQUENCE FUNCTIONAL FAILURE

-- Loss of Reactor Coolant System (RCS) integrity.
-- Failure to replenish lost RCS inventory.

SEQUENCE EVENT SYSTEM FAILURES

Q -- Failure of PCS to provide makeup water.
U -- Failure of the HPCI and the RCIC systems to provide high pressure makeup to the reactor core.
V -- Failure of the Low Pressure Core Spray (LPCS) and the Low Pressure Coolant Injection (LPCI) systems to provide low pressure makeup to the reactor core.
X -- Failure to depressurize the reactor vessel at the appropriate time (i.e., failure of the ADS).

SEQUENCE EVENT SYSTEM UNAVAILABILITIES

	T_T	T_M	T_F	T_E	(Actual T_E calculation includes failure of diesels and nonrecovery of diesels and offsite power).
Q --	2E-2	7E-3	2E-1 (nonrecovery)	1	
U --	4.9E-3	4.9E-3	4.9E-3	4.9E-3	(for four hrs -- 1.0 after four hrs if no AC is available)
V --	7.7E-5	7.7E-5	7.7E-5	1	(If no AC)
X --	2E-3	2E-3	2E-3	--	

SEQUENCE EVENT SYSTEM SUCCESS CRITERIA

Q -- One Feedwater (FW) and one condensate pump (if RX >540 psia) and one MSIV open (so that FW can operate) and low vacuum interlocks on MSIVs and on bypass valves overridden if condenser vacuum falls below 7" hg.
U -- HPIC or RCIC.
V -- One out of four LPCI pumps or one out of four LPCS pumps.
X -- Operation of two out of five ADS valves.

DOMINANT FACTORS DRIVING SEQUENCE

-- Operator fails to initiate ADS in a timely manner.
-- Transient results in a loss of indication for need of ADS.
-- Failure to restore offsite power with thirty min.
-- Common mode failure of diesels.
-- Failure to recover diesel generator within thirty min.
-- Hardware failures of HPCI turbine.
-- Hardware failures of RCIC turbine.

PLANT: Limerick

SEQUENCE: TPE

SEQUENCE FREQUENCY: 2E-7 (From Limerick PRA)

INITIATING EVENT FREQUENCY: T_E -- 5E-2, T_F -- 1.78, T_M -- 3.2, T_T -- 3.90, transients/year

CORE DAMAGE CONTRIBUTION: 1%

SEQUENCE DESCRIPTION: This sequence represents a transient (T) with a stuck open relief valve (P) in which all injection fails (E). The TPE sequence for Limerick also actually consists of four sequences: TPQUV, TPQUX, T_EPUV and T_EPUX. These sequences, except T_EPUV, all result in early failure of core injection. For T_EPUV, high pressure injection (High Pressure Coolant Injection and Reactor Core Isolation Cooling - HPCI and RCIC) may operate until battery depletion (probably > four hours). Loss of injection and subsequent core melt was assumed to occur at that time.

INITIATING EVENT

$T = T_E + T_F + T_M + T_T$ where T_E -- Loss of Offsite Power.
T_F -- Main Steam Isolation Valve (MSIV) closure and Loss of Feedwater, Offsite Power.
T_M -- Manual Shutdown.
T_T -- Turbine Trip.

SEQUENCE DISCUSSION

TPQUV -- A turbine trip (T_T), a manual shutdown (T_M) or a loss of Power Conversion System (PCS) (T_F) transient followed by a stuck open relief valve and a failure of or a failure to recover the PCS (Q), failure of high pressure injection (U) and failure of low pressure injection (V).

TPQUX -- Same as TPQUV except that V becomes X: failure to actuate the Automatic Depressuirzation System (ADS) in a timely fashion.

T_EPUV -- A loss of offsite power transient (T_E) followed by a stuck open relief valve and a loss of all injection (U and V). This sequence is the most probable of the four types and includes the station blackout sequence.

T_EPUX -- T_E followed by loss of high pressure injection (U) and a failure to actuate the ADS in a timely fashion.

All sequences except T_EPUV result in early failures of core injection. In the T_EPUV sequence, the high pressure injection systems (HPCI and RCIC) can conceivably last for more than four hours. At some time greater than four hours, the batteries will deplete and control of the turbine driven HPCI and RCIC systems will be lost. Failure of HPCI and RCIC is assumed at this time and core melt will eventually occur.

SEQUENCE FUNCTIONAL FAILURE

-- Loss of Reactor Coolant System (RCS) inventory.
-- Failure to replenish lost RCS inventory.

SEQUENCE EVENT SYSTEM FAILURES

P -- Failure to reclose all safety relief valves.
Q -- Failure of power conversion system to provide makeup.
U -- Failure of the HPCI and the RCIC systems to provide high pressure makeup to the reactor core.
V -- Failure of the Low Pressure Core Spray (LPCS) and the Low Pressure Coolant Injection (LPCI) systems to provide low pressure makeup to the reactor core.
X -- Failure to depressurize the reactor vessel at the appropriate time (i.e., failure of the ADS).

SEQUENCE EVENT SYSTEM UNAVAILABILITIES

	T_T	T_M	T_F	T_E	
P--	1E-2	1E-2	1E-2	1E-2	(Actual T_E calculation includes failure of diesels and non-recovery of diesels and offsite power).
Q--	2E-2	7E-3	2E-1 (non-recovery)	1	
U--	4.9E-3	4.9E-3	4.9E-3	5E-3	(For first two hrs. -- 1.0 after two hours if no AC is available).
V--	7.7E-5	7.7E-5	7.7E-5	1	(If no AC).
X--	2E-3	2E-3	2E-3	--	

SEQUENCE EVENT SYSTEM SUCCESS CRITERIA

P -- Closure of all safety relief valves.
Q -- One Feedwater (FW) and one condensate pump (if RX > 540 psia) and one MSIV open (so that FW can operate) and low vacuum interlocks on MSIVs and on bypass valves overridden if condenser vacuum falls below 7 hg.
U -- HPCI or RCIC.
V -- One out of four LPCI pumps or one out of four pumps.
X -- Operation of two out of five ADS valves.

DOMINANT FACTORS DRIVING SEQUENCE

-- Operator fails to initiate ADS in a timely manner.
-- Transient results in a loss of indication for need of ADS.
-- Failure to restore offsite power with thirty min.
-- Common mode failure of diesels.
-- Failure to recover diesel generator within thirty min.
-- Hardware failures of HPCI turbine.
-- Hardware failure of RCIC turbine

PLANT: Sequoyah

SEQUENCE: T_{23} ML

SEQUENCE FREQUENCY: 3E-6 (From Sequoyah RSSMAP)

INITIATING EVENT FREQUENCY: 7 transients/year

CORE DAMAGE CONTRIBUTION: 3%

SEQUENCE DESCRIPTION: This sequence is initiated by any transient except loss of offsite power involving automatic reactor trip with an interruption of main feedwater injection (T_2) or any transient involving automatic trip with no main feedwater interruption (T_3). This is followed first by failure to recover the Power Conversion System (PCS) (for T_2 transients) or by PCS hardware and other system failures for T_3 (both are referred to as M); and followed, second by failure of Auxiliary Feedwater System (AFWS), (L). These failures result in loss of normal and emergency means of supplying water to the steam generators. The steam generators boil dry, the PCS pressure increases, water is discharged through the safety relief valves and the core uncovers and melts.

INITIATING EVENT	$T_{23} = T_2 + T_3$ where T_2 -- Transient due to an automatic trip with interruption of main feedwater (3/year). T_3 -- Transient due to an automatic trip without interruption of main feedwater (4/year).
SEQUENCE DISCUSSION	Sequence may be reduced more than an order of magnitude if feed and bleed credit can be given. It does depend, however, on procedures and specific plant characteristics such as availability of PORV support systems during feed and bleed operation. Without such information, this insight cannot be applied at this time.
SEQUENCE FUNCTIONAL FAILURE	Failure of core decay heat removal to the ultimate heat sink.
SEQUENCE EVENT SYSTEM FAILURES	M -- Failure of the PCS. L -- Failure of the AFWS.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	M -- 1E-2 L -- 4E-5
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	M -- PCS Operational. L -- 1. One of one steam driven pump or one of two electric pumps AND 2. One of five safety valves per generator or two of four steam relief valves.
DOMINANT FACTORS DRIVING SEQUENCE	-- Failure of single isolation valve between the condensate storage tanks and the AFWS pumps. -- Failure of the Essential Raw Cooling Water system.

PLANT: Sequoyah

SEQUENCE: S_2HF

SEQUENCE FREQUENCY: 5E-6 (From RSSMAP PRA)

INITIATING EVENT FREQUENCY: 2E-3 SLOCAs/year

CORE DAMAGE CONTRIBUTION: 5%

SEQUENCE DESCRIPTION: This sequence is initiated by a small LOCA having an equivalent diameter between one half inch and two inches (S_2) followed by failures of the Emergency Core Cooling Recirculation System (ECCRS), (H) and the Containment Spray Recirculation System (CSRS), (F).

INITIATING EVENT	S_2 -- Small (LOCA) break of the size of one half inch to two inches.
SEQUENCE DISCUSSION	Failures of the ECCRS and the CSRS are dominated by a common mode contributor. Between the upper and lower containment compartments are two drains that must be closed during refueling operations. The ECCRS and CSRS draw water from the sump in the lower containment. The water that the CSRS sprays into the upper compartment must pass through the drains to return to the sump for further recirculation. Closure of the drains would cause all water to ultimately be transferred from the lower compartment to the upper compartment. Attempting to draw water from the dry sump would fail both ECCRS and CSRS. This sequence could be reduced by an order of magnitude or more if the operator can depressurize during the injection phase to Residual Heat Removal without going to the recirculation mode or if the procedures for double checking the drain plugs after refueling have been improved. (TVA has improved procedures for checking the drain plugs.)
SEQUENCE FUNCTIONAL FAILURE	-- Failure of Reactor Coolant System integrity. -- Core decay heat removal during recirculation phase. -- Radioactivity removal from containment during recirculation phase.
SEQUENCE EVENT SYSTEM FAILURES	H -- Failure of the ECCRS. F -- Failure of the CSRS.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	HF -- 3E-3
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	H -- 1. One of two Low Pressure Recirculation System (LPRS), AND 2. One of two centrifugal charging pumps or one of two safety injection pumps, AND 3. Two of four heat exchangers corresponding to the operating LPRS. F -- 1. One of two containment spray pumps.
DOMINANT FACTORS DRIVING SEQUENCE	Operator failure to remove plugs from intercompartment drains following refueling

PLANT: Sequoyah

SEQUENCE: TMLB' ($T_1B_3MLB'_{13}$), (Case A); TB' (Case B)

SEQUENCE FREQUENCY: Case A -- 1E-6 (From ASEP Rebaseline)
Case B -- 6E-6 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: 0.1 transients/year

CORE DAMAGE CONTRIBUTION: Case A -- 1%
Case B -- 5%

SEQUENCE DESCRIPTION: This sequence involves a loss of offsite power which fails the Power Conversion System (PCS) followed by a loss of onsite power which results in the failure of the Auxiliary Feedwater (AFW) motor driven trains. A subsequent failure of the AFW turbine driven train results in complete failure to remove core decay heat. It is also possible that a loss of all AC power which results in a loss of Reactor Coolant Pump (RCP) cooling, can cause a catastrophic RCP LOCA. In this case, the sequence is actually a TB' sequence. To account for these differences, two cases are presented here. Case A -- TMLB' where the loss of RCP cooling does not result in a catastrophic RCP seal LOCA. Case B -- TB' where the loss of RCP cooling does result in a catastrophic seal LOCA.

INITIATING EVENT

T -- Loss of offsite power causes reactor trip.

SEQUENCE DISCUSSION

Case A: TMLB' = short term effects + long term effects

Short Term:	Long Term:
This assumes L(AFW turbine) fails independently and power is not restored in three hours.	This assumes L(AFW turbine) works initially and power is not restored in eight hours.

Case B: RCP seals fails catastrophically (1200 gpm) and success of PCS and turbine driven AFW are irrelevant because reactor inventory is lost.

SEQUENCE FUNCTIONAL FAILURE

Case A: Failure of core decay heat removal to the ultimate heat sink.
Case B: -- Failure of Reactor Coolant System (RCS) integrity.
-- Failure to replenish lost RCS inventory.

SEQUENCE EVENT SYSTEM FAILURES

Case A:

Short Term	Long Term
M -- PCS fails due to loss of offsite power.	M -- PCS fails due to loss of offsite power.
L -- AFW turbine driven train fails to supply water to steam generators.	L -- AFW turbine driven train fails due to battery depletion.
B'-- Failure of onsite power and failure to restore any AC power (either offsite or onsite) in one hour.	B'-- Failure of onsite power and failure to restore any AC power (offsite or onsite) in eight hours.

Case B:
M -- NA
L -- NA
B'-- Failure of onsite power and failure to restore any AC power (either offsite or onsite) in 1/2 hour.

SEQUENCE EVENT SYSTEM SUCCESS UNAVAILABILITIES

Case A:

Short Term	Long Term
M -- 1.0	M -- 1.0
L -- 4E-2 (AFW turbine driven train)	L -- NA
B'-- 1E-4 * 0.45 where 1E-4 -- failure of diesel generators 0.45 -- non-recovery of power in one hour	B'-- 0.12 * 1E-4 * 0.7 where 0.12 -- non-recovery of offsite power in eight hours 1E-4 -- unavailability of two DG 0.7 -- non-recovery of a diesel in eight hours

Case B:
M -- NA
L -- NA
B'-- 1E-4 * 0.6 where 1E-4 -- failure of DGs
0.6 -- non-recovery of AC power in one-half hour

SEQUENCE EVENT SYSTEM SUCCESS CRITERIA

Case A:

M	L	B'
1. One Main Feedwater (MFW) and condensate train and heat removal to condenser, OR 2. One MFW and condensate train and heat removal through steam relief valve, OR 3. One condensate train and heat removal through power steam relief valves.	1. One AFW turbine driven train OR 2. One of two AFW motor driven trains.	1. Offsite power OR 2. Onsite power.

Case B:

M	L	B'
NA	NA	1. Offsite power OR 2. Onsite power (AC power is needed for safety injection and containment systems to function).

DOMINANT FACTORS DRIVING SEQUENCE

Case A: -- Long term effects dominate due to operator failure to recover either offsite or onsite power (battery depletion).
Case B: -- Operator failure to recover either offsite or onsite AC power.

PLANT: Surry

SEQUENCE: V (Interfacing LOCA)

SEQUENCE FREQUENCY: << E-6 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: << E-6 ILOCAs/year

CORE DAMAGE CONTRIBUTION: < 1%

SEQUENCE DESCRIPTION: Breach of high pressure reactor cooling system boundary at its interface with the low pressure cooling system.

INITIATING EVENT	V -- Failure of Low Pressure Injection System (LPIS) check valves separating LPIS from High Pressure Injection System.
SEQUENCE DISCUSSION	A portion of the Emergency Core Cooling System (ECCS) uses double check valves in series as a barrier between the LPIS, which is outside the containment, and the high pressure Reactor Coolant System (RCS) which is inside the cc tainment. Failure of this barrier would result in reactor coolant discharge to the LPIS outside the containment. The LPIS would then fail due to overpressure and result in a core melt. When the components of the low pressure injection system are subjected to high primary system pressure, failure is expected to occur at some point in the system. The location and mode of failure is uncertain. It is possible that some delay in core uncovery could be achieved by operation of the high pressure injection system if this system is operational. Because of uncertainty in the response of the system and the ability of the operator to properly interpret and respond to the accident, it was assumed in the source term analysis that the active components of the ECCS are inoperable.
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	V -- Loss of barrier between RCS and LPIS.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	V -- << E-6 (based on testing and monitoring LPIS check valves).
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	All three LPIS trains isolated from RCS.
DOMINANT FACTORS DRIVING SEQUENCE	Failure of two LPIS check valves in series.

PLANT: Surry

SEQUENCE: AB

SEQUENCE FREQUENCY: ε (<< E-8), (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: 1E-4 lLOCA/year

CORE DAMAGE CONTRIBUTION: < 1%

SEQUENCE DESCRIPTION: This sequence is initiated by a large LOCA having an equivalent diameter greater than six inches followed by loss of power. The loss of power prevents the Engineering Safety Features (ESFs) from operating. Loss of ESFs result in failure of Emergency Coolant Injection (ECI) which is needed to mitigate the accident. The ECI functional requirements for a large LOCA are the accumulators (unaffected) and the low pressure injection system (failed).

INITIATING EVENT	A -- Large LOCA (pipe break) > six inches.
SEQUENCE DISCUSSION	---
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	B -- Loss of offsite and onsite power.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	Loss of offsite power -- 1E-3 Loss of onsite power -- 2E-3 B -- 2E-6
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	Sufficient AC and DC power to emergency buses to operate the minimum required ESF subsystems which are: 1. One of two Low Pressure Injection System trains AND 2. Two of three accumulators (passive).
DOMINANT FACTORS DRIVING SEQUENCE	Importance calculations were not done for this sequence by ASEP since ASEP did not find it to be dominant.

PLANT: Surry

SEQUENCE: S_3D

SEQUENCE FREQUENCY: 9E-5 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: 1E-2 SLOCAs/year

CORE DAMAGE CONTRIBUTION: 58%

SEQUENCE DESCRIPTION: This sequence is initiated by a small LOCA having an equivalent diameter of less than two inches (a Reactor Coolant Pump (RCP) seal LOCA) followed by a failure of Emergency Coolant Injection (ECI) system.

INITIATING EVENT	S_3 -- Small LOCAs (< 2") caused by a reactor coolant pump seal failure. The frequency was based on operational data.
SEQUENCE DISCUSSION	S_3D is a new sequence. ASEP expanded the Surry S_2D (which is defined as < 2") into two break sizes: S_2 and S_3 where S_2 -- Small LOCA not including RCP seal leak. S_3 -- Small LOCA caused by a RCP seal leak.
SEQUENCE FUNCTIONAL FAILURE	-- Loss of Reactor Coolant System (RCS) integrity. -- Failure to replenish the lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	D -- Failure of ECI: failure of high pressure injection. Depressurization of the primary system using the Auxiliary Feedwater System and subsequent low pressure injection is not considered.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	D -- 9E-3
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	One of three High Pressure Injection System trains.
DOMINANT FACTORS DRIVING SEQUENCE	-- Failure in sensing a low temperature condition of the operating Boron Injection Tank (BIT) heater. -- Hardware faults leading failure of alternate means of sensing BIT low temperature.

PLANT: Surry

SEQUENCE: TMLB' (Case A); TB' (Case B)

SEQUENCE FREQUENCY: <u>Case A</u> -- 2E-5 (From ASEP Rebaseline)
<u>Case B</u> -- 1E-4 (From ASEP Rebaseline)

INITIATING EVENT FREQUENCY: 0.1 transients/year

CORE DAMAGE CONTRIBUTION: <u>Case A</u> -- 13%
<u>Case B</u> -- 43%

SEQUENCE DESCRIPTION: This sequence involves a loss of offsite power which fails the Power Conversion System (PCS) followed by a loss of onsite power which results in the failure of the Auxiliary Feedwater (AFW) motor driven train. A subsequent failure of the AFW turbine driven train results in complete failure to remove core decay heat. It is also possible that a loss of all AC power which results in a loss of Reactor Coolant Pump (RCP) cooling, can cause a catastrophic RCP LOCA. In this case, the sequence is actually a TB' sequence. To account for these differences, two cases are presented here. Case A -- TMLB' where the loss of RCP cooling does not result in a catastrophic RCP seal LOCA. Case B -- TB' where the loss of RCP cooling does result in a catastrophic seal LOCA.

INITIATING EVENT

T -- Loss of offsite power causes reactor trip.

SEQUENCE DISCUSSION

<u>Case A</u>: TMLB' = short term effects + long term effects

<u>Short Term</u>:
This assumes L(AFW turbine) fails independently and power is not restored in three hours.

<u>Long Term</u>:
This assumes L(AFW turbine) works initially and power is not restored in eight hours.

<u>Case B</u>: RCP seals fails catastrophically (1200 gpm) and success of PCS and turbine driven AFW are irrelevant because reactor inventory is lost.

SEQUENCE FUNCTIONAL FAILURE

<u>Case A</u>: Failure of core decay heat removal to the ultimate heat sink.

<u>Case B</u>: -- Failure of Reactor Coolant System (RCS) integrity.
-- Failure to replenish lost RCS inventory.

SEQUENCE EVENT SYSTEM FAILURES

<u>Case A</u>:

<u>Short Term</u>

M -- PCS fails due to loss of offsite power.
L -- AFW turbine driven train fails to supply water to the Steam Generator (SG).
B'-- Failure of onsite power and failure to restore any AC power (either offsite or onsite) in one hour.

<u>Long Term</u>

M -- PCS fails due to loss of offsite power.
L -- AFW turbine driven train fails due to battery depletion.
B'-- Failure of onsite power and failure to restore any AC power (offsite or onsite) in eight hours.

<u>Case B</u>:
M -- NA
L -- NA
B'-- Failure of onsite power and failure to restore any AC power (either offsite or onsite) in one half hour.

SEQUENCE EVENT [illegible]

<u>Case A</u>:

<u>Short Term</u>

M -- 1.0
L -- 1E-2 (AFW turbine driven train)
B'-- 2E-3 * 0.45 where 2E-3 -- failure of diesel generators
0.45 -- non-recovery of power in one hour

<u>Long Term</u>

M -- 1.0
L -- NA
B'-- 0.12 * 2E-3 * 0.7 where 0.12 -- non-recovery of offsite power in eight hours
2E-3 -- unavailability of two DG
0.7 -- non-recovery of a diesel in eight hours.

<u>Case B</u>:
M -- NA
L -- NA
B'-- 2E-3 * 0.6 where 2E-3 -- failure of DGs
0.6 -- non-recovery of AC power in one half hour

SEQUENCE EVENT SYSTEM SUCCESS CRITERIA

<u>Case A</u>:

<u>M</u>
1. One Main Feedwater (MFW) and condensate train and heat removal to condenser, OR
2. One MFW and condensate train and heat removal through steam relief valve, OR
3. One condensate train and heat removal through power steam relief valves.

<u>L</u>
1. One AFW turbine driven train OR
2. One of two AFW motor driven trains.

<u>B'</u>
1. Offsite power OR
2. Onsite power.

<u>Case B</u>:

<u>M</u>
NA

<u>L</u>
NA

<u>B'</u>
1. Offsite power OR
2. Onsite power (AC power is needed for safety injection and containment systems to function).

DOMINANT FACTORS DRIVING SEQUENCE

<u>Case A</u>: -- Long term effects dominate due to operator failure to recover either offsite or onsite power (battery depletion).

<u>Case B</u>: -- Operator failure to recover either offsite or onsite AC power.

PLANT: Zion

SEQUENCE: S_2D (SEFC - loss of Component Cooling Water)

SEQUENCE FREQUENCY: 2E-4 (From ZPSS Review)

INITIATING EVENT FREQUENCY: 2E-4 SLOCAs/year

CORE DAMAGE CONTRIBUTION: 50%

SEQUENCE DESCRIPTION: The ZPSS review identified the most duminant sequence as one initiated by a loss of the Component Cooling Water System (CCWS), which fails the charging pumps and Reactor Coolant Pump (RCP) seal thermal barrier cooling. In this situation, the RCP seals are assumed to fail in thirty-five min. The safety injection pumps will actuate on low Reactor Coolant System (RCS) pressure. The Safety Injection (SI) pumps will fail in about ten minutes due to the loss of CCWS. Primary systems makeup will be lost. Core melt will occur unless cooling to the SI pumps or charging pumps is restored within forty-five minutes.

INITIATING EVENT	S_2 -- Loss of the (CCWS) which leads to a small LOCA.
SEQUENCE DISCUSSION	No pipe break small LOCA initiated loss of injection sequences (S_2D) were found to be dominant by either the Zion Probabilistic Safety Study (ZPSS) or the ZPSS review (NUREG/CR-3300). Information on the loss of CCWS sequence is therefore presented here. The assumption that a catastrophic seal failure occurs due to loss of seal cooling is a big uncertainty in this sequence. There is information that shows that a catastrophic seal LOCA (1200 gpm) may not occur in Westinghouse pumps. If no catastrophic seal failure does not occur this sequence would become bogus.
SEQUENCE FUNCTIONAL FAILURE	-- Failure of RCS integrity. -- Failure to replenish lost RCS inventory.
SEQUENCE EVENT SYSTEM FAILURES	D -- Failure of SI pumps caused by failure of CCWS.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	Loss of CCWS: D -- 2E-4 (loss of CCWS)
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	1. Two of five CCWS pumps AND 2. Two of six SWS pumps. 1. One of five CCWS pumps AND 2. Three of six SWS pumps. * Both success criteria result in similar numbers.
DOMINANT FACTORS DRIVING SEQUENCE	-- Pipe rupture in CCWS. -- Hardware or Maintenance outages of CCWS pumps. -- Failure to recover the CCWS.

PLANT: Zion

SEQUENCE: TMLB' (SE - seismic induced)

SEQUENCE FREQUENCY: 6E-6 (From ZPSS and ZPSS Review)

INITIATING EVENT FREQUENCY: Different probabilities for different magnitude seismic events

CORE DAMAGE CONTRIBUTION: 1%

SEQUENCE DESCRIPTION: In this sequence, a seismic event occurs that is large enough to fail both offsite power and the service water pumps. Failure of the service water fails the diesel generators due to lack of cooling. A loss of all AC power (station blackout) occurs which results in a failure of Reactor Coolant Pump (RCP) cooling, a RCP LOCA, failure of safety injection and failure of the containment systems. Core melt results.

INITIATING EVENT	T -- The initiating event is a seismic event large enough to fail both offsite power and the service water.
SEQUENCE DISCUSSION	This sequence does not strictly meet the description of a TMLB' sequence. It is more of a TB' sequence. Success of either PCS (M) or AFW (L) is irrelevant because it is assumed that the RCP seals fail catastrophically (1200 gpm) and a LOCA is created. However we have taken TMLB' to represent station blackout sequences. The sequence described here is an early core melt with failure of the containment systems which is what was analyzed in the source term study. It assumes that a catastrophic RCP LOCA occurs within one half hour after loss of cooling to the RCPs. The probability of this sequence would decrease if the assumption that a loss of RCP cooling caused a catastrophic seal failure were not made.
SEQUENCE FUNCTIONAL FAILURE	-- Failure of Reactor Coolant System (RCS) integrity. -- Failure to replenish loss RCS inventory. -- Failure of containment heat removal. -- Failure of radioactivity removal.
SEQUENCE EVENT SYSTEM FAILURES	M -- NA L -- NA B'-- Failure of offsite and onsite emergency AC system leading to failure of safety injection and the containment systems.
SEQUENCE EVENT SYSTEM UNAVAILABILITIES	The description of the unavailabilities (component fragilities and magnitudes of different seismic initiators) goes beyond the level of this description.
SEQUENCE EVENT SYSTEM SUCCESS CRITERIA	1. Any AC bus for front line systems AND 2. Support cooling systems require two buses between two units.
DOMINANT FACTORS DRIVING SEQUENCE	-- The seismic initiator. -- Fragility of service water pump shafts.

APPENDIX B

TECHNICAL BASES AND USER'S MANUAL FOR SPARC -- A SUPPRESSION POOL AEROSOL REMOVAL CODE

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