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UNITED STATES NUCLEAR REGULATORY COMMISSION'S
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION
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713TH MEETING
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
(ACRS)
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OPEN SESSION
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THURSDAY
MARCH 7, 2024
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The Advisory Committee met in a hybrid format, In-Person and Video-Teleconference, at 10:30 a.m. EST, Walter Kirchner, Chairman, presiding.

COMMITTEE MEMBERS:

WALTER L. KIRCHNER, Chair
GREGORY H. HALNON, Vice Chair
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VICKI M. BIER, Member
VESNA B. DIMITRIJEVIC, Member*
JOSE MARCH-LEUBA, Member

ROBERT P. MARTIN, Member
THOMAS E. ROBERTS, Member
MATTHEW SUNSERI, Member

ACRS CONSULTANT:

DENNIS BLEY*
MYRON HECHT*
STEPHEN SCHULTZ*

DESIGNATED FEDERAL OFFICIAL:

CHRISTINA ANTONESCU

ALSO PRESENT:

STEVEN ALFERINK, NRR
CHRISTIAN ARAGUAS, RES
LUIS BETANCOURT, RES*
NORBERT CARTE, NRR
STEPHEN E. CUMBLIDGE, NRR
SAMIR DARBALI, NRR
MATTHEW DENNIS, RES*
JARED GILLESPIE, PNNL*
KENNETH HAMBURGER, RES
RICHARD JACOB, PNNL*
IAN JUNG, NRR
KEVIN McGRATTAN, NIST

NICK MELLY, RES
CAROL A. NOVE, RES
JASON PAIGE, NRR
JEFF RADY, RES
PRADEEP RAMUHALLI, ORNL
REINALDO RODRIGUEZ, JR., NRR*
STEVE RUFFIN, RES
MICHELE SAMPSON, RES
GABE TAYLOR, RES
SUNIL WEERAKKODY, NRR

* present via video-teleconference

C-O-N-T-E-N-T-S

P-R-O-C-E-E-D-I-N-G-S

10:30 a.m.

CHAIR KIRCHNER: Okay. We're back in session. We are going to hear from the research staff on high energy arcing faults research.

(Off the record comments.)

CHAIR KIRCHNER: Okay. Thank you. Okay. Let's proceed, then. Christian, you're going to make the introductory remarks?

MR. ARAGUAS: I am, yes.

CHAIR KIRCHNER: Please, welcome. Go ahead.

MR. ARAGUAS: Can you hear me?

CHAIR KIRCHNER: Yes, very good.

MR. ARAGUAS: Excellent. All right. Good morning, ACRS members. My name is Christian Araguas. I'm the Director for the Division of Risk Analysis in the Office of Nuclear Regulatory Research. And I appreciate this opportunity to kick off.

I know this is part of the training overview that we're doing. So kicking it off as the first topic for our division to come and to talk to you about the research we've done under high energy arcing faults. So I did want to just take a few minutes, not much because we have a lot to get through, just to highlight some of the abbreviated history that got us to the point of talking about the results today and the deliverables that we have generated thus far.

And certainly I think you'll hear the team kind of expand on a lot of those as they go through the presentation. But HEAF came onto our radar in June 2013. OECD, or the Organization for Economic Cooperation and Development Nuclear Energy Agency, what we will use throughout, OEC NEA, put out a report on international operating experience, documenting 48 HEAF events which accounted for about 10 percent of the total fire events reported.

And of course, that was of interest to the NRC because those can be accompanied by losses of power to essential equipment in ensuing fires and could have other impacts which could complicate operator response. So to confirm the PRA methodology for HEAF analysis documented in NUREG-6850, it's titled EPRI NRC Research Fire PRA Methodology Nuclear Power Facilities. The NRC led an international experimental campaign.

I know this group has heard this already. But from 2014 to 2016 time frame, it's what we call our HEAF Phase 1 program. And the results indicated an unexpected hazard posed by aluminum components in or near electrical equipment as well as potential for unanalyzed equipment failure mechanisms. So as a result of the observations on the Phase 1 testing, the NRC conducted a review of our own operating experience.

And this review on uncovered six events in the U.S. where aluminum effects like those observed in the Phase 1 testing were present. That led to staff to issue an information notice in the 2017 time frame, drawing attention to those six events as well as the results that were coming out of the Phase 1 testing. In parallel, we put the HEAF issue into the generic issue program.

And that was screened in around the 2017 time frame. And subsequent to that in 2019, we launched a second international program that we were the operating agents for through OECD NEA, again, to continue a second round of testing, what we call our Phase 2 HEAF test program which included both or small, medium, and large scale tests. And it included both aluminum and copper components to address not only the NRC's or U.S.' interest but those member countries under the agreement.

So just a little bit more to scope out the research needs, in Phase 2, the staff engaged in a variety of activities. I'm sure this group is familiar with the PIRT process. But we do conduct a PIRT with experts around the world to help public meetings and issued Federal Register notices to solicit public input.

And to continue our efforts to advance the state of knowledge related to HEAFs, the NRC teamed up with its collaborative research partner, EPRI, or the Electric Power Research Institute, through an MOU that we have that allows us to engage. And so leveraging that knowledge and expertise both within the NRC and EPRI, we thought that would certainly be an avenue that would lead to a positive outcome and the research that we wanted to engage in. And I'd be remiss if I didn't also add in there the various groups that we also contracted with, specifically NIST, Sandia National Laboratories, and KEMA Labs where a lot of the tests were completed.

The results which we're excited to share with you today led to the development of a new PRA method and model consistent with experimental data, operating experience, and modeling tools. And these new methods which are captured in NUREG-2262 which is titled High Energy Arcing Fault Frequency and

Consequence Modeling was piloted at two plants and accomplished a goal of providing a framework for further enhancing the realism of fire PRAs. So I want to run through that because I'm really proud of the work that the team has done.

I think it's an example of an exemplary research program. It has all the components that you would like to see in a program, right? It looks at leveraging expertise not only within the NRC but bringing to bear expertise from around the world and through various stakeholders, seeking feedback from a variety of stakeholders, leveraging the various process to get us to the products that we have today.

So again, I'm excited to share with you. And with that, I will turn it over to, I think, Nick Melly. He's one of our senior fire protection engineers to start the discussion on the specifics.

CHAIR KIRCHNER: Thank you, Christian. That was an excellent summary. Are there any questions? We can go to lunch early.

MR. ARAGUAS: Did I cover it all? You guys are off the hook.

CHAIR KIRCHNER: No, Nicholas, please proceed.

MR. MELLY: Sorry, I'll repeat myself. My name is Nick Melly. I am the project manager or was the project manager for the high energy arcing fault program, and I'm going to start by giving a background as to why we entered into this project, how we approached it, and some of the challenges that we were faced solving the high energy arcing fault issue.

So what you see on the screen here right now is the methodology that was in place in NUREG-6850. That is the methodology that we follow for fire PRA and how HEAFs were handled. High energy arcing faults are typically occurring in electrical enclosures or in bus ducts.

There are two separate methodologies for each type of event. And NUREG-6850 breakdown of an electrical enclosure into two specific fire bins: one for the generic electrical fire that occurs in electrical cabinet and one for the high energy arcing fault. That is the -- the energy release is the determinator between where the frequency gets to the end.

Some of the lessons learned from NFPA-805 were that the bin 16 was too broad. It was a one size fits all model for both the medium voltage, the low voltage, anywhere in the plant. You use one methodology to model your high energy arcing faults.

So the low voltage cabinets were seen as the same risk as the medium voltage cabinets, which didn't necessarily align with the frequency or the severity of the events that we were seeing from the OP-E (phonetic). So the lesson learned was the need was there to create a more realistic vision between how high energy arcing faults were treated throughout your plant.

Next slide. As what I just described here, it's kind of graphically you have your normal electrical fires on the left-hand side which are your thermal fires with your classical heat release rate associated with them and then the zone of influence of damage based on that severity of fire, so that heat release, right?

And the zone of influence will typically encapsulate many cable trays or outside targets that assume damage in the fire PRA. Whereas on the right-hand side, you have your high energy arcing fault which has a different type of zone of influence where components can be initially damaged by the blast of energy and the immediate release of energy from the arc fault event as well as the ensuing fire at a later stage. So it's treated in two separate modes. Next slide.

One of the big questions for the working group as well as how we approach this was, how do we define a high energy arcing fault? There are many different things that can occur within a cabinet. You can have your arc flashes, your arc blasts, and then your high energy arcing fault.

And what I mean by the arc flash and the arc blast, these are typical events that are handled correctly by the electrical protection where you will have a short circuit in the electrical enclosure. But the breaker will immediately isolate that event and you only have an energy release in terms of milliseconds. So these events still do -- can damage the electrical enclosure, but they don't release enough energy to have your zone of influence damage things outside of that particular electrical enclosure.

What we're really focused on with these high energy arcing fault events is the events that that protection was either not present or it failed. So when we looked at the frequency of events and we're calculating the fire events database, we really wanted to focus on those events that had impact to external targets as well as had an extreme energy release associated with them. Next slide.

MEMBER MARTIN: Can I have you define high energy with the threshold?

MR. MELLY: So there was not a threshold in terms of megajoules of energy released for the high energy arcing fault. Definition for this bin, it was typical for us to do the EPRI review. And for the EPRI review, you don't necessarily always know the energy release for a particular event, especially because some of these are legacy events of what was the defining factor there was, were external targets damaged? Was the cabinet breached? Did the ensuing fire damage the external targets?

MEMBER MARTIN: Or of a damaged --

MR. MELLY: It's a damaged threshold rather than a total energy threshold.

MEMBER ROBERTS: Question about the overall research objective. You said that by definition of HEAF then is where the protection was either ineffective or failed. Did you look at ways to make the protection more effective or look at failure modes to try to make the frequency lower for the HEAF event?

MR. MELLY: We did not look for ways to make the protection more effective. But rather, we wanted to understand the protection schemes of the plants there were where it was in place, for instance. How many breakers were aligned to limit the energy to a particular event?

Does a plant, for instance, have a generator breaker which could limit the energy to the downstream event? We also looked for ways for protective features to mitigate the damage from that event. But in terms of making the breakers more effective, that was not part of the scope of the program. Our partner, however, EPRI, did do a large research effort to look at their maintenance practices of those breakers and issued several documents to inform the plants how to perform better maintenance procedures to limit the frequency of an event occurrence.

MEMBER MARTIN: Thank you. So is that something that folks take credit for in their fire PRAs?

MR. MELLY: It is if they adopt this new methodology. Moving forward, they can take credit for their electro coordination in a much more refined manner.

MEMBER MARTIN: Okay, thanks.

MR. BLEY: This is Dennis Bley. I recall after you guys first presented this stuff to the committee research stalled for a while. What kicked it off again? Were there a series of OPI events that did it or just some additional results from other people's research?

MR. MELLY: So one of the main reasons that research actually stalled was there was somewhat of a disagreement with EPRI and NEI on the data that was being collected in terms of coming up with a final result to the zone of influence. That resolved, those issues with EPRI in terms of the data that we are collecting and how it would be used in the modeling space as well as the development of the ZOI. Another stalling factor was the COVID pandemic limited the ability for us to perform research in person as well as prepare for the research to be conducted at NIST.

So COVID shut us down for about a year and a half to two years in terms of performing any physical testing. During that time period, we relied heavily on the analytical methodologies that we've developed working with NIST as well as EPRI to advance the fire modeling tools that we were using to expand the data set that we had already collected from previous testing so that we could answer the question in a more analytical manner with the limited test data that we did have.

MR. BLEY: Okay, thanks.

MR. MELLY: The next slide showing a skyscraper chart of -- in this slide, it's 27 plants that reported their fire PRA data to EPRI. And what you're seeing on the screen here is a breakdown of where the CDF contributions are coming from in terms of an ignition frequency bin per 6850. So on the right-hand side of the screen, you see the bins such as the electrical cabinets, transients, HEAF, other control board, and transformers and so on.

And on the bottom of the screen, you see the plant identifier. And how you read the chart is you can see from top to bottom where their highest contributors to the overall fire risk is coming from. So in a large majority, most of the risk is coming from the electrical cabinets followed by the transients, and then the high energy arcing faults.

MEMBER BROWN: Well, those are in cabinets, aren't they?

MR. MELLY: They're in cabinets, yes.

(Simultaneous speaking.)

MR. MELLY: Yes.

MEMBER BROWN: Are you double counting?

(Simultaneous speaking.)

MR. MELLY: We're not double counting

because you split the frequency between the electrical cabinets and the high energy arcing fault.

MEMBER BROWN: Okay. So you separate those out. Yu could add those up and say that's a compendium of the electrical from a cabinet standpoint?

MR. MELLY: Exactly.

VICE CHAIR HALNON: So from the transformer perspective, there's no ATF contribution to the transformer?

MR. MELLY: So that's treated slightly differently in that the large transformers that do experience these arc faults, typically, they're catastrophic failures in the transformer if they don't usually damage many components inside the plant.

(Simultaneous speaking.)

VICE CHAIR HALNON: That's because you design for it.

MR. MELLY: Correct. And there's a unique bin associated for transformers for both catastrophic transformer failures and non-catastrophic transformer failures which they'll have oil spills associated with them. You can see those in the transformer bin, the yellow further down the list.

VICE CHAIR HALNON: So that high energy

arcing fault line there or the landscape, whatever you want to call it, doesn't include transformer -- it only includes where there's damage to other components?

MR. MELLY: Yes. So for this bin, it specifically handles the transfer, the high energy arcing faults that occur in medium voltage, electrical equipment up to 6.9 kV within the plant, the low voltage, high energy arcing fault of 480 Volt or 600 Volt as well as the bus duct events -- the non-seg bus duct as well as the isophase bus duct events.

VICE CHAIR HALNON: Okay.

MEMBER BROWN: So what's the causal relation then between the heat event and the electrical cabinets which are the major contributors? The heat is like an initiating event. The electrical cabinet itself is the vulnerability. So how do you --

MR. MELLY: So we split that into the two particular bins just based on the occurrence of frequency. So for instance, the for electrical cabinet event, let's say I have an arc flash or an arc blast. That is initially -- immediately terminated by the breaker within the cabinet.

However, there is enough energy to initiate the internal components in that cabinet, the combustible components, yes. So we would then grow that fire within the cabinet per the guidance in 6850 or NUREG-2178 for a normal heat release, right? And the frequency would be assigned to the electrical cabinet fires rather than the HEAF bin. And the electrical cabinet bin also takes into account things like overheating components and a fire that can occur from age degradation or things like that. The real separators is just the HEAF is usually that quick initiating event that has the large release.

MEMBER BROWN: Is the plant listing, that's all nuclear plants?

MR. MELLY: All nuclear plants, yes.

MEMBER BROWN: And is the -- the heights of the bars is solely associated with how you associate with CDF?

MR. MELLY: Yes.

MEMBER BROWN: It's not an increased frequency -- not an increased -- it's not like a number of HEAF or fires in a cabinet, what have you. It's only the mathematical construct of whatever you do to associate with the CDF?

MR. MELLY: Exactly. So it's a culmination of a CDF from those scenarios that are associated with that amount.

MEMBER BROWN: Is there any compilation of the number of HEAF events? I mean, are these hypothetical events or these are actual HEAFs or this is projected --

MR. MELLY: These are --

MEMBER BROWN: -- CDF for a plant based on the assessment of it, not necessarily the results from an actual event occurring?

MR. MELLY: Exactly. These are using the values that were determined as the frequency which is a portion of the plant. So these are not actual events. This is how the plant model is read, even that they're using the frequency that is associated with operating experience.

MEMBER BROWN: Is there a tabulation in all those nuclear power plants, how many high energy arcing faults have occurred over the last -- since 1960?

MR. MELLY: Yes, and this report, 2262, does have an appendix which goes into great detail of every event that has occurred since 1979 as well as the details of that event, how it's classified. And we also include the disposition of other types of events like arc flashes and arc blasts. So there's an appendix that will go into all the operating history, why it's being binned in this particular frequency bin because we updated the frequency for this report.

MEMBER BROWN: Okay. Next question is how many high energy arcing faults have occurred in all the plants since 1979? Is it 10 or is it 300?

MR. MELLY: You're looking at around 20.

MEMBER BROWN: So over 50 years roughly, roughly 20 HEAFs?

MR. MELLY: Yes.

MEMBER BROWN: And you do your calculations based on that number, the actual number of occurrences. Twenty is pretty small.

MR. MELLY: Twenty is a small bin. But, in the scope of the consequence, it is fairly large.

MEMBER BROWN: As a result of that, haven't vendors -- have they installed -- let me backtrack. Forty years, I've worked in the naval nuclear program for 35 years. And then early '80s or sometime in that point, it was early '80s, we had a severe actual arc fault occur in one of the 450 volt switchboards.

Had three switchboards going along the bus about to queue into the maneuvering area for a submarine. And instead, it blew out into the space between two rows of cabinets. There was a guy sitting there.

Fortunately, he bent down to tie his shoelace and a fire ball went over his head and into the other side. Very exciting. My boss who was a four star came down and ripped my head out and says, what are you doing to fix this?

And at that time, I was doing nothing to fix that because nothing to fix. Didn't know we had to fix it. And he then encouraged me to work with the rest of the Navy to develop arc fault detection systems which these are enclosed water tight cabinets, the spray type.

And so we developed a process for doing that and installed arc fault detected systems in submarines. And then in the aircraft carriers, we had another one where another operator or chief as a matter of fact was sitting down by the exciter cabinet for the 4160 Volt switchboard. Blew out right over his head.

He happened to be bent over and he did not get injured. Two fortunate circumstances. So we had to then adapt it to not water tight necessary, but a little bit spray type but not totally air tight. So we had to modify it. So we actually developed systems to put in. Does the commercial world install arc fault detection systems if this is contributing to CDFs or not?

MR. MELLY: To my knowledge, there's been no plant that doesn't solve arc fault detection.

MEMBER BROWN: Okay. Just curious.

MR. MELLY: Yeah, and -- yeah.

MEMBER BROWN: Twenty is a pretty small number. And these are big open plants. They're not compact engine rooms or machinery spaces or engine rooms like a submarine has. And there are not people standing right by the cabinets all the time. Submarines and air craft careers are manned at every place. All right. Thank you.

MEMBER ROBERTS: Okay. And that's why I asked the question that your response was EPRI was working on this. So it sounds like EPRI has done research to figure what can practically be done to lower the frequency of the HEAF, which is what Charlie is talking about, because it depends on what you consider the consequences. If the consequence is acceptable from an operational standpoint, maybe you have a different view than worrying about fire PRA.

The conclusion and the summary in here was the consequence was not acceptable, both operational and safety perspectives, so there was more effort done. That's why I was wondering -- it's not your research, it sounds like, but it's EPRI's research -- is the benefit is clearly to lowering those, you know, whatever color that is, brown bars, whatever those are, is good in PRA space. But in terms of operational space, it's also good not to have the massive fire you're going to show in a few slides interrupt your plant.

MEMBER BROWN: And there's other consequences. Submarine, when you're boring holes in the water and one of those occurs, that's not a friendly event. And on an aircraft carrier, you're trying to take off and land aircrafts. So the carrier has got to be going on top of the water 25 knots or whatever it is to take off and land airplanes.

So, if you lose a plant, you lose a major switchboard like that, you can take a plant down for some period of time. You can operate the other plant in a carrier. But it's still not a good thing to have happen.

MR. MELLY: And, operationally, for nuclear plants, it's also an issue. The most recent one in -- or not the most recent one. But one that occurred in 2017 at Turkey Point did have a worker in the room when it occurred. And he was blown off of the switchgear and did injure himself when it occurred. So there are operational and safety concerns with these events. But I still --

MEMBER BROWN: But, economically, it hasn't paid off to go put stuff into the switchboards themselves. So you deal with the consequences from the PRA and analysis standpoint in terms of CDF.

MR. MELLY: So far, yes.

MR. BLEY: Hey, Charlie.

MEMBER BROWN: Yeah?

MR. BLEY: It's Dennis. Just to put this in a little bit of perspective, 20 events in 50 years, over roughly 100 plants is about 4 times 10 to the minus 3rd per year per plant. And then given that most of these don't need the scenarios where there's core damage. The contribution to core damage events might not be high enough to really engender the kind of response you're talking about. But it's when we order it, it's getting close.

MEMBER BROWN: Ten to the minus 3rd is not a trivial number. So we do other things for 10 to the minus 3rd. But I do understand the configuration of the plant and the --

MR. BLEY: I'm sorry. That's all I had to say.

MEMBER BROWN: It's hard to wrap my brain around 4 times 10 to the minus 3rd. I think that's the number you calculated quickly when I didn't do. But you've got other assumptions that lead to core damage as a result of it also.

I mean, it's other circumstances have to compile themselves in order to deal with that. So points are pretty voluminous. So it's if on an engineering judgment standpoint, I can see where the commercial would not spend -- it's a lot of money to go develop, particularly with switchboards that are not tight --

MR. MELLY: Right.

MEMBER BROWN: -- because then you -- as opposed to using pressure sensors and photo sensors and other type of stuff to trigger the upstream breakers to clear it, it's not very easy in non-airtight or spray tight cabinets.

MR. MELLY: Right. And as we get further along, the events that occur in bus ducts that are generator fed, another fault detection system may not even work for those types of events as we discuss later today.

MEMBER BROWN: One other question, are the bus work primarily aluminum in the commercial plants in the major switchboards as opposed to copper?

MR. MELLY: We will get to some of that. But I wouldn't say primarily. We did find in a --

MEMBER BROWN: It's more susceptible to loose connections?

MR. MELLY: More susceptible. I'd say it's about in 50 percent of the plants, the aluminum. And in terms of whether it's in the bus duct housing or the conductive material, 100 percent of the plants do have some type of aluminum in their plants. That was from an EPRI survey that was performed in 2019.

MEMBER BROWN: It's cheaper than copper.

MR. MELLY: Economics.

MEMBER BIER: If I can comment briefly, kind of following up on Dennis 10 to the minus 3 remark, it seems like the bigger issue may be an industrial safety issue rather than a PRA issue. And I'm remembering I think it was Savannah River, one of the nuclear waste cleanup sites that was shut down for, I think, a period of two years maybe or a year or more because of an industrial accident. There was no, like, radiation spill or whatever.

Some worker got hit in the head in construction and died. And the plant was shut down for a long period of time while they went over everything and had their audits and whatever. So the industrial safety side can be pretty significant too. It's not necessarily our purview here but it can be a big issue.

And back to some of the reasons why we began this work. Christian mentioned we have been doing this through the OECD and with the NEA. One of the first programs we did with them was a literature search in the fire events database project to actually try and figure out how many of these events were occurring.

As you can see, there's 48 out of the 415 events from the, at that time, ten member countries who were involved with this program were classified as high energy arcing fault events. So we saw that this was happening in all countries. And these led to complicated shutdowns.

And these were the types of events that you don't miss in a fire database because they're the headliner event of the year. So from that, we initiated the Phase 1 of the testing program which was very much a voluntary effort where the countries who were participating in the program donated equipment to us. So we got to test a wide range of types of equipment for a wide range of HEAF types. We served as the operating agent for that program. And that was from 2014 to 2016. Question, yes?

MEMBER MARTIN: Do you have a feel of those 48 events how many were -- when the plant was at power versus not at power?

MR. MELLY: Most of them were running the plant at power or leaving to power. So coming off of shutdown to on that power state, a lot of these events occurred during the transitional period. So bringing the switchgear into alignment and going to power operation.

MEMBER MARTIN: Okay. So that gives you a feel. I mean, it probably lowers the number a little bit as far as the principle threat at power.

MR. MELLY: Yes, one of the notable events that we've seen internationally was the Onagawa high energy arcing fault event. This occurred during the great earthquake in 2011. The event occurred because Japan was using hanging magne-blast breakers which are vertical lift breakers into their electrical enclosures.

And the Onagawa plant was actually the closes plant to the epicenter of the earthquake. And as the ground motion increased, the hanging breakers actually were damaged which initiated an arc in one of these enclosures. They postulate that arc then migrated and they actually had separate high energy arcing fault events in this lineup.

And what was complicated from this type of event was the fire for this arc fault lasted for eight hours. That was because the onsite fire brigade could not even enter the room from the amount of smoke that was concurrent with the HEAF event. And the offsite fire brigade could not arrive on the scene because of the tsunami impacts and effects of that nature.

So this damaged roughly, I think, ten electric cubicles within that particular cabinet lineup. And one unique factor that led to or that exacerbated the spread was Japan employees, their cable trays inside of the electrical enclosures, a cable tunnel that's directly above the electrical enclosures. So the fire readily spread across the top of all of the electrical lineup.

MEMBER MARCH-LEUBA: Did you go to different -- you have divisions?

MR. MELLY: This did not go to different divisions.

(Simultaneous speaking.)

MEMBER MARCH-LEUBA: It's the only one division?

MR. MELLY: Yes.

MEMBER MARCH-LEUBA: And how does it compare with PRA assumptions and obviously that's not good?

MR. MELLY: It was in line with our PRA assumptions. However, the fire was not in line with how they typically --

(Simultaneous speaking.)

MEMBER MARCH-LEUBA: And it's still confined to a single room.

MR. MELLY: It was confined to a single room, yes.

MEMBER MARCH-LEUBA: I don't know if it was lucky or if it was good.

(Simultaneous speaking.)

MR. MELLY: Yeah, this is probably the fire you would've been hearing about if Fukushima wasn't occurring.

VICE CHAIR HALNON: The violent portion of this, the arc, how long does that last?

MR. MELLY: It depends on the electrical lineup. But typically for the high energy arcing fault in the frequency that we're discussing, it can last anywhere from a second and a half up to 14 seconds.

VICE CHAIR HALNON: Okay. So the fire and everything resulting from it is what damaged the cabinets, not the fault itself?

MR. MELLY: It's a little bit of both. So you can --

(Simultaneous speaking.)

VICE CHAIR HALNON: And I don't understand fire brigade not being able to enter because there's too much smoke. When has that ever stopped firemen from going into a room?

MR. MELLY: It really depends on the capability of the plant fire brigade. If this made -- if this plant -- I don't know the specifics, but it may just have been made up of operators with generic equipment. But these events, as you'll see from the videos, do create a large amount of smoke. And from speaking with the fire brigade from the reports, it said that the room was actually too hot to enter.

VICE CHAIR HALNON: Too hot is different from too much smoke.

MEMBER MARCH-LEUBA: Is the smoke toxic?

VICE CHAIR HALNON: The smoke is typically not toxic. I mean, as far as smoke goes, but you're not breathing --

VICE CHAIR HALNON: Well, most fire

brigades, the reason they're brigades because they got the SCBAs that they can get in there and make the entry. And that's what they train for. But too hot is different than too much smoke.

MR. MELLY: Well, because of the smoke and because of the heat, they actually couldn't find where the fire was within the room.

MEMBER BIER: So I have a question that maybe one of the fire experts in the room can answer for me. My impression is that in the kind of commercial world, like, if you have a building on fire and your local fire department responds, my impression, my understanding from people I've talked to is that the fire department has an obligation to save lives. They will go into a burning building to rescue a kid or whatever.

But no obligation to protect property. So, like, if you have a warehouse fire and conditions are considered dangerous for the fire brigade, they will stand outside and watch it burn because they're not obligated to risk their lives to save an Amazon warehouse or whatever. So I'm curious what the rules of engagement are kind of for fire brigades at nuclear plants. Are they expected to respond at risk to their own lives to prevent a core melt or whatever consequence it might be?

VICE CHAIR HALNON: It's a graded approach, having been in that situation. In real fires, you make your judgment. But life safety is first. But then you just change your tactics basically.

There's a tactic called surround and drown. You just back off and just drain water. But electrical fires are a little bit special. You don't want to necessarily do that and experience says it could cause problems.

MEMBER DIMITRIJEVIC: Hi, this is Vesna Dimitrijevic. I have a question. I'm very curious about this fire in Onagawa. So this happened a switchboard room, I assume, right? And you said all the cubicles within the cabinet which it was initiate the loss to damage, right?

MR. MELLY: Yes.

MEMBER DIMITRIJEVIC: And how about other cabinets in the room?

MR. MELLY: So no cabinets across the aisle were stated to be damaged. It was only the cabinets within this particular lineup that were damaged.

MEMBER DIMITRIJEVIC: But see, I'm very

curious. You said the room temperature went very hot, right, because first they insulated because of the smoke. And you have a fire source and the fire brigade said the room was too hot. So how come this heat just did not damage the cabinets in the room?

MR. MELLY: That's a good question. I don't know if I've read the answer to that in any of the reports from this event. But I can reach out and try and get a more detailed evaluation of this event.

VICE CHAIR HALNON: So Vesna, the fire brigades are trained to make entry into the room and find the seat of the fire and put it out. It sounds like -- and just by looking at this -- there's a very large seat of the fire if you will. And it's right close to the door. So they probably couldn't --

MEMBER DIMITRIJEVIC: I'm not so concerned about the fire brigades entering or not entering. What I'm concerned is because you have multiple cabinets there. So they specify the cabinets which initiate the loss of the breakers cubicles.

But what happened to the cabinets which are in the room, let's say, across from that cabinet? Even if nothing is on and influence the really hot area, there is the temperature limit on the breakers, how long you can consider them operable and what the spurious operation that happened. And I'm concerned about other equipment in the room, was that lost due to temperature?

(Simultaneous speaking.)

VICE CHAIR HALNON: If you look at the detection on the far left, even that cabinet that was on fire --

(Simultaneous speaking.)

MEMBER DIMITRIJEVIC: Yeah, I know. I was wondering what is --

(Simultaneous speaking.)

VICE CHAIR HALNON: So they're very localized, very hot fires. And they're high up. So that's probably why the other cabinets were not greatly affected.

(Simultaneous speaking.)

MEMBER DIMITRIJEVIC: But it should be affected by the temperature, period. There is a limit where you can consider the breakers operable up to the --

(Simultaneous speaking.)

VICE CHAIR HALNON: Don't confuse operable with no damage from the standpoint of --

(Simultaneous speaking.)

MEMBER DIMITRIJEVIC: From the standpoint of the PRA operable and the damage, we are considering agreement can be credited to mitigate things.

(Simultaneous speaking.)

MEMBER BIER: Yeah, another point is that the difference between when something can be sort of assured to be operable and you can take credit for it in PRA maybe be more conservative than, gee, most equipment that goes through this would still be useable. We just don't take credit for it.

MEMBER DIMITRIJEVIC: Very true. But I'm talking from the PRA perspective. And this analyzes that from the PRA and see their perspectives. I was wondering how much agreement could be credited in this situation.

VICE CHAIR HALNON: That's a good point.

MEMBER BROWN: Somebody mentioned how long the arc fault lasts a minute ago, and you said something between up to 14 seconds or whatever.

MR. MELLY: Yes.

MEMBER BROWN: That's really dependent upon the cabinet configuration like in the submarine circumstances that was thee cabinets in a row. It beavered through one steel wall through the next steel wall down to -- conductor down the next steel wall and a fourth steel wall and through the fifth steel and beavering away on the maneuvering area. A wall, when it blew out across the operators.

So we literally took out three switchboards. And nothing happened in that time. And that was minutes, many minutes in order to do that. So it all depends on configuration of the cabinet in terms of how long one of these arc faults can last.

MR. MELLY: Yeah.

MEMBER BROWN: The carrier one was much faster.

MR. MELLY: And you're absolutely right. It is based on the electrical protection, the voltage as well as the current. And I misspoke a little bit. We did have one in the U.S., Fort Calhoun that lasted for 42 seconds and a low voltage that had to be cut off by the operators.

And that was because it was a low current event that did not trip any of the thresholds of the upstream breakers. So sometimes they can last for a little bit longer. And a methodology that we have developed takes that into account.

The next event that I wanted to discuss, also an international event. It occurred at the Maanshan Plant in Taiwan. It occurred in 2001, and this was a unique event because it did lead to a station blackout.

Multiple trains were affected from this high energy arcing fault. But the most important aspects of this, I think, we do have a CCDP calculated from this event. It was 2.2 e to the minus 3.

That is a very high risk threshold for an event like this. And it's because both safety trains were unavailable for over two hours. And it also led to complications for the operators.

The reason they lost both safety trains is because they could not realign the emergency diesel generator, the backup, because there was a CO2 system that operated as well as the smoke from the event. They could not get into the room that they needed to do the realignment until the smoke effects had dissipated.

MEMBER BROWN: The plant was shut down.

MR. MELLY: The plant was shut down during this event, yeah. Next slide.

VICE CHAIR HALNON: Do you what induced the heat event?

MR. MELLY: For this event, they postulated that it was seawater, a corrosive effect on the --

(Simultaneous speaking.)

VICE CHAIR HALNON: The cumulative effect.

MR. MELLY: It was an outdoor electrical enclosure that had the sea fog typically rolling in and affecting.

VICE CHAIR HALNON: We had at Crystal River during a no named storm back in '93. Whole switchboard started arcing.

MR. MELLY: So I'll go over this quickly because I think I'm already way over time. But we had the Phase 1 test that performed 26 tests in 2014 to 2016. We had eight member countries at that time.

The objective of this was to confirm or refine the existing methodology in NUREG-6850. And as I said, various equipment classes were donated for this program. Next slide. From this testing, we did see that 2 of the 26 tests, both of which were the only tests that had aluminum, showed a much higher energy release state which led us to believe that there could be a difference in the way that aluminum behaves within these high energy arcing faults.

Both the tests that contained aluminum damaged our instrumentation equipment which was located three feet from the electrical enclosure. So we were not able to accurately even assess the heat flux and the temperatures at three feet because we completely vaporized the equipment we were using to do testing. Since then, NIST did develop a little bit more robust measurement device so that we can actually get as close as we needed to, to these types of events so we would ensure data collection.

So that was one of the notable differences was just the severity of the event. But also we did observe that there was a difference in the smoke behavior. With a copper event, you're going to ejecting this large black cloud of soot and particulate from the event.

With the aluminum event, you're going to coat the entire surfaces with the aluminum oxide. And it almost looks like you've whitewashed the entire space after a test. The question became with that type of aluminum deposit influence other electrical components within the room and what impact it'd have to cross aisle electrical gear.

Or could it initiate a fault in a secondary power supply? From that, we also entered into the phenomena identification and ranking table, the PIRT, to understand the phenomena a little bit better to figure out what we needed to focus our Phase 2 testing program. What were the notable fields that we needed to focus our research and to answer the question of how to refine the zone of influence.

The countries that sent representatives for that were U.S., South Korea, Germany, France, and Japan. Next slide. We also initiated a joint working group with EPRI. It had equal parts NRC representation as well as our contractors from NIST and Sandia.

And it also had an equal part member from EPRI, including some of their contractors, including Jensen Hughes which is a contractor that handles a lot of the probabilistic risk, as well as we had plant representation, particularly Paul Cannon (phonetic) from TVA. So we could get both the implementation side of how things are being treated in the PRA as well as what are the plant impacts, what are the responsibilities of the plant PRA managers and owners as to how this would get implemented into future PRA updates.

MEMBER MARTIN: Quick question. You mentioned the PIRT. See any more from basically the conclusions of the PIRT?

MR. HAMBURGER: The PIRT was conducted in 2017 and it created a ranked list of research priorities which basically died at the research roadmap that we took between 2017 and essentially now.

So there was a number of areas identified that we felt were important avenues to go down. And Gabe is going to talk about how we responded to the conclusion of the PIRT. I believe actually that document, NUREG-2218, was reviewed by the ACRS in one of their reviews. So the conclusions were used in formulating the research plan.

MR. MELLY: And we do have a backup slide on those conclusions or it's covered in another future slide.

MEMBER MARTIN: Okay. I'd be curious when you bring the backup slide into the conversation.

MR. MELLY: For the record, that was Kenneth Hamburger speaking.

MEMBER BIER: Okay. Was the expert solicitation quantitative or it was mainly just kind of a consensus process?

MR. HAMBURGER: It was mainly a consensus process. So we presented several figures of merit and the items to be gleaned from any particular scenario. And then we ranked both the phenomena in terms of their important state of knowledge as well as the parameters associated with those phenomena in terms of their importance and state of knowledge.

So they're on the screen here. So the

main conclusions here were we needed a better way to characterize the fragility of targets when exposed to these types of extremely short but high heat flux events. We needed a better way to characterize the probability and severity of that ensuing thermal fire feeding heat as an initiating event.

And then there were all the unknowns related to aluminum. So how do we characterize these aluminum arcs versus copper arcs, what their ejecta looks like, metal oxidation. And the lowest priority on this list was characterizing pressure effects because we have seen some pressure effects in OPI, including damage, fire barriers and fire doors.

MEMBER MARTIN: I think you already kind of mentioned in the case studies that you presented, the role of moisture as contributor to these events. I would've expected the her conclusion to lead to, I don't know, moisture characterization or strategies to reduce that source or that failure mode.

MR. MELLY: So at the time that we conducted the PIRT, I don't know that we necessarily had done the full scope OPI review on the cause of the events and the root cause. But the report, 2262, does address the moisture intrusion aspect for a leading cause of these types of events. So it will direct you to now postulate a high energy arcing fault at, for instance, a barrier between an exterior building and an interior building where there could be typical water intrusion. It will also address the fact that if your bus duct has openings which you could postulate water intrusion into that area, you will initiate an event at that location. So the water intrusion factor is tied in both with the frequency and methodology.

MR. TAYLOR: Okay. Good morning. My name is Gabriel Taylor. I'm a Senior Fire Protection Engineer in the Office of Research, and I'm going to guide you through how we characterize the hazard primarily through testing.

Kenny is going to talk a little bit about the modeling. But testing was important for both informing the models and also informing fragility basically once components begin to fail. Ultimately, we wanted new ZOIs for the HEAF hazard. And we didn't have enough resources to just go out and do 100 tests. So we had to really rely on modeling and data to support validation of the models to make sure that they are predicting the hazard accurately. As far as planning experiments, we had the Phase 1 program that Nick talked about.

After that, the international community was very interested to look at the aluminum and some other aspects of this hazard. So we put together a test plan and had a public workshop back in early 2018 to go through that. And basically, what we were proposing, get feedback from stakeholders, change parameters, and so forth, make sure we were doing something that's really applicable to plant configurations.

After that, EPRI also did a number of research on their own. The survey was very helpful in forming the project planning. And it was a living document. We've changed it as we've learned more through the process. But, primarily, it guided us to develop data for the news on the modeling fragility for the experiments. On the actual testing, there was three scales.

And we didn't actually start off on the small bench scale. Back in '18, after we met with ACRS, we went and did four medium voltage full scape tests. And from that, we realized that there's some data that we weren't capturing to really support the model.

And that kind of made us step back and go do some smaller bench scale experiments. So bench scale is really to look at the particulate characteristics, size, distribution, oxidation levels, things of that nature that we can then use to inform the models that we're developing. One step up from that was what we call intermediate.

But it was really an open box type experiment, a box with one open end, similar to what the IEEE and MFPA have done for their arc flash modeling. And there we're able to really look at the arc behavior. We're able to look and see how the electrodes degrade and vaporize and melt.

Also interactions with the electro enclosure surrounding the arc was important to make sure that our models were predicting that reasonably. And then we did additional full scale because then you get the actual configurations of equipment that's out in the plan. The configuration does actually have an impact on how the hazard progresses and develops in those types of events.

Looking into the particle characteristics, one thing that we did learn from the 2018 workshop was the question of, okay, you know what you -- you know your initial mass of your electrodes are. You know what your final is. We can't -- no way to measure mass loss rate.

But we know the delta. But how much is that actually contributing to the overall oxidation that adds energy to the system? And we really couldn't answer that.

So collecting particles in our resting at full scale. Taking those back and utilizing them through SCM and EDS to get those types of characteristics helped us out substantially. Full scale, it's an industrial environment. We couldn't collect everything and analyze it down to the nth degree.

So that's where the bench scale and the closed calorimetry type of experiments really helped us out to get that fraction of actual mass loss that contributes to the oxidation and additional energy. As far as the oxidation results, there was kind of different grouping of particle sizes on a very small nanoscale. There are fully oxidized particles.

But the total mass is really not that much. So it's not adding much to it. And in a larger scale, you'll have droplets that are just falling out from gravitational forces out of the reaction zone. And they're not contributing either.

So you're left with that's really adding extra energy to the system is these micron sized particles. And based on the work that we've done, we're able to estimate an upper limit of both the oxygen -- or excuse me, the aluminum and the copper oxidation levels. He will talk about shortly and how he used that in the modeling.

Moving on to the intermediate scale, these open box text, the configuration shown in the upper right illustration with three vertical electrodes entering the box. The arc is initiated in the center of the box. And then we had instrumentation surrounding the enclosure, both thermal.

And what I'm really showing here is that following our '18 tests, some of the electrical folks, the NRC said it's a real missed opportunity if you don't go look into EMI and conductivity characteristics of these types of events. So in '19 when we did these experiments, we used some DDOT sensors, look at the EMI signature. We also use some other types of devices to look at air breakdown, air conductivity, and surface conductivity. But those three things ultimately what we were measuring wasn't anything to be of a significant concern to the type of equipment we find in the plant. It was definitely an increase, but it wasn't at a threshold that we or our experts at Sandia felt that --

(Simultaneous speaking.)

MEMBER MARCH-LEUBA: In one of these typical events, is the EMI pulse significant to damage or you're just concerned about heat?

MR. TAYLOR: Yeah, so the data from this showed that EMI wasn't significant to damage anything around it.

(Simultaneous speaking.)

MEMBER MARCH-LEUBA: I guess the heat is bigger.

MR. TAYLOR: Just a quick video here. What I want you to notice is just the large melted molten metal coming out of the opening on the boxes. So that gets to the question of how much.

Definitely those large masses aren't contributing to the oxidation. But you also see the arc dancing around between phases and phases of the ground. And that was also important to the modeling because we didn't do, like, a multi-physics model.

We were looking at that route, but it didn't pan out. And ultimately, we used a CSD code. And for that, you need to characterize your source term. So putting that source term in the right location was important.

And the magnetic fields and the literature that we're aware of helped us locate that. But also data like this was very helpful. Other things that we needed to help support the characterization was arc voltage, right?

The energy that goes in the model, voltage current duration, voltage is not your system voltage. The voltage collapses. It's dependent on the impedance of the arc which has other influencing parameters.

There are a number of models out there. Some of them were very good. But from a PRA application standpoint, we felt it was just too much additional resources that the analyst would have to do. And given the minimal difference it would have on just doing a point estimate, we came up with point estimates to use, one for medium voltage and one for low voltage.

Model tests, the lecture of mass loss, important to know the total mass loss, and then using the data from the particulate analysis to estimate the fraction that contributes. A method of Standback Junior (phonetic) worked really well and we ended up using that. And then there's other information on enclosure mass loss which we looked at empirical trends as well as geometry as I mentioned earlier.

MEMBER BROWN: The voltage levels, are those the switchboard voltage levels. Or those are relatively low.

MR. TAYLOR: Correct. So the -- for example, let's take the 650 volts for medium voltage. The data that supported that was the system voltage for that was at either 4160 or 6.9 kV. And, you know, during the arc, your voltage across the arc because your impedances are different.

MEMBER BROWN: Okay, okay.

MR. TAYLOR: So the first term for the modeling is really dependent on the arc.

MEMBER BROWN: Okay. So for your -- okay. You're measuring it at the location?

MR. TAYLOR: As close to the location as you can.

MEMBER BROWN: Got it. Okay. Thank you.

MR. TAYLOR: As far as measurement techniques, we measured a lot of different items with a lot of different sensors. Actually, in this kind of development center, we caused it a tungsten slug calorimeter. And basically because some of the other devices were actually melting in previous experiments.

So what's presented here on the thermal side at least provides coverage of a broad range of types of exposures, whether it's a plate thermometer, the ASTM slug that they use for arc flash, or the tungsten slug calorimeter. We also measured pressure inside the enclosure through a piezoelectric pressure transducer, the number of video and IR imaging. I talked about the particle analysis and also we had cable samples.

So they were just qualitative feature. We take some cables and put it on our instrumentation racks and then look at them after the experiment to see if there was observable damage. There was some issues actually trying to instrument them to measure circuit functionality that we had to --

(Simultaneous speaking.)

MEMBER BROWN: Was your cabinet airtight or vented?

MR. TAYLOR: All of our cabinets have vents in them.

MEMBER BROWN: Replicated plant configuration, not kind of theoretical testing configuration.

MR. TAYLOR: Right, and I have a slide that will touch on that. Here's just a general layout of the instrumentation racks. We take an array of our sensors and put them on these stands that are about 10 feet tall and 3 foot wide.

And we position them certain distance away from the enclosure. Have that back to our data acquisition system through some optical oscillators to measure the data. And the array is located pretty much where the arc is initiated.

There is some cases where the arc will migrate. But we try to minimize that by experimental configurations as much as possible to get usable data. I think this is kind of getting to your question on enclosures.

EPRI did a survey of the types of equipment. And this is just medium voltage equipment that they had. The GE magne-blaster from 41 percent while the ITE HK BB or BBC configuration, about 25 percent.

So for those two, we tested both those types of cabinets in our testing. And as you can see on the bottom, the one on the bottom right is the GE type gear. And the one on the center bottom is the ITE HK type.

And they are different where the main buses are located, how they're either drawn in a vertical lift. Why is that important is where the arc initiate at and where we see that initiate in the actual OPI. So we wanted to make sure that we were being represented not only in equipment design but how the OPI was showing us where these types of events were.

MEMBER BROWN: Medium voltage, but that runs at 4,00 -- 4,160 is a typical medium voltage, up to 13.8 and sometimes a little bit higher than that. If you try to do anything, a lot of the plants have 4,160 switchboards in them. Did you do a range to calibrate to say is the severity more or less depending on the initial characteristics of the switchboards?

MR. TAYLOR: For Phase 2, we did not do a range. We primarily focus on 6.9 kV. And Phase 1, we had some 10 kV experiments as well as some 4,160 experiments. And I think part of the reason why we didn't include that variable is that when you look at the arc voltage between the different system voltages, there wasn't that much difference.

VICE CHAIR HALNON: You're testing two different type of breakers translating to an opinion on what the configuration would be better for this versus not?

MR. TAYLOR: I don't think there's really one is better than the other. It primarily depends on where the arc initiates. So in the case -- if it initiates in a load type of configuration where it's very close to the back where you make your primary cable connections, that's going to be a worst case than if it's in, say, at the breaker stabs or the main bus in certain configurations.

VICE CHAIR HALNON: Okay. So no one design is better from the standpoint of preventing and/or limiting the damage?

MR. TAYLOR: Not really. The only thing I would say to that is in some cases, there may be extra enclosures that it has to breach through to get outside of the cabinet. So the ITE one in the center actually has an enclosure around the main bus. And then you've got the overall structure of the switch -- the skin of the switch gear. So it's got to breach through both --

VICE CHAIR HALNON: Okay.

MR. TAYLOR: -- to damage targets.

MR. MELLY: Yeah, and this is Nick Melly. We did not provide an opinion of which one was better. However, the methodology that we developed will allow you to take advantage of the differences in equipment design in terms of how you're calculating your zone of influence. For a certain type of cabinet, you can take advantage for the things that Gabe said, that extra layer of protection. And it will affect the zone of influence that you're calculating in the detailed approach for that cabinet.

VICE CHAIR HALNON: Okay. I mean, I assume the cabinet happens and that's toast. Now we're just talking about collateral damage at this point. Thanks.

MR. TAYLOR: Photometrics, in some cases we can get quantitative information. But it's primarily relied on for qualitative information, looking at the models and comparing them to the results of the actual experiments to see how the arc progressed, where the jet was coming outside of the enclosure. But we did use a number of different technologies to document it.

Here's just a short video. This is a medium voltage bus duct that we ran last year. It's got a (audio interference) overlaid the actual video. You can kind of see where it's kind of a cone shape to the side.

That's actually because soon after the arc initiated the panels blew off. And what we're seeing is that the arc going through the grounded enclosure, the bolts, the current is going through those bolts and it's just chewing the bolts up. And also some pressure increases causing that type of failure.

But you really see here in the later parts of -- I mean, we're two seconds in right now. You see the jet type nature and the extension of the arc away from the power supply. The power supply is coming in on the left side of the screen.

And we try to locate our sensors that is capturing the highest energy. We actually looked at testing to look at angles and figure out where we should put those instruments. Didn't always work, but in this case, it worked fairly well. In most cases, it worked.

But you can see, again, a lot of large chunks of metal, molten droplets. All that is falling out, not really contributing to additional oxidation energy to the system. Okay. Moving on to fragility, it's really trying to find what the thermal energy that equipment becomes damaged or ignited.

We felt that running HEAFs some inconsistencies between experiments. And to reduce that uncertainty, we wanted more consistent in prescribable exposure. We did use some of our previous information to characterize the profile of exposure for these in certain experiments.

But basically, we used Sandia's solar furnace facility to exposure very small section of cable samples in this case to certain heat flux profiles and monitoring them for function electrically as well as the ignition visually. So we ran a number of tests at Sandia, got that data, and then took it back to a sub-working group, the NRC EPRI working group, to actually develop the fragility guidance and thresholds. As part of this sub-working group, we broke into teams.

We tried to follow the shack process to the extent practical with certain time limitations. So we had a technical integration team that looked over the project and made the kind of final recommendations. And we had two separate teams that really did the technical analysis to support the position.

On the actual threshold, both teams were almost identical in what type of energy threshold it takes to damage the cables. There were slight differences in opinions on the cable admission. But through iteration and actually some modeling, we were able to come to an agreement on the admission piece.

Beyond cables, I mean, there's other important equipment in the plants than just cables.

We looked at what it takes to damage cables and conduits, cables and raceway trays, bus duct housing, whether it's aluminum or steel. Looked at enclosures, baseline enclosures.

How could that be damaged from these HEAFs from conducting a particular thermal nature. So while I think the bulkier targets in the PRA is going to be cables. We do touch on those other aspects in two of our reports.

Also, on this slide, fire barrier systems, if you have a pre-qualified, installed, maintained barrier, you can assume that it doesn't ignite and it doesn't damage whatever it's protecting. And that's a little different from 6850. 6850 had damaged whatever it's protecting. But you don't ignite it. So we are able to make some advancements there. And some plants are taking -- making use of that.

MEMBER MARTIN: On the megajoules per square meter unit, is there another time element there? Because it seems like you have a different response for a half second or 30 minutes arc.

MR. TAYLOR: There's no time -- it's an NG measurement. So it's taking your heat flux and basically integrating it over a certain time frame. And what we saw is not just the arc time frame.

It's also that arc heats up a lot of equipment. You get cherry hot metal that's radiating to your target. So it also includes any of that radiation thermal input, that measurement.

MR. HAMBURGER: This is Kenny Hamburger. When we ran the models and we were trying to figure out what duration beyond the extinguishment of the arc, we needed to run the models. We looked at the experimental data to see how long past the extinguishment of the arc those -- our instrumentation was still receiving heat flux.

And we found that upwards of 95 percent of that incident energy was received by eight seconds after the extinguishment of the arc. So when we apply the models to those thresholds, what we're really looking at is the duration of the arc plus eight seconds. So if it hits that threshold within that timeframe, we would consider (audio interference).

MEMBER MARTIN: Do you mean the one hour? Does that correspond to the 15 and the 30? So does that say that if you got 30 over an hour, that's okay?

MR. TAYLOR: Yeah, so, what we looked at there was actually we had data that showed one hour -- to meet ASTM E119 you actually put about 300 megajoules of energy into that system. So it's still maintaining a temperature, delta T, of less than the criteria in that standard.

So based on that, that's where that's coming from. So it's not really tied directly to the 15 or the 30. It's showing that that test, you can get 300 and you still have survivability of your protective equipment.

MR. HAMBURGER: Right. So that one hour is directly tied to the rating of the standard -- or of the electrical raceway fire barrier system.

MR. TAYLOR: And I guess last point, I didn't put a specific list of parameters. But for our test parameters, we typically followed what the survey showed as far as voltage and current. Voltage, whatever the operating of the equipment that we're using in nominal voltage, we use that. Current, for many voltages it's typically around 30,000 amps.

20.5 is kind of the average from the events that we were seeing. So learned about that. And then on the low voltages, it was slightly lower, about 18 to 20,000 amps.

The duration piece, we were somewhat limited on medium voltage at the experimental laboratory that we were using. So we pushed their machine as far as it could go. But we could typically get about 4 seconds out a medium voltage piece of equipment.

And we could go a little longer of low voltage. We were trying for 17 seconds in one experiment. We had a number that went 8 seconds.

MR. HAMBURGER: Okay. Good morning. I'm Kenny Hamburger, and I'm going to walk us through the modeling component of this research effort. And just before I begin, I want to mention that significant modeling contributions were made by Jason Floyd from Jensen Hughes and Dr. Kevin McGrattan from NIST who is here with us in the room this morning. Hopefully, he can answer your hard questions.

So one of the objects of our modeling was to fill a lot of the gaps that were left by the experimentation. The gaps namely are the different configurations that EPRI found when they did their plant surveys. So they found several hundred configurations in terms of system voltage, currents, the equipment style, whether it's horizontal draw or vertical lift or bus duct configuration, the aluminum electrodes, the copper electrodes.

You end up with quite a number of configurations. And like Gabe said, it's not practical to test all those configurations. And additionally, some of the longer duration arcs that we were postulating, our test laboratory couldn't provide those energy levels.

We were running up against the thermal limits of their generator. So we needed some way to evaluate the consequences of those very long duration HEAFs. And then lastly you saw our instrumentation array.

We essentially had an array of instrumentation at discrete distances from the cabinet. So we could tell you whether you are inside or outside of that 15 or 30 megajoules per meter squared at that point. But if we're going to refine these zones of influence, we need something a little bit more precise than that to cover the distances in between.

And unfortunately, we can't field an unlimited array of instruments in three dimensions because we start to block the instruments behind other -- so there's only so much we can do in terms of measurement space. So again, we need some way to fill in those gaps. AT the outset, we actually embarked down a couple of parallel modeling paths.

We weren't sure which one was going to pan out. This is a fairly complicated event in terms of the physics involved. So we looked at a multi-physics modeling suite from Sandia National Laboratories.

We looked at a modified empirical model from IEEE. And we actually conducted those modeling exercises through to the end result to compare with what we ultimately decided to use in developing these zones of influence which was hydrodynamic simulator or FDS. So just a little introduction to FDS.

It is a computational fluid dynamics code. Generally, it's used for evaluating the effects and behavior of fire. You can see a number of the features of FDS here.

It has heat transfer models. It has a number of other sub-models that are useful. And this is a model that's used fairly extensively in nuclear fire safety and fire PRA.

So this is a model that we were familiar with that many of our working group members have either used or evaluated. And that certainly contributed to our decision to proceed along this path with FDS. So again, going into this, we knew that there were certain things that FDS was not going to model. You can play that video here.

So this is one of those videos from the intermediate scale box tests. And the behavior in the arc is very chaotic. It strikes and it re-strikes as the voltage cycles.

This is not something that FDS is going to model. So one of the assumptions that we made here is that this arc behavior in this little zone here can be averaged out in both space and time. And we can represent it as a volume within our computational domain that simply dumps energy into the computational domain at a rate and magnitude consistent with the arc's thermal energy.

So if what we were interested in was taking place in that little box there, FDS would not be the tool to use. But what we're really interested in is what happening beyond this enclosure at one, two, and three feet in which case our assumption does hold up, that we can just represent that arc as a volume of space that's just pouring energy into our computational domain at the proper rate. Other things that the FDS is not inherently going to model is the dissociation of molecules at high temperature, formation of plasma.

It's not going to model any of the structural mechanical aspects of the cabinet response. So we have to -- where those things are important, we have to tell FDS how to handle those. Next slide. So we also recognize that this was a fairly novel application for FDS.

FDS has not been traditionally used to model these types of very brief, very high energy events. So there were significant model development activities that the working group undertook. And like Nick said when we were on testing hiatus over the course of COVID, we spent a lot of time, probably the better part of that year working on enhancements to the model, figuring out what inputs we needed, how to get those inputs, and actually, enhancements to the model source code itself to provide us with the mechanisms we need to get meaningful results out of this.

At the end of each of these intermediate confidence building steps here, the working group would evaluate the data. They would evaluate any additional inputs that were needed. We would look at the potential enhancements to the model.

And we did actually end up making some enhancements to the FDS source code to support this exercise. So this -- Dave, that's not a video, is it? No? Okay. So this is a typical -- you can go to the next slide.

This is a typical result of some of our

intermediate scale FDS modeling here. And I'm shying away from the quantitative data which can get a little messy. But from a qualitative -- from a quick look here, what we see is that the FDS does a fairly good job in predicting the direction of the energy flow.

Does a fairly good job at predicting where our enclosures are going to breach and the size of those breaches. And there is some limited instrumentation here in these intermediate scale tests. You can go to the next page.

This is again what a typical -- typical results from those intermediate scale experiments would look like. It looks like some of my text is covered there. What we found here is that while FDS doesn't do a great job mimicking the exact temporal nature of the energy, it does produce a magnitude of energy that is comparable to what we're seeing in the experiments.

Again, when you consider what we're actually trying to get out of this modeling exercise which is the total incident energy at points distant from the source of the arc, the temporal nature of this really just averages out and gets lost in the noise. What we're really concerned with her is getting the magnitude of the heat flux correct and making sure that it's sensitive to the appropriate parameters. So again, this is an intermediate step.

After we analyze this data, we would again go back. We would refine our inputs. We would look at the model. We would make recommendations and then proceed to the next step to build confidence that what we're getting out of this model is matching what we're seeing in our experiments and producing meaningful results.

When we were finally sufficient confident that FDS was producing meaningful results and scaled up our models to match the full scale experiments against which we ultimately benchmarked these models. So this is a cutaway of a medium voltage switchgear. And you can see in that small compartment where the energy is coming from, that would be the main bus compartment in a vertical lift breaker configuration.

A couple modeling features here. We represented the vent areas in the switchgear as vent areas in the simulation. And the way we handle the melting of the enclosure was essentially when each grid cell representing a steel enclosure reached the melting temperature steel or about 1,350 degrees Celsius. We simply took that that steel out of the simulation. And that was represented by a hole through which energy and particles could flow.

(Simultaneous speaking.)

MEMBER BALLINGER: That's an interesting point. I mean, when this steel would slump, there would be a lot more things happening before it melted. And so that influence --

(Simultaneous speaking.)

MR. HAMBURGER: So what we saw when we analyzed the breach areas in the intermediate scale test, the open box tests, the FDS was predicting smaller openings than we saw in the experiments because FDS was not considering the fact that at about 800 degrees Celsius, steel loses most of its yield strength. And when you're bombarding with metal particles, it's shredding like tissue paper.

MEMBER BALLINGER: Yeah, yeah.

MR. HAMBURGER: But that effect is mostly seen very near the arc. When you start to go through these internal partitions and get to the steel, the external enclosure and beyond, the yield behavior still becomes less and less important. But we're more interested now is the heat -- the far-field heat transfer effects that are melting the external enclosures and then how that het is being propagated through the computational domain.

VICE CHAIR HALNON: Quick question. Any difference in the copper versus aluminum? You showed pictures earlier where it was clearly a different --

MR. HAMBURGER: So that came -- that realization came all the way at the end of this exercise. What we saw was actually not much of a statistical difference between the copper and aluminum electrodes. And you'll spend some time puzzling over that because it didn't match up with what we had observed in the experiments.

And the way that I best understand this is essentially to consider an energy balance. When we take, for example, a 32 kA medium voltage 4 second HEAF, and we look at the energy that the arc is introducing, we're getting about 144 megajoules just from the arc, not totally neglecting metal oxidation. When we look at the total energy contribution of the metal oxidation using all those things that Gabe talked about, the stand back mass loss times the fraction that is converted to those micron scale particles times the fraction that's actually oxidized, what we find is about 7 megajoules of energy evolved for aluminum and about 1 megajoule of energy evolved for the copper.

When you look at the overall energy

balance, you're talking maybe 5 percent of the overall energy is actually due to metal oxidation. Now when you're looking at that just from the video, you're seeing 6 megajoules additional energy being evolved in this cloud of particulate. It looks pretty fantastic.

But as a fraction of the overall energy, it's not significant enough. And further consider the fact that when we reach the external enclosure, the energy if you could approximate it as a shape, it would probably be a cone spreading out from those enclosures. The aluminum and copper particles are oxidizing as the move through space in this ever growing cone.

The farther away you get from the enclosure, the greater the area over which that energy is being evolved. So when we define our fragility thresholds in terms of megajoules per meter squared, at one, two, and three feet away, that 6 megajoule delta is now being diluted essentially by the volume in which it's evolving.

So, at the end of the day, it turned out not to be a significant factor in the ZOIs between the copper and the aluminum electrodes. And this is as good a time as any to talk about how we model the aluminum and copper oxidation in the FDS. What we essentially did was define nozzles at each of the electrodes that would inject particles -- micron scale particles that would then emit either aluminum or copper vapor depending on electrode material. And then that vapor was allowed to combust according to FDS' combustion model.

So using all the information gathered from Sandia and the bomb calorimetry and the SEM to determine the extent of oxidation, we essentially defined the rate of vapor production to match what it should be as a fraction of a total electrode mass loss. And then we just allowed it to combust where it would in the computational domain. So that's the way we handled the metal oxidation within the model. This is one of the full scale experiments.

(Video played.)

MR. HAMBURGER: Two holes in the side panels. And then we have -- this is that same test simulated. You can see those little squares. Those are the simulated instruments to match those which we had in the test.

Again, just on the next page, I think I had a side by side. Just a quick qualitative check here. What we're seeing is the breach, the size of the breach, the timing of the breach, the direction and geometry of the energy flow. You can make a judgment for yourself here. But the proof is in the pudding as we say.

MEMBER MARCH-LEUBA: That's a cool invention. I want to go back to what you said. So if I'm looking at the event and (audio interference) aluminum, it looks awful. But if I wait an hour and I look and the holes are the same, copper will be the same energy?

MR. HAMBURGER: Ultimately, there's more energy involved.

MEMBER MARCH-LEUBA: It's just the --

MR. HAMBURGER: There are some differences. One of the differences is in the radiant fraction, an aluminum arc versus a copper arc. That is going to have some impact, especially on the internal partitions of how they melt, when they melt. So --

MEMBER MARCH-LEUBA: What I was trying to do is, after the first experiments, and the conclusion I got was everybody was rushing to change all the aluminum bars, or copper bars. And now you're saying don't waste your money. That's a big conclusion.

MR. HAMBURGER: What we're saying is that from the models that we ran and the evidence that we have, we could not draw a statistically significant conclusion that aluminum will damage more equipment or equipment farther away than the equivalent copper test.

MEMBER MARCH-LEUBA: So if I go to a plant and I see an aluminum bar, it's not dangerous. It's not more dangerous than copper.

MEMBER BROWN: Yes, it is.

MEMBER BALLINGER: There's another variable here. And that has to do with aluminum. It has to do with time, time and moisture, because that aluminum oxide between fittings and things like that that forms and the way they have to connect them.

You gradually develop an oxide. So when you try to push current through that joint, that thickness of that oxide can make a heck of a difference. And it gets to a certain point.

Then you get a big -- then you can get an arc copper. You don't ever see that. It's copper to copper. You don't ever see that.

And also the connectors that they use for aluminum at one point unless they've changed them, when they started to heat a little bit, you start getting creep in the aluminum. And that caused things to loosen up even worse. And so aluminum is way different when it comes to the timing.

MEMBER MARCH-LEUBA: So you're saying an aluminum change would have higher frequency of events. It would be more likely to fail?

MEMBER BROWN: More propensity for a problem to occur, depending on the environment.

MEMBER MARCH-LEUBA: Once it happens, it's about --

(Simultaneous speaking.)

MEMBER BROWN: Yeah, once it --

MEMBER BALLINGER: You know, it's a couple of million amps.

MEMBER MARCH-LEUBA: I mean, it is important. That's why you do research to find things that you do not expect.

MR. HAMBURGER: And aspects of that would be handled in the EPRI maintenance and surveillance, some documents that they published as to how to maintain and service your pieces of equipment. But in terms of the zone of influences that we developed, we did not develop a different zone of influence for the aluminum versus the copper. Also, the propensity, we did not see a frequency difference in those that were occurring in copper versus those that were occurring in aluminum components.

Now that may be because, like we discussed earlier, there's a limited number of events to pull from. And there's a large amount of equipment. So the frequency difference between the aluminum and copper is not apparent in the data that we have or it's not statistically significant enough to make a different frequency for components that have aluminum versus components --

MEMBER MARCH-LEUBA: But maybe the Navy has different data.

MEMBER BALLINGER: The difference is cost.

MEMBER BROWN: We preferred copper.

MEMBER BALLINGER: Yes. That's a different stress.

MR. HAMBURGER: And, as the report does show, there is a large difference in bus duct material. That it may actually vaporize much more aluminum bus duct material if it is aluminum versus copper. And that is evident in the majority thresholds that we developed for the aluminum bus ducts versus the copper bus ducts. Aluminum bus ducts are tied to the 15 megajoules per meter squared. Whereas the steel bus duct would be tied to 30 megajoules per meter squared.

So, now I'm going to shift to, okay, we

built these models, we ran these models. What did we do with these models? How did we get from there to levels of influence? The green dots that you see in the lower right picture, those are essentially singulated heat flux gauges that are time integrated.

So, at each of those green dots, and we constructed a 3D array of them at levels and axis along the location of the arc as well as outside any bent areas where we thought energy was likely to exit the cabinet.

At each of those dots, we are recording time integrated heat flux or total instant energy. And, what we do with that is at each plane, at each distance from each phase of each enclosure, we look at the maximum instant energy and we plot that as a function of distance from the cabinet.

So, at each of those green, 3D green, you know, rectangles, we're looking at the planes at each distance from the cabinet, finding the total incident energy, and that gives us an incident -- some instant energy as a function of distance from the cabinet.

From there, it's going to triple and get the order. The OI, if you're looking at your 30 and 15 megajoules per meter square thresholds.

One thing I'll note here is that we didn't have all the breakers inside of these cabinets. You can see that lightest blue box inside of the switch here, we modeled that as an inert mass, essentially just a big block of mass that helped dictate where the energy would flow.

So, to Mr. Halnon's question about which one is better and how do they perform against each other, the first thing that we found was that the massive breaker blocks energy.

So, if you have a horizontal dry off breaker, stabs are behind the breaker near the front of the cabinet.

And if there's a break -- if there's a fault on the breaker stabs, even after that breaker is sitting between you and the arc, and you don't get quite as much ZOI out of the front of the cabinet. The energy is shunted out to the sides.

Whereas, for a vertical breaker, the breaker sits between the location of the stabs and the floor, it doesn't do anything to stop the energy from flowing out the sides and out the front.

So, that's where we see the differences, because we modeled that breaker as just a big mass that directs energy in one direction or another. So, I think I discussed this.

So, the quantity that we're interested in is total incident energy at distances from the enclosure. Because we need this to match up with the way we defined our target fragility in terms of megajoules per meter square.

The treatment of model uncertainty. You may have seen these plots before. These are the types of plots that you'll see if you open up the FDS Validation Guide. And what they are, essentially, is the experimental values plotted against the predicted values. And, from those data sets, we can calculate the model bias, which is how far does the model deviate from reality for a given quantity? And we can calculate the relative standard deviations of both the experimental and the predicted modeling values, from which we can determine uncertainty bounds.

The model bias factor here was about .6. Which indicates that the model is systematically under-predicting the incident energy by about 40 percent.

I'd just like to contextualize that number a little bit, because, you know, I'm not sure how familiar everyone is with what we typically see when we look in the FDS Validation Guide.

The typical quantity that we validate in the FDS Validation Guide has a model bias factor much closer to one. Point six is not the most outlined quantity, but it is out there.

But where this differs is that we are not predicting the bias of a simple traditional quantity that's defined by a simple physical phenomenon. If you look at the FDS Validation Guide, we're validating things like hot gas layer temperature or seating temp velocity, seating temperature. Things that are defined by a singular physical phenomenon.

What we're -- the bias that we're looking at here is sort of the compounded bias of a number of physical phenomena. We're looking at the bias introduced by our choice of source term, the special mechanical full response of the cabinet, the heat transfer, the metal oxidation.

So, this is really the bias of the phenomena from A to Z here. So, if you contextualize it that way, .6 is really not bad at all. It's very much on the order of magnitude of what we're seeing. And what gives us confidence is that the model is sensitive to the appropriate parameter. So, we varied duration. We varied current. And we varied, you know, the parameters of our models.

We're seeing the appropriate

sensitivities. And we're also seeing the appropriate sensitivities when we look at the incident energy at the phases of the enclosure as we move around the enclosure.

So, I have some backup slides if anybody is interested in getting into the nitty-gritty of the model uncertainty. And maybe Dr. McGrattan has anything he'd like to add to that.

But the group did review this in quite a bit of details to determine whether or not a model was producing reliable results here. And the conclusion was that with the bias adjusted values, we could generate reasonable values for our ZOIs.

MEMBER MARCH-LEUBA: From where I'm sitting, not knowing much about this, 1/6th looks like you're cheating. It doesn't look good.

And so then, don't apologize.

(Laughter.)

MR. HAMBURGER: But here's --

MEMBER MARCH-LEUBA: Here's where it gets difficult. For a point of -- yours and the whole part, you are doing good.

MR. HAMBURGER: Thank you. That's how we saw it. Nice to hear you say that. So, here's where the rubber hits the road.

And this is a plot that we put together for each phase of each piece of equipment, for each model that we ran. The black line you're seeing that total -- maximum total incident energy at each distance from the phase of the equipment.

The red line, the solid red line is the bias adjusted exposure. So, we take that .6 into account. And then, you've got your dashed red lines at the 5th and 95th percentile. Values there are of our highest adjusted exposure.

So, getting our ZOIs here is how, for the exercise to see where that red line crosses our 30 megajoules per meter squared threshold and where it crosses the 15 megajoules per meter squared threshold.

So, for this example here, our solid red line crosses our 30 megajoules per meter squared threshold at about .6 meters. So, that would be our thermoset ZOI at this phase of the equipment.

And then, if we look out towards the 15 megajoules per meter squared intersection, it's about, looks like about one meter. And that would be our thermoplastic ZOI for this phase of this piece of equipment.

So, we didn't just blindly take all of these numbers and put them in some methodology. These were compiled into a large matrix of cases that we ran at each phase of each equipment.

And then, the working group processed that data. We consolidated the bend end where we could. And, generally, for the ease of PRA practitioners actually implementing this into their plan, we ended up fitting them in half foot intervals.

So, anything that ends up between say 2.5 and 3 feet, they were shunted to a three-foot ZOI bin for that particular phase of that particular bin of equipment.

MEMBER MARCH-LEUBA: I hate to be morbid. But where is the dense zone?

MR. HAMBURGER: So --

MEMBER MARCH-LEUBA: You know, for a person that's involved in one of these things, you know, I mean, gee whiz.

MR. HAMBURGER: I don't have a great feel for what 30 megajoules per meter squared does to the human body. I know -- I have a good feel for what it does to cables.

But I would suspect that maybe two, three meters away, my goodness. There is guidance in several documents for -- there is guidance in several documents for humans to withstanding rating to similar exposure and to heat flux exposure. We did not include that in this report.

But it would -- it is on the order of what it feels like or for a burn to human skin at a certain distance. The IEEE lists it as well. It's right below both 30 and 15.

PARTICIPANT: Yeah, well. I would -- I would expect in your -- and you'll label all that stuff. I would expect that the principal threat would be the airway --

(Simultaneous speaking.)

MR. HAMBURGER: That's 30 and that's not helping. That is the critter territory.

PARTICIPANT: Yeah.

MEMBER MARCH-LEUBA: It's from anything else combustion of others.

MEMBER BALLINGER: It's just dangerous.

PARTICIPANT: Yes.

MEMBER MARTIN: I wanted to ask you about reduced order modeling. So, CFD, when it comes to applications and safety spaces, because of its complexity requirements on B&B and such, it's rarely used as the ultimate basis there for any kind of decision making.

Reduced order models by either the agile or, you know, that allow you to incorporate, explicitly incorporate uncertainties and biases. You know, to address the breadth of uncertainties.

FDS, it's free, right? That's a good reason to use it if you're, you know, for doing a research. It's also going to be expensive.

Is there any consideration for, you know, agile analytical methods that you're pursuing in any way? And, you know, it goes to the point that Charlie made earlier about, you know, only 20 events in 50 years. You know, that if you're taking a C&D approach, it definitely isn't cost effective.

But if you have an agile approach, you can, you know, do a plan assessment, you know, and to the time. I know for the time it might actually merit, you know, a kind of, you know, analysis.

MR. HAMBURGER: So, that's exactly right. And we're going through this FDS to show the background of how we developed these.

But we understood that exact point. Because we're working with some of the PRA practitioners, who are doing this. We don't expect them to ever run the FDS or our particular case.

Only 262 was developed using the information that the working group developed, using this as background materials so that we could develop the zones of influence in a tabular format so that any PRA practitioner can pick those up and use them in a reduced scale model.

Not using the FDS, but using the analytical tools that we provided in the table format, to take a look at an electrical enclosure, look at the zones of influence that we developed using these tools. And then, implement them at the plant.

So, we do not expect any applicants to actually pick up FDS and run it according to these parameters. We expect them to use the tables that we have developed to do their analysis.

MR. TAYLOR: And the other thing I just wanted to mention, related to that, you know, as we were progressing through kind of the COVID phase where we couldn't do much physical testing, we looked at other alternatives.

And, one of them, the naturally 1584 method for arch flash, hazards for personal safety. And we ended up taking that model, modified it because there was a number of gaps that weren't directly applicable to our situation, and turned it into a tool that we could use to predict kind of a bounding ZOI.

When we went with EPRI to fully develop

the ZOIs that Nick will talk too here in a minute, based on the FDS, we ran that modified IEEE model. And in like 95 percent of the cases it was almost identical the maximum ZOI that, you know, was predicted.

So, it's a tool that we publish as our research information model that's out there. We're really in communication with IEEE to feed that information back in case they want to use our test data or anything to improve their map.

CHAIR KIRCHNER: So, I need to interrupt us here and just take the temperature, pardon the metaphor. I'm looking at the screen.

I'm also actually looking at the clock. So, we need to take a quick break for lunch. You've got, roughly, you've gone two-thirds. But you've got a lot more material.

How much time do we need to lunch? About 20 minutes? Is that enough?

No, I'm looking at the members?

MEMBER BROWN: You can just go to the bathroom and then go eat your lunch.

MR. HAMBURGER: When is Vicki going to be back? Because this next part is pretty important.

CHAIR KIRCHNER: I don't think she's back until 2:00.

MR. HAMBURGER: Okay.

CHAIR KIRCHNER: So, at this point why don't we take a break until quarter of 1:00, 12:45, a little bit more than 20 minutes.

That would give us a chance to get something to eat. And then, we'll come back and continue from there. And we'll add a pretty hard stop at 2:00. Okay.

So, you may have to pick up the pace in the next part of the briefing.

PARTICIPANT: That's a great idea. Let's blame them for being so slow. Yeah.

(Laughter.)

CHAIR KIRCHNER: No. It's typical there are a lot more questions up front than things. Okay. We are recessed until 12:45.

(Whereupon, the above-entitled matter went off the record at 12:15 p.m. and resumed at 12:46 p.m.)

CHAIR KIRCHNER: Okay. We're back in the session and back to the NRC research staff. Nick, are you next?

MR. MELLY: Yes. I'm going to give an overview of some of the PRA advancements that we developed as part of this program.

All right. So, the culmination of all this research that we've been talking about earlier today, as well as the testing, the modeling, and some of the international work, has led to the development of a new PRA methodology and PRA report.

The NRC and EPRI jointly report -- or, published NUREG-2262, which gives the new methodology for modeling high energy arching faults.

This is meant to update the NUREG-6850 Appendix M methodology, as well as the NUREG-6850 Supplement One methodology for bus ducts. Next slide.

So, some of the main differences that we tackled in the PRA and in the advancements were held to one of the main questions that we got from the industry and complaints, was they wanted to be able to use their plant specific details in terms of their electoral configuration to take credit for aspects of their plant that gave them benefits for high energy arching faults.

So, we specifically modeled the electrical distribution systems differently. We took into account the fault clearing times for breakers and how that will affect the amount of energy that can be deposited from a high energy arching fault event.

We adjusted the damage criteria as Gabe spoke to in detail earlier. We also adjusted the fire frequency as we discussed in terms of the definition of what a HEAF is, as well how it is bent within the plant.

And, in line with that, we also adjusted the non-suppression probability that is used throughout the plant that ties to those specific events.

We also did a significant update to the zones of influences, allowing for different zones of influence to use depending upon where you are in the plant, what equipment.

We also redefined what the bus duct to virtual origin is. That is, where the zone of influence is defined during a bus duct event, and where those thresholds begin.

And I'll talk a little bit in detail about all these as we move through my slides. We also have dealt with advancing how the fire propagates from one of these events. How it propagates from the enclosure where the HEAF begins, but then also how that fire can spread to or adjacent electrical enclosures as well as how it will behave when it interacts with cable trays or outside targets.

We also dealt with some mitigation as we discussed earlier, the electrical race with fire barrier systems, how they impact the ability to spread and damage targets outside of the enclosure as well as how generator circuit breakers can be tied into the methodology.

Just to give you a refresher of where we started and what those zones of influence look like, we started the NUREG-6850 Appendix M and that assigned essentially a five-foot vertical zone of influence to an electrical enclosure and a three-foot horizontal zone of influence to an electrical enclosure.

In any of that zone of influence you would assume that target would be initially damaged. And, if it were a cable tray, the first cable tray within that five-foot vertical zone of influence would also be ignited if it were not protected.

There was some other caveats, but typically that was the zone of influence that we're talking about, five-foot vertical, three-foot horizontal. And it was one size fits all. That was for all medium voltage and low voltage electrical equipment.

You also lose all components within the cabinet of origin as well as your losing power to the electrical lineup in the adjacent enclosures. Next slide.

One of the important aspects that we looked at, we wanted to take a look at the electrical distribution system. And, to do that, we did an extensive review of the operating experience, where have these events occurred in the actual plant so that we could understand the cause as well as what could be impacted from these events.

You can see on the left-hand side, this is typical to the events that have occurred on the auxiliary transformer side. We had three events occurring near the generator.

Like we said, those can last anywhere from four to 15 seconds and they're typically tied, a lot of these are typically tied to generator spin down type of events, where the generator will continue to feed the fault even after the generator has been shut down, because you still have that residual energy tied up in the generator that can feel the fault.

MEMBER BROWN: Does that mean the generator breaker didn't clear the fault?

MR. MELLY: Right.

MEMBER BROWN: In this extra breaker, I can see that. But --

MR. MELLY: In some instances, or in many instances, the generator does not have a generator circuit breaker. About 20 percent of the fleet has generator circuit breakers where it can isolate the generator from the downstream effects.

But the majority of the U.S. operating fleet does not have a generator circuit breaker.

CHAIR KIRCHNER: Very good then.

MR. MELLY: Yes.

CHAIR KIRCHNER: This is really big, Charlie.

MEMBER BROWN: Oh, I know that is. It's just from a protection standpoint and fault clearings, thinking of normal fault clearing standpoint that, to me, is a very bad distinction. I don't care how big they are.

And I'm sure Greg will take me to task on this.

VICE CHAIR HALNON: Well, no. I'm just curious, because we -- most plants put on this, where you drop a phase. I can't remember the name of it. But --

MEMBER BROWN: In the fuzzy?

VICE CHAIR HALNON: Well, it happened out west, the plant that had a degraded phase of their three phases. And it dropped and it -- things were, it wasn't a back there, it was voluntary.

But they put in a system that attacks a phase and it disconnects. So, I'm just wondering, I know that your classic output breakers don't necessarily clear the fault.

But there might be some other things that mitigate this. So, we might be looking at a conservative analysis depending on what individual plants may have configured there, their system as.

MR. BLEY: May I?

CHAIR KIRCHNER: Go ahead Dennis.

MR. BLEY: The open phase events and fixes for that were, happened because of open premises out on the grid. And then, you can separate at the transformer.

And that's another event. All those are events that were considered before.

VICE CHAIR HALNON: Yeah. I think you're right. Yeah. My memory is downstream. Yeah, okay.

MR. MELLY: Yeah. We'll get into that a little bit when we talk about the generator fed type fault. But that is the ones that have a lot of energy associated with them but have the spin down of the generator.

MEMBER BROWN: But that's the clearing function, is spinning down and turning it off.

MR. MELLY: Yes.

MEMBER BROWN: Maybe a giant water break.

(Laughter.)

MEMBER BROWN: I'm just teasing you.

MR. MELLY: Well, maybe they can install something like that. But, to do this to kind of shape where we are putting our operating experience on how we're going to treat these events, we really needed to understand where they occurred.

You can see six non-segregated bus duct events. These are the durations four to 15 seconds. There were five medium voltage events that occurred on the medium voltage switch gear.

And four of those events occurred on the breaker stabs themselves. So, that helped us inform the modeling when we were placing the faults. We'll show you where we put the, or hardwired that into the PRA as well.

MEMBER BROWN: So, these, the bus duct -- go backwards. The bus duct itself, I mean, which is a, kind of an insulated, isolated one of copper as opposed to connections.

You actually have the fault within the bus duct? Is that a manufacturing quality control?

MR. MELLY: So, there are multiple ways where it can occur in the bus duct. One of the typical ways in how we postulate it is, in a typical bus duct, one of the bus duct connections, you'll have voltage connections. So, --

MEMBER BROWN: So, it's like a -- But still at connections is what it is. Oh, okay. I was thinking it was a large continuous roll.

MR. MELLY: Well, no. Those voltage connections are within that large continuance run. So, typically you'll have around 12 feet of bus duct and then a voltage connection, a self-connection, and then another --

MEMBER BROWN: And that was not in the bus duct itself. It's at the connections of one bus duct section to another.

MR. MELLY: It's a little difficult to tell. Because if you look up at the ceiling in any switch gear room, it will look like one continuous bus duct.

MEMBER BROWN: I got that.

MR. MELLY: But you have to have a connection between that bus duct. So, in every 12 feet.

MEMBER BROWN: So, the connection is covered and not -- it's insulated also then.

MR. MELLY: Yes.

MEMBER BROWN: Oh, okay. So, you've actually got a mechanical connection within a large bus duct that could have two or three --

MR. MELLY: Yes.

MEMBER BROWN: Sections. And then, it's connected in. That's a lousy thing.

MR. MELLY: Yep. And there are some plants that went to welded connections rather than bolted connections.

But we've seen that you can also have these events in bus ducts for things like water intrusion or foreign material intrusion into the bus duct.

So, they do happen in the bus ducts about an equal likelihood. We'll get into the frequency split.

MEMBER BROWN: Thank you.

MR. MELLY: But that is one concern. And it's modeled completely differently than an electrical enclosure.

And, you can see here, here's how we mapped the operating experience down to the system level, the electrical distribution system level in the plant. And we tried to separate these into specific bins of where we saw these events occurring.

You can see the bin closest to the generator is pretty isophase bus duct type events. As we move further down the system we have our zone one bus ducts that are connected to the auxiliary transfer.

On the right-hand side when you go to the blue, it's the bus ducts associated with the station auxiliary transformer. And then, we move down into the one, is our medium voltage switch gear.

One important note there is that these are not -- there was a discussion at the beginning of whether this could be called the safety related, or the non-safety related bus duct.

But, from plant to plant, there are differences in whether that zone one is safety related equipment or if it's non-safety related equipment.

So, the way the working group approached this was, we were simply looking at how many breakers are potentially in between the generator and where the fault can occur? How many changes do we have to limit the energy to this type of event?

Result one is medium volt switch gear

directly off the bus ducts. Then, you have your zone for ED One, which is the bus duct between your medium voltage zone one and your medium voltage zone two. Again, that interaction between the safety related and non-safety related equipment typically.

And, as you move further down this list, you get to the bus duct between your medium voltage and your low voltage equipment. And then, to zone three, which is your low voltage switch gear and your load centers.

And, typically, as you move down the progression, these zones of influence become smaller because you'll have less energy to feed that fault.

MEMBER MARTIN: Since when, well, why does it matter whether it's safety related or not? Either one is a fault, you know, had an arch one bus fire.

MR. MELLY: Well, the initial thought was can I take credit for being -- it being safety related?

Is there going to be less of a frequency of occurrence where safety related equipment versus non-safety related equipment due to the types of maintenance that are conducted on safety related equipment.

But it turned out when we looked at it in greater detail, there was no way this slipped our frequency simply because you had a small number of safety related equipment and a very large number of non-safety related equipment. And the frequency kind of fell out in the wash.

MEMBER MARTIN: Okay.

CHAIR KIRCHNER: But isn't there some partitioning though and how the actual physical bus fires are located once you get to the canvas, like the reactor protection system and such?

And then, I mean, my concern would be taking out say something like the protection system. The cascading set of failures.

So, isn't there -- don't they split the electrical supplies coming into divisions and such and get physical separation?

So, that becomes, I would think, pretty important in the PRA analysis of fire.

MR. MELLY: Yeah. And we'll go into that in how we -- when we get down to the electrical cabinet lineup system, how we then apportion to do that.

MEMBER BROWN: Relative to your question, in the reaction protection systems and safeguards cabinets and stuff, I've only been in two commercial plants on one of our visits, region visits.

And the cabinets themselves were in a room separated with low voltage cables coming in. There was no high energy bus duct type stuff in those rooms.

I don't know whether that was intentionally the cause of -- potential for arch faults or high voltage cables in the room.

But they were largely kept in a protected space as opposed to -- now, those are -- that's a two out 100 in operating -- of roughly 100 operating plants right now.

So, what is -- so, I'm just trying to reflect on Walt's comment about the protection systems. But it seemed to me that they're not as susceptible in being damaged as they are as to being de-energized as a result of one of these faults.

And if you had -- if you look at separation of buses and different power going to various channels, then you should have at least one or two channels left depending on how -- if they design it for the drop in stuff that's supposed to be done.

That's why I asked the question. I'm just trying to amply it a little bit and make sure I understood.

MR. MELLY: No, that's exactly right. I

mean, the model will allow you to check if they do have enough distances between their alternate power supply systems and then, the interaction between them if at all possible.

But, also, the challenge when it came to creating this methodology is every plant is designed differently. So then, there's some plants that have these long runs of bus ducts in their BDU AT sections. And so, other plants have virtually no logistical bus ducts.

So, they're going to have to treat it differently, so this methodology allows them the flexibility to look at each particular zone and model it as their plant is designed.

MR. BLEY: Well, this is Dennis Bley again. For the plants that have bus ducts and have fewer bus ducts within a subsection set, does that snuff the arch?

Can we not have this happen if you have a subsection bus duct?

MR. MELLY: You can still have this arch with that subsection of bus duct.

MR. BLEY: You can use this, and through the metal, I guess, break up the arch, because the bus won't support it.

MR. MELLY: Yeah. Once the arch beings and creates a three-phase arching role, have enough energy just from the arch itself to breach the bus duct housing, and at that point, you're in the open.

MR. BLEY: Oh, okay. So, it's going outside for it. Okay.

MR. MELLY: We did not test any SF-6 build equipment simply due to safety concerns of the test lab.

(Simultaneous speaking.)

MR. BLEY: Understood.

MEMBER ROBERTS: I'm thinking of what Charlie said about the consequences being loss of power to the protection system. You said you looked at EMI, you said you looked at a potential for EMI. What about voltage spikes on the bus between the time of the arc occurring and the fault being cleared by the breaker? Would that be beyond the spec of the power equipment?

MR. TAYLOR: So we didn't look at, like, a secondary bus and any type of induced voltage on a secondary bus. We have all the electrical, you know, measurements from the actual test bus that we're using to see the current spike and that sort of thing, voltage decay.

So, yeah, we didn't explicitly look at voltage, induced voltages on other equipment, but we did look at the EMI signature.

MEMBER ROBERTS: I'm thinking about the actual voltage coming out of the breaker that's got that arc. Not a secondary concern but a primary concern. So what does voltage look like while the arc is there before it's -- gets killed?

MR. TAYLOR: Okay, I understand your question a little better now. So the voltage, it basically decays to a much lower level. So you'll be at like 4160, and it'll drop down into the 5-600 fault range.

MEMBER ROBERTS: Okay, so it doesn't spike. Thanks.

MR. MELLY: The next slide. So this is breaking it down into how we're actually looking at an electrical lineup. So for this methodology, we're no longer looking at an electro-enclosure by itself. So they're not treated the same.

We're now looking at a lineup of electrical equipment. We call it -- or it's the -- we've now binned it into gear that is in a lineup. So we'll treat differently the potential faults that are occurring on the primary supply, the secondary supply, and then the loads of the equipment.

Each one of these specific enclosures is going to have a different frequency of occurrence because from the OP-E feeds into this of where do we see these faults occurring. Typically they're occurring on the breaker stabs. So that's why you'll see a predominant amount of frequency going to the normal supply and to the secondary supply, that .57.28.

And then the rest of the frequency is occurring on the loads as you get further down the equipment. And as we get into the zone of influence, there will be a different zone of influence associated with these particular types of events based on the testing and the modeling.

Another key impact for this methodology is that we're now taking into account the fault clearing time. What is the ability of the electrical protects to actually clear the fault? That's going to have a direct and proportional link to the amount of energy that can be released during the specific event.

So we've tied the -- the total energy that can be expected from a certain event to that plant's fault clearing times. And then the very tiny picture on the left-hand side, you can see the results from a survey that EPRI performed asking all the plants what their specific fault clearing times were, associated with their UAT and SATs were.

And they typically ranged anywhere from .2 seconds up to 4 seconds. Those plants fault clearing times baked into their analysis will have a larger zone of influence because they have the ability to feed more energy to the fault.

So the plants now have the ability to actually look and take credit for their electrical distribution system as well as what can benefit them in the occurrence of an event

MEMBER HALNON: Nick, you went into this assuming, I guess, that the breaker coordination was all just as designed. Did you look at any times when, okay, so, four seconds, that would be if everything works great. Did you all get times when maybe it didn't work great and just double it or something to that effect, to get a cliff-edge effect issue?

MR. MELLY: So, we did, and that's captured in the other branch points of the tree. Is we took into account if the breaker does not work, and we can also have the -- or the generator spin-down effect. The generator fed the fault, as we call it.

So if the breaker does not limit the

energy at all and we're now taking the full effect of the generator spin-down up to 12 to 15 seconds, that's also a branch point that we're looking at.

MEMBER HALNON: Okay, thanks.

MEMBER BROWN: If you look at the initiation, excuse me, of the arc fault, one of the difficulties -- in the experience I relayed earlier was that the levels initially were not high enough to go in clear. But the currents got high enough that you could actually see the contact braidings of the breakers.

So that you ran the -- we never saw that, it was just the Gedankenexperiment that you do after you see this, and you run the risk of possibly fusing contacts such that the breaker can't clear. It tries but doesn't make it.

Was there any time -- initial arcs, which don't have to be ginormous, they can be small. But as they heat, heat, heat, expand the joint, the joint opens up, the arc gets worse. And then you start melting stuff.

That doesn't happen necessarily in one seconds or two seconds, that can be going on for minutes. And it can generate quite a higher level of currents, but which are all below the tripping characteristic, you know, their sensing capability of the breaker, the next breaker up-stream level.

Any looking at that, or how does that configure into this whole plot?

MR. MELLY: We did look at that explicitly, because that was something that came out of the 2008 public workshop that we had with EPRI and the public, as well as the industry. The event that brought that to our attention was really the Fort Calhoun event. That was what was described as a sputtering fault around 5KA.

And when we did the breaker investigation, it looked like that breaker wouldn't activate anywhere between -- until it hit 12, or 8-12 KA. So the fault was allowed to persist below that threshold value.

So when we looked at that, we looked at well, where are these ranges occurring. And we actually tested at that voltage level where we might defeat the breaker operation.

And when we did the modeling, we actually tied this specific model back to that Fort Calhoun event where we have an extended duration event. And the exact amount of energy released from that event, which was roughly 91 to 92 megajoules.

So we were looking at that when we tied it to our postulated zone of influence for these voltage events. What is the worst case that we can tend to experience? And we fit that to the model.

MEMBER BROWN: So t you kind of made an assumption that the breaker didn't clear?

MR. MELLY: Yes.

MEMBER BROWN: Okay. For whatever reason.

MR. MELLY: Mm-hmm. And we then assigned a probability of that, as well.

And you can see, a little bit bigger picture, this is a direct result from the survey as to what the various fault clearing times are per plant, as you can see the horizontal axis. And, again, ranged anywhere from .2 seconds to 4 seconds.

MEMBER BROWN: Is that .00 font?

(Laughter.)

MR. MELLY: It's very small. If you are interested in this, it is part of EPRI survey. It is in the fire modeling report. Yeah. Next slide.

We already talked about this a little bit earlier, the fire frequency changes. And I said earlier that it was 20 events. The exact number is 25 total events that occurred in bus ducts and electrical equipment.

In this methodology, we split the voltage or split the frequency into several bins different than we've done in the past. We provide you a frequency for low voltage electrical cabinets.

And as you can see in our current methodology, it -- the frequency has gone down for this specific bin. And that is because we removed a lot of those arced flash and arced glass types events that done really damaged the equipment or equipment outside of the origin of the HEAF. So a lot of -- that's why the frequency of that bin went down.

For the medium-voltage electrical cabinets, that Bin 16.B, the frequency did slightly go up, 2.1E to the minus 3. For the segmented bus ducts, we then split the frequency into the two different zones that we discussed earlier in the electrical distribution system, ones that were directly coming off the auxiliary transformer and the station auxiliary transformer.

Those tended to have a much higher frequency than the ones that were further down the system, so that we felt that it was enough of a difference to split the frequency for these specific bins.

CHAIR KIRCHNER: You -- every time I see something like this, I want to ask you how do you get three significant figures with the data that you're using?

MR. MELLY: So it is directly tied --

CHAIR KIRCHNER: I know you're using means for consistency --

MR. MELLY: Yes.

CHAIR KIRCHNER: And so on, because that propagates through the entire PRA exercise. But just what's feeling? I'm assuming you're going to show us sensitivity analyses coming up that shows varying these frequencies. But that's three significant figures.

What did you learn between the last time and this time that allowed you to portion it so well?

MR. MELLY: So the methodology that we're following is -- consists in a -- from -- or from NUREG-2169, which is the updated fire events frequency report. And in that report, there is a specific effort to actually take this into account, that for certain bins, we do not have a lot of data.

There's a lot of reactor years and in some instances there is potentially only or two events over the entire course of operating history. So there is a specific method that was developed to look at these low likelihood events. We call them -- we separate the frequencies into what we call non-sparse and sparse bins.

Spare bins are anything that have less than an event history of 2.5 over the total operating history. Since we're in the 20 to 30 range, this would actually be considered a non-sparse bin, so we have a lot of -- well, we have 25 to 30 events over the entire history of reactor operating years. But we treat that in the non-sparse bin.

And you use Bayesian updating methodology to get the fire frequency over the total reactor years. There -- we can argue as statisticians kind of all day whether three significant figures is appropriate for that type of a bin. But it has been the standard that we have used and developed as part of 2169.

MEMBER BALLINGER: It's the TI-89 syndrome.

MR. MELLY: Yeah. And we didn't choose to deviate from the methodology in that report for this methodology.

CHAIR KIRCHNER: No, I understand the need to be consistent in line with that.

MR. MELLY: Yeah.

CHAIR KIRCHNER: It's just that I'm always taken aback by the precision that you're doing your work at.

MR. MELLY: It is -- there's debate there to be had for sure. And we do provide uncertainty values associated with these values, as well as the confidence intervals that we have in this data.

MR. BLEY: Of course you're right, and it's a little silly. I think when we -- folks carry that kind of significant figures, they do it so when you add everything up it comes out to the right total. But yeah, it's kind of meaningless to have that many significant figures.

MEMBER BALLINGER: Talking to thermal hydraulics and materials people who are used to plus or minus an order of magnitude.

MR. MELLY: Now, contingent anytime we change the fire frequency, we also have to change the non-suppression probability. Those two values live together in all the fire models. For this specific update, the non-suppression probability did get a little bit worse.

And that is because we filtered those lower severity events, the arc flashes and arc blasts. Typically those were associated with a very quick suppression time or no suppression time at all.

So as you take those events out, the non-suppression probability does tend to go up. It wasn't a significant increase, but it did increase from the previous methodology.

Now we get into the actual zones of influence. So this what Kenny described in how we were developing using the thresholds of the 15 megawatts per meter squared versus the 30 megawatts per meter squared.

And we approached this like we have other fire methodologies, kind of in an iterative approach, where the plant does not need to dive into significant detail if they wanted to redo their analysis.

So we provided a methodology to use a screening zone of influence at your first stage if you wanted to adopt this. And then also provided a more detailed methodology to get into a plant-specific or a scenario-specific configuration.

What you see in the screening zone of influence is actually just the largest value of the zone influence that you'll see in that detailed methodology reported below.

The screening is simply just saying, well, this is my worst-case scenario for any particular case. I don't want to look into more detail of whether it's normal supplied load or the secondary supply.

I just want to look at an electrical enclosure and know what the worst-case possibility is. So we provide graded approaches so that they can look at their electrical enclosure.

We also, if they did want to get into the detail, they could look at a specific enclosure and say this is my normal supply. I'm interested in the zone of influence on the left-hand side of the enclosure because I have a cable tray, a vertical cable tray running near that equipment.

Then we'll be able to identify if they have targets of importance outside of that enclosure to, as Kenny said, the half-foot metric. So the zones of influence were developed to that metric so that they would be able to understand the damage footprint for the zone of influence.

Now the one thing --

MR. BLEY: Dennis again.

MR. MELLY: Yes.

MR. BLEY: When I calculate the zone of influence using all your cables here, does your guidance tell us to fail everything within that zone of influence? Fail it in the worst possible way? Or do they -- what's the guidance there? And is it laid out in 2262?

MR. MELLY: Yes, it is laid out in 2262. And the guidance is that if you are within the zone of influence, you do electrically fail that cable. And you also will have the potential to have spurious operation of that cable if it is electrically failed. However, you do not initially ignite that cable.

The only way that you would ignite that cable is if you would have the sustained heat exposure from let's say a thermal fire within the electrical cabinet, which can continue to provide heat in a vertical direction to a cable tray that is above that electrical enclosure.

MR. BLEY: So it sounds like you're saying if something's within the zone of influence and it's electrical, I assume it's both open and shorted in the worst possible ways.

MR. MELLY: Yes.

MR. BLEY: Okay. So that's, well, maybe not conservative because sometimes when these things happen, it progressives from one to the other, I understand that. But what about non-electrical equipment? Do you assume it's failed?

MR. MELLY: So we do provide specific

guidance for non-electrical equipment such as air instrumentation lines. We provide guidance for a specific, or a different zone of influence where they would be impacted.

We also provide guidance for where other things like a cross-aisle piece of electrical equipment. We go through all of those different types of targets and provide guidance.

MR. BLEY: Okay, thanks.

MR. MELLY: We'll go back to the other side. So this does look very busy and you have a lot of different rows in this detail guidance. But it does very quickly simplify when you understand that at a particular plan, you're tying this back to their SATs or their fault clearing times.

So you can see the power source and duration column there where we list different SAT/UAT times, time ranges, 0-2 seconds, 2 seconds to 1 second, 3 seconds. A particular plant is only going to be picking one of these rows that ties back to their particular fault clearing time and the following that across.

So all rows will not be fully applicable to all plants. It's going to then dictate back to their fault clearing time. Next slide.

Now we get into what we've done for the bus ducts. The previous methodology, which is documented in NUREG-6850, Supplement 1, had a 1-1/2 foot sphere zone of influence that was put on the bus duct itself. And then it had what was colloquially referred to as the zone of death that came out of the bus duct.

It had an increasing zone of influence of damage for 37 feet at a 15 degree angle as you approach the floor. We found that that was excessive to what we saw in testing.

But we also noticed that, functionally, many plants were choosing that 1.5 foot zone of influence for their bus duct at the center of the bus duct rather than the exterior sides of the bus duct. Which functionally meant when they applied this methodology, you damaged the bus duct, but no external targets.

And we saw that from testing, external targets could be damaged as well as OP-E. We've seen that the zone of influence can escape that bus duct. Next slide.

So we did redefine how you are calculating the zone of influence for a bus duct. The zone of influence now starts from the plainer surface of the bus duct, all four sides. And the zone of influence that we report is then measured from that surface to external targets.

Now, that does have a large impact on potential targets that can be damaged from these types of events, and also the bus duct zone of influence for certain cases did expand quite significantly, which means the bus ducts are going to have a larger important role in many fire PRAs.

We also changed that cone to a specific waterfall of damage, 1-1/2 feet beyond the surface of the bus duct directly to the ground. And we did that because we saw operating experience where you will have a high energy arcing fault within the bus duct, and a lot of the metal slag, either aluminum or steel, will then drop into or onto equipment that is below bus duct.

And you also have the potential to then drop it in a cable tray and ignite cables within that cable tray from the slag, providing you the heating mechanism to continue heating targets or cables below.

Again, here's a typical non-segregated bus duct zone of influence. Again, it's separated into again your fault clearing times, which is on your left-hand side and then the particular material that you were interested in.

For this we provide both a zone of influence for steel enclosures, as well as a zone of influence if you are aluminum enclosure. And that is because we saw a significant difference in the mechanism of heating if you had a steel enclosure versus aluminum enclosure.

The aluminum enclosures melted away far more readily and allowed the heat flux and the incident heat to escape that bus duct enclosure to get to external targets.

So just coincidentally, it is the same fragility thresholds, the 15 megajoules per meter squared for steel and the 30 megajoules per meter squared for -- I'm sorry, the other way around, 30 for steel, 15 for the aluminum.

Now, the impact that that has, if you are a plant that has aluminum bus ducts, you have a higher likelihood of having one bus duct potentially impact and breach an adjacent bus duct, which could then involve an alternate power supply.

You could potentially induce a secondary arc in a secondary power supply. And we've seen that in operating event history. The notable one that comes to mind is Diablo Canyon had a 13 kV bus duct, which then initiated a secondary arc in a 60 kV bus duct.

The next portion of the analysis that we wanted to alter was how we treated the ensuing fire. We've now had the HEAF within the electrical enclosure itself. How does the fire grow?

So we linked it to our other work that we did with NIST on how electrical enclosure heat release rates will progress in an electrical cabinet. And we relied on that to then build the fire.

So what the methodology now says is that at time T=0, you will have an ensuing fire within the cabinet of origin that is linked to 170 kilowatt heat release rate of that initial cabinet. And you now also have the potential to have that fire spread from to the left or to the right, to adjacent electrical enclosures because you could potentially be breaching interior panel walls and allowing the fire to spread.

This was an area of specific concern when we went out for draft for publication. And it had significant revisions in the final methodology.

We now provide specific energy thresholds that it will take to breach the enclosure walls, depending if you have a single enclosure wall or a double enclosure wall between electrical enclosures.

So we are now providing the ability to spread the fire differently, depending on your specific configuration.

And that is what I described here. The threshold limit for a single wall construction ties to 101 megajoules of energy that is deposited in with the initial cabinet. And as you go to the double wall configuration, you now double that energy required to breach the enclosures. So you're gaining, you have additional layer of protection.

As you can see just here visually, if that energy level is tied to the type of duration of event, as you do have longer and longer events, you're going to be releasing more energy, which is going to allow that fire to potentially spread from one enclosure to multiple enclosures.

Now, the impact that has on the -- yes?

MEMBER BROWN: Can you go back to 65? No, it's the next one, the one that had the 101 on it.

MR. MELLY: Yes.

MEMBER BROWN: It says you've got a double barrier that takes 202 megajoules to penetrate.

MR. MELLY: Yes.

MEMBER BROWN: Why wouldn't a 101 just take longer to penetrate two barriers? That's based on an actual experience?

MR. MELLY: That is true. Well, we tied --

MEMBER BROWN: That's just a longer -- a little bit longer time. You go through one and then you start beavering away on the next one.

MR. MELLY: That will be true, but we've tied the duration of the event to the energy of the event. So, per the modeling, it does take that amount of energy to --

MEMBER BROWN: Oh, if you're going to be quick.

MR. MELLY: Yeah.

MEMBER BROWN: Okay, all right. On the timing, all right.

MR. MELLY: And we're already talking about a time duration somewhere between two and eight seconds. So.

MEMBER BROWN: The timeframe was a little off.

MR. MELLY: Yeah. If it were minutes, we're in a whole different discussion. Next slide.

The other thing that came out of the public comment period was that those adjacent cabinets, they do not peak to the 170 kilowatt type fire at time T=0. They gain the full benefit of the distribution of potential fires that can occur within that cabinet and the normal cabinet growth rate that is in NUREG-2178.

So the functional effect of that was flowing the total amount of energy into the room. Because when we do have propagation from cabinet to cabinet, it leads to potentially having a hot gas layer in the room, which can quickly elevate the fire PRA and the importance of an event. And we've wanted to make sure that we were using all the tools at our disposal to be as realistic as possible when you do have these larger energy-type events.

And it was a good comment from a public comment period. It made the report better.

Some of the key findings in terms of damage were cables outside the enclosure of origin would be damaged but not ignited. No sustained ignition would occur if they did not experience sustained heating. That is different from the NUREG-6850 model. It is a more realistic modeling approach.

Also, we changed the cables inside the enclosure of origin. We do still assume ignition of all components inside the enclosure or origin, and we more realistically and definitively define how that fire would behave.

That time T=0 was never codified in Appendix M. And we've gone ahead and changed that.

And all of these findings in terms of the damage were based on the operating experience as well as the test.

Now the discussion of the generator circuit breaker. These are in less than 20% of the plants, but they do have a significant benefit when you look at the PRA, especially as well as if you look how these events will progress. If plants do have a generator circuit breaker, we're treating that as a frequency modifier on having the generator-fed fault to begin with.

So any generator-fed fault events would then be applied with the failure probability of the generator circuit breaker, which is 3.5 to E to -5. So that's applied outside the methodology as a modifier to the frequency of occurrence of these generator-fed faults. So, and that is based on the C-grade (phonetic) data and the reliability of that generator circuit breaker.

And as you can see, 3.5 E to -5, if we put that towards the probability of occurrence, we're beyond the space where we're worried about it in terms of a typical fire PRA.

MEMBER HALNON: That really surprises me that there's less than 20%, the circuit breaker. Trying figure out, how do you synchronize with the grid without one? I've worked at nine nuclear plants and they all had it, so it must be in that 20%.

(Simultaneous speaking.)

MEMBER BROWN: I can only surmise that there's some control over the switch yard, not in-plant circuit breaker, but a different breaker that they can synchronize across --

MEMBER HALNON: Yeah, I'm looking at just that simplified diagram.

MEMBER BROWN: Yeah, but that's a simplified diagram.

MEMBER HALNON: Yeah, but there's got to be something. I mean, you only had a disconnects and a circuit breaker.

MEMBER BROWN: Yeah.

MEMBER HALNON: Okay.

MR. MELLY: And that's all I had in terms of the methodology upgrades. That was quick, but the report has -- covers all of that in great detail, and if anyone has any further questions or interest to look at how it's done.

MR. TAYLOR: So, if not, we have Reinaldo

Rodriguez, who's going to lead us through the LIC-504 discussion. And Reinaldo's remote, so I think you're able to unmute yourself, Reinaldo, and please begin.

MR. RODRIGUEZ: Yes, good afternoon, everyone, can you all hear me?

MR. TAYLOR: Yes, we can hear you.

MR. RODRIGUEZ: All right. So my name is Reinaldo Rodriguez, and I'm a reliability and risk analyst in the Division of Risk Assessment in NRR. And I was the team leader for the LIC-504 evaluation that was done on HEAF. So I will brief you on what we did as part of the evaluation.

Before I get into details, I thought I would take this opportunity and provide a little bit of background on what LIC-504 is for those in the audience that may not know.

So this was developed as a lessons learned from Davis-Besse vessel head degradation and basically provides a structured process for documenting these issues the agency makes for emerging issues.

So it provides guidance on things to consider and how to document how the decisionmaking process for these type of emerging issues. And it's not intended to be a substitute for other NRC processes. Next slide, please.

So based on the evaluation, the team that is doing the evaluation can come up with different recommendations. And this is here to provide you a illustration of I guess the different outcomes that we could have as part of the LIC-504 evaluation based on, in this case, in changing CDF. That's not the only metric that the team could use, but it's the most common one.

So depending upon where we land, the recommendations coming out of the evaluation could be anything from no actions at all, we don't need to do anything, to issue information notices, bulletins, or any other kind of generic communications to the industry.

We could perform a formal backfit analysis. And even we can recommend to issue orders. So again, it depends on where land and what kind of metrics we use. Next slide.

So LIC-504 is basically divided in two major steps. The first step is to determine do we have an immediate safety concern. Do we need to do something right now, we cannot wait. So in the case of the HEAF LIC-504, we did do an immediate safety concern evaluation and we determined that there was no immediate safety concern.

And that was primarily based on the fact that plants are designed with defense in depth concept. Basically prevent fires from -- from starting, detect them early, put them out quickly. Also, the equipment that is in the plants, when properly maintained, they should protect the plant from fault.

So breakers, relays, protection schemes, fuses, those type of equipment are designed to protect the plant from faults. And when properly maintained, we don't have reason to believe that they're not going to work.

So there was -- there were some other considerations too. And we have that documented and publicly available if you're interested. We then move on to step number two, which was to do a detailed evaluation. Next slide.

So at the beginning when we first started the LIC-504 evaluation, there was a belief that the reason we were seeing what we were seeing in the testing and the operating experience was due to the fact that there was differences between copper and aluminum. And those materials will behave differently when you have a high energy arcing fault.

So that was the primary scope of the LIC-

504, was the difference between copper and aluminum. When we were in the early stages of the analysis, we received new information from the Office of Research and the working group.

And, basically, the information we received was that, based on what we have now and what we know and the state of the art, for modeling purposes, for fire PRA purposes, we should not treat copper and aluminum differently. Yes, there are some differences, but they are not enough to justify different methodology between the two.

So then we refocus the LIC-504 evaluation on okay, so what's the difference between NUREG-6850 and this new methodology that we're developing? So basically we have a different understanding on how this phenomena works from what we had back in 6850. Now we have new testing, we have more experience, we have a different methodology, different understanding how HEAFs behave.

So that was the new focus of the LIC-504. Okay, so what is the difference between what we understood back then in 6850 and what we understand now? The next slide.

So one thing that we wanted to do was to add as much reality, if you will, as possible to the analysis. Fire is a very configuration-dependent phenomenon. It behaves, you know, not the fire but what happens after you get a fire or a HEAF depends heavily on the configuration of the plant, depends heavily on the configuration of the switch gear room or the bus ducts and what's around.

And each plant out there is different. So what we did was we partnered with the industry and basically we identified two reference plants. So we had one BWR and one PWR plant. And what we did was we went out to these plants and tried to exercise the new methodology. At the time we had a draft publication from the working group, so that's what we used for the analysis.

And we did our own independent analysis and the plants did their own independent analysis. And then at the end we compare note and see okay, this is how we implemented the new methodology, this is how the licensee or the plant implemented the new methodology. We had the same draft methodology, if you will.

One thing that we did was, since we're only looking at two plants, we tried to do several sensitivity analysis. So what the team did was, okay, let's analyze the configuration of the plant that we are in right now. So this is what this BWR plant numbers will be, if you will.

But then we decided, okay, so what if we are at a plant that has a different fault clearing time and therefore a different zone of influence? So what would the analysis be if we go with the worst-case scenario from a zone of influence standpoint? So that was one sensitivity analysis we did.

Another sensitivity analysis we did was for several of the fire areas, we were in a room and we're looking at a source, so a breaker or a bus duct. And then we're looking at the targets of interest. So okay, so what are the sensitive targets here that if they were to get damaged, then that would potentially be a problem for the plant?

So for those targets, there were some that were within the zone of influence for the particular plant. But there were others that were on the other side of the room, and they were not in the zone of influence. So as part of the sensitivity analysis, we said okay what if at another plant this target, instead of being at the end of the room, is right on top of the ignition source?

So those are examples of the type of sensitivity analysis that we did to try to cover more configurations or potential configurations that are out there.

Based on the analysis that we did and the different sensitivity analysis, the team came up with recommendations for management to consider. And those are publicly available in a memo that we published, and you can see the ADAMS number there if you're interested.

I haven't heard any questions. If you have any questions, you know, feel free to interrupt me. And hopefully you can hear me still.

So what are the insights that came out of this evaluation? So as you can imagine, it depends, right. So at some configurations, the risk from high energy arcing fault was higher than in 6850. There are others that were lower than 6850.

And the risk can vary significantly based on the configuration. Some of that is due to the different zone of influence sizes, if you will. Some of that is also due to the fact that now, in the new methodology, electrical raceway barrier systems could be credited.

So, for example, if a plant had thermal attic or hammock installed, under the old 6850 methodology, those fire barriers could not be credited. And if you think about it, if you had a fire barrier, it meant that there was a target there that we were concerned about.

So in the old methodology you are potentially damaging those sensitive targets. With the new methodology now you can credit your fire barriers and therefore the equipment that would have been lost in the old 6850 methodology now will be available for the plant to safely shut down.

So those are some of the major impacts that we saw when we exercised the new methodology. At the end of the day, based on the numbers that we were getting, the team recommended that no additional regulatory requirements are warranted at this time.

We did have some other recommendations that we'll go into in the next couple slides. The other thing is that even though we were not officially piloting the new methodology, we were exercising the new methodology. And as part of that, we did have some feedback that we provided to the working group based on our experience in using the new methodology. And that feedback was used to improve the final method. Next slide.

So what were the recommendations? The recommendation was to issue an information notice, which we did in 2023-01. And it's currently out in public. And basically that was to communicate with our external stakeholders on the information that we gathered from the analysis and the different insights that we gathered from the analysis.

We also recommended that this will be taken into consideration as part of the ongoing PRA configuration control initiative that the NRC is having. We're also recommended that we consider this as part of the regular reactor oversight process change control process.

And also to communicate in other avenues, for example, we had public meetings, we have public workshops. We did communicate with industry groups. We had training sessions and knowledge management sessions with our senior reactor analysts and also with the inspectors at the regions and at the sites. Next slide.

So that's the end of the my presentation. Any questions?

MR. TAYLOR: Okay, thank you, Reinaldo. With that, we're going to turn it back to Christian for some closing remarks.

MR. ARAGUAS: Yup, and I know we're pressed for time and we still have a handful of slides to get to with sort of next steps or ongoing activities with research.

But I did want to take a minute just to highlight the incredible team that we have here between Gabe, Nick, and Kenny that have brought to bear the expertise, lend credibility to the research that's been done over the better part of a decade in trying to address the focus on HEAF.

And so you know, this slide really just represents a lot more than just those three individuals there, as you've seen. But it's, again, it's a recap of the organizations that have been heavily involved in supporting our research activities. And so just wanted to take a second to highlight that.

Thanks, guys. And I will turn to Jeff. I think you've got the next steps. Okay.

MR. RADY: I realize we have a hard stop at 2:00, so I'll be brief.

So good afternoon, everyone, my name is Jeff Rady, I'm the Chief of the Fire and External Hazards Analysis Branch in Research, is Division of Risk Analysis.

One of the things that we wanted to do was carve out some time today so that you understand where our focus is in the near term, as well as some future activities. So what you'll see there, first bullet is for low power shutdown of non-light water reactors, there is, as part of Part 52 as well as the licensing modernization process, PRA, the requirement is for PRA to encapsulate all hazards and all different plant operating states.

So our staff will be looking at low power and shutdown operations and the risks associated with that due to fire.

The second bullet is for cable aging management. As you know, more than half of the operating nuclear power plants are into their license extension. And there's also license amendment requests to extend that out to 80 years.

So the focus of that would be on what are the -- what are the potential characteristics, and then the integrity of the insulation of the cables. And that will be some near-term testing of that to see if the behavior of those particular age cables is differently than most of what you've heard in its HEAF, where readily -- they were newer in their life. So that's another interesting project and research activity that they'll be performing.

And then the other piece is for the both cable tray and ignition criteria. There was an FAQ, 160011, that is going to be refined. So to reduce uncertainty. And this really is a basis of establishing in this particular research the configuration of the plant from the electrical cabinet and to the reality of what we see at a typical nuclear power plant in terms of cable trays and cable fill.

So that will be improving modeling guidance for the industry and advance our understanding of that. Next slide please.

MR. BLEY: Quick question.

MR. RADY: Oh, sure.

MR. BLEY: That FAQ, was that one of the ones that were generated during the fire PRA first half a dozen applications?

MR. TAYLOR: This is Gabe Taylor. So that's correct, it's one of the FAQs that was issued during the transition for some plants to the NFP 805.

MR. BLEY: Okay, thanks.

MR. TAYLOR: But just to be clear, Dennis, this is not captured in NUREG-6850 Supplement 1. This is one of the FAQs that was completed after the publication of Supplement 1. So this was a standalone, you won't find it in 6850 Supplement 1.

MR. BLEY: Okay, thanks.

MR. RADY: Okay. And so the next -- on this slide, the top bullet is, is to understand the fire risk associated with co-located hydrogen generation. As most of these nuclear power plants, they're considering for flexibility in their operations and generation.

There is excess thermal and electrical power that they would, for they're pursuing or considering in developing through an electric -- electrolysis process to develop hydrogen for other clean energy needs.

Now, the interesting piece of that is that these are -- these are co-located. Sometimes near the existing nuclear power plants. So this research will help us update any potential impacts that are associated with that particular near-term goals for hydrogen generation.

And then lastly, the component-based fire frequencies. Originally there as a plant-based analysis done. And what that had is it skewed the results a little if some of the plants didn't have the exact quantity of the components across the gamut. So using a component-based frequency, that will add more clarity and certainty to be prescriptive in the fire risk associated with the plants.

And that will update NUREG-2169, which is the fire ignition frequency and non-suppression probability for using those events, the fire data models.

And then looking forward. So, some of the items that we're considering for wildland and urban interface fires. And it was -- there was a little bit of a discussion here about even SCBAs for safe shutdown. Well, if there's higher ignition frequency with fires, what is the impact of that? You may a tremendous amount of smoke, and what is the impact on habitability of the power plants if they have to evacuated, abandonment from the control room.

Some of the actions that they perform for safe shutdown, whether they go to an alternative shutdown panel or a primary control station, there are time-critical actions and what the impact if they need to don an SBCA or they have to leave the power block and go to alternate locations in order to implement their operating procedures. So that's an interesting topic that we'll be considering investigating.

And the other is for molten salt reactor fire protection standard. This particular, it's, as you can see, it's antiquated, 1988. And one of drawbacks right now is it's considered deterministic.

So it's not performance-based. So this would be an opportunity for us to ingest risk-information into this particular ANSI standard. And then --

MEMBER BROWN: Why would you want to have risk-informed for liquid metal fires, which are just explosive? I mean, gee, why would I have a very deterministic processes and say, well, maybe it won't catch fire. I mean, give me -- excuse me.

MR. RADY: Nick, would you help us address that?

MR. MELLY: I don't think it's -- I think you bring up a good point, though. These are very explosive type events. But the old standard didn't have any aspects of bringing risk into the licensing procedure or bringing a PRA focused intent into the plant at all. And that is one of the larger efforts for licensing these new reactors.

(Off-microphone comment.)

MR. MELLY: Depends who you ask.

MEMBER BROWN: -- it costs to actually build a plant that works, even though it's dangerous?

MR. MELLY: And that's going to be part of the discussion for the bringing that up to date from 1988, is does the deterministic meet the needs and can we just simply license to deterministic. Or does there need to be an option to incorporate PRA into your licensing basis.

MEMBER BROWN: Not going to make it any safer. Excuse me, that's my opinion.

MR. RADY: We appreciate that.

MEMBER BROWN: Oh, I'm sorry. Sorry about that.

MR. RADY: Oh that's --

MEMBER BROWN: That's too bad I didn't get recorded.

MR. RADY: And this is Jeff Rady again. So the second-to-last bullet is understanding the impact for fire-safe shutdown of advanced reactors. There's more digital technology that's being utilized now and really it's a great opportunity for us to understand.

In the event of achieving and maintaining safe shutdown, what kind of operational challenges, what impacts there are that as far as either a fire risk or operator actions, to whether it's -- whether it's shutting down the plant from the main control room, or abandonment issues. So that's an opportunity for us to advance our knowledge of that technology.

And then lastly, and this is probably -- sure.

MEMBER BROWN: Are you saying digital systems increase the fire hazard relative to the old analog standards?

MR. RADY: No --

MEMBER BROWN: That's the way I read the sentence, evaluate fire hazards associated with digital systems. That sounds like I put in a digital system, now I've got more a fire risk than I did before.

MR. RADY: No, I -- the digital systems would reduce the risk. It's really a matter of when the safe shutdown activities occur of what additional challenges may occur, not necessarily from fire risk but from an operational standpoint. Will there be a less of a risk to achieving safe shutdown than versus digital.

MEMBER BROWN: First, the analogs works just fine, just this advantages operationally that --

MEMBER MARCH-LEUBA: Just thinking of all the -- in a digital system, they tend to be more centralized, closer together than analog, which can be much more distributed. So, definitely, they're more susceptible to fire --

MEMBER BROWN: You tend integrate some systems, as you're going to discover on one of our upcoming reviews.

MEMBER MARCH-LEUBA: You have the fire in a cabinet, analog cabinet, disable only one system. You get a fire on the digital, disable all.

MEMBER BROWN: That part I agree with. All right, I'm sorry.

MR. RADY: No, no.

MEMBER BROWN: I can't resist.

MR. RADY: Okay, we appreciate it. And then the last bullet is for lithium battery fires. Just from the news standpoint, you see that the frequency as well as the impact of those lithium battery fires versus other traditional reserve power sources, DC power sources, like the vented lead acid batteries.

Currently, in NUREG-6850, the heat release rates for those batteries are modeled really as an electrical motor. So we have opportunities to investigate and understand the impacts for any kind of consequence to those lithium batteries using the plants.

MEMBER BROWN: They're modeled as motors?

MR. RADY: Currently, yes.

MEMBER BROWN: Lithium battery model -- oh, you're talking -

MR. RADY: Existing lead acid.

MEMBER BROWN: Oh, the existing, I apologize. I -- didn't quite understand, thanks.

MR. RADY: So that's just keeping is within that two o'clock window. Any other questions for myself or my staff before we adjourn?

CHAIR KIRCHNER: Thank you, Jeff. Members, do one or two?

MEMBER HALNON: I'll just close it. You know, when this first came out, HEAF was -- there was a lot of drama between the industry and the NRC relative to where's it going, what kind of backfit, what kind of safety issues we're going to have, what -- all kinds of stuff.

But this is a real success story in understanding it. You know, the factions coming together. And it turned out that we know a lot more about it, probably advanced your ability to model greatly. And the impact is -- seems right.

So I think it's a real good success story, and thank you for thoughtfully going through that.

CHAIR KIRCHNER: Yeah, I would just add to Greg's comments to say that where we've left off about circa 2018 spectacular videos showing a lot smoke and fire, and it looked very -- like a very intractable problem.

So I just want to acknowledge the staff, that you've done a great job in taking something that was pretty spectacular and very messy and turning it into something with good engineering that you can take a look at and actually work in improving the safety of the plants. So thank you for your very good work.

MEMBER MARCH-LEUBA: Stepping one step behind looking at the whole process, the staff has done a fantastic job. But this success story points to the need of doing research. Because, before you guys started doing this research, we thought we had to get rid of all the aluminum. Everybody did, because so spectacular -- what could you want to believe? Your results or my lying eyes, right? And I have to believe your results, because my eyes can lie.

And if you don't start doing that research that you're doing (audio interference) you don't get to have results. That's something that management needs to hear. And I hope when you move it up the chain, you give that story.

MEMBER PETTI: Well, that's one of the reasons we write letters.

MEMBER MARCH-LEUBA: We will. We will help. But if we can --

(Simultaneous speaking.)

MEMBER PETTI: I'm taking notes, I mean, I got that half. Didn't take much.

MR. RADY: We would happily appreciate that being in the letters. Thank you.

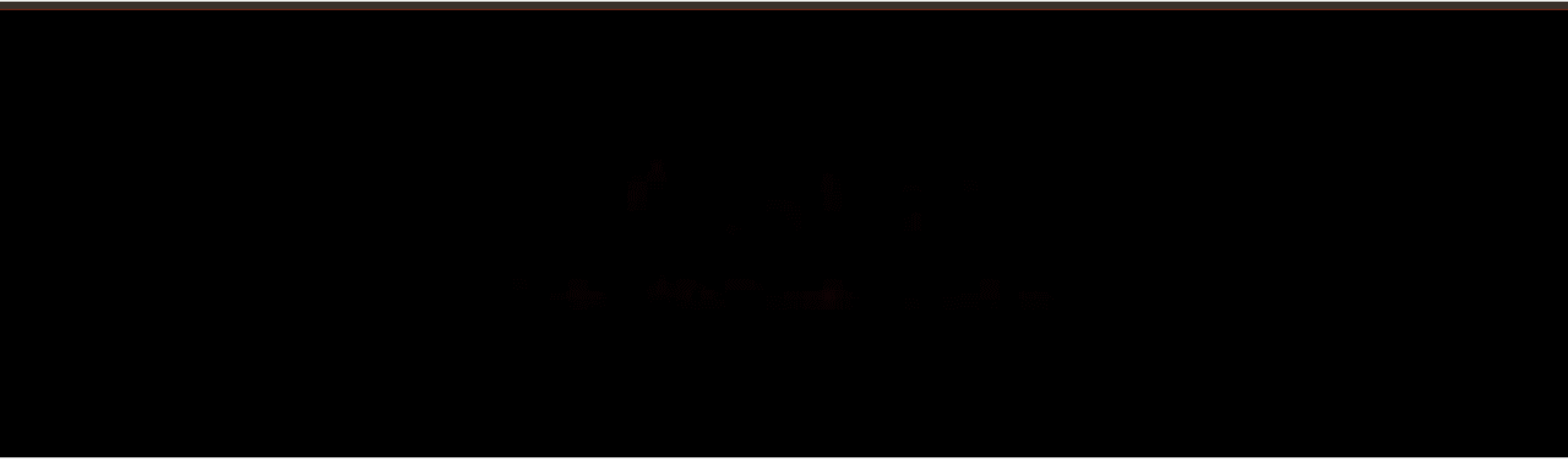
(Simultaneous speaking.)

CHAIR KIRCHNER: Thank you very much.

MR. ARAGUAS: And thank you for the opportunity to allow my staff to present. Thanks.

CHAIR KIRCHNER: Okay, do we have the court -- at this point, we can release the court reporter. Thank you very much. I don't think we will need your services tomorrow. Thank you.

(Whereupon, the above-entitled matter went off the record at 2:02 p.m.)



High Energy Arcing Faults Research

ACRS Briefing March 7th, 2024

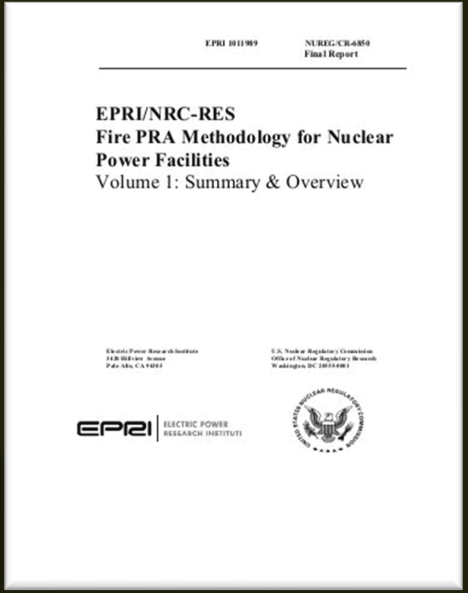
HEAF – A Model Research Program

- Potential safety issue observed during confirmatory testing
- Operating experience reviewed for evidence of similar phenomena
- Licensee notification
    - Information Notice 2017-04 “High Energy Arcing Faults in Electrical Equipment Containing Aluminum Components”
- Potential safety issue entered into NRC’s Generic Issues program (later transitioned to LIC-504)
    - Immediate safety review conducted
- Phenomena Identification and Ranking Table (PIRT) exercise conducted to prioritize resources and plan future research (NUREG-2218)
- Joint NRC/EPRI working group assembled with SMEs from NIST and SNL
- Physical experiments conducted at small, medium, and large scales
- New PRA methods and models developed consistent with experimental data, operating experience, and modeling tools
    - New methods and models piloted at two plants
- Final updated PRA methodology published (NUREG-2262)
    - NRC/EPRI joint workshop held to roll out the updated methodology to licensees and stakeholders

HEAF RESEARCH
BACKGROUND

NUREG/CR-6850 EPRI 1011989

- NUREG/CR-6850 forms the basis for nuclear power plant (NPP) fire PRAs
  - Fire initiators are broken down by “bins”
  - Bin 15 Electrical cabinets
  - Bin 16 HEAF
- NFPA 805 Lessons Learned
  - Bin 16 too broad
  - Low voltage control cabinets considered same risk as medium voltage switchgear
  - Create realistic divisions for Bin 16 ignition source binning



EPRI 1011989
NUREG/CR-6850
Final Report

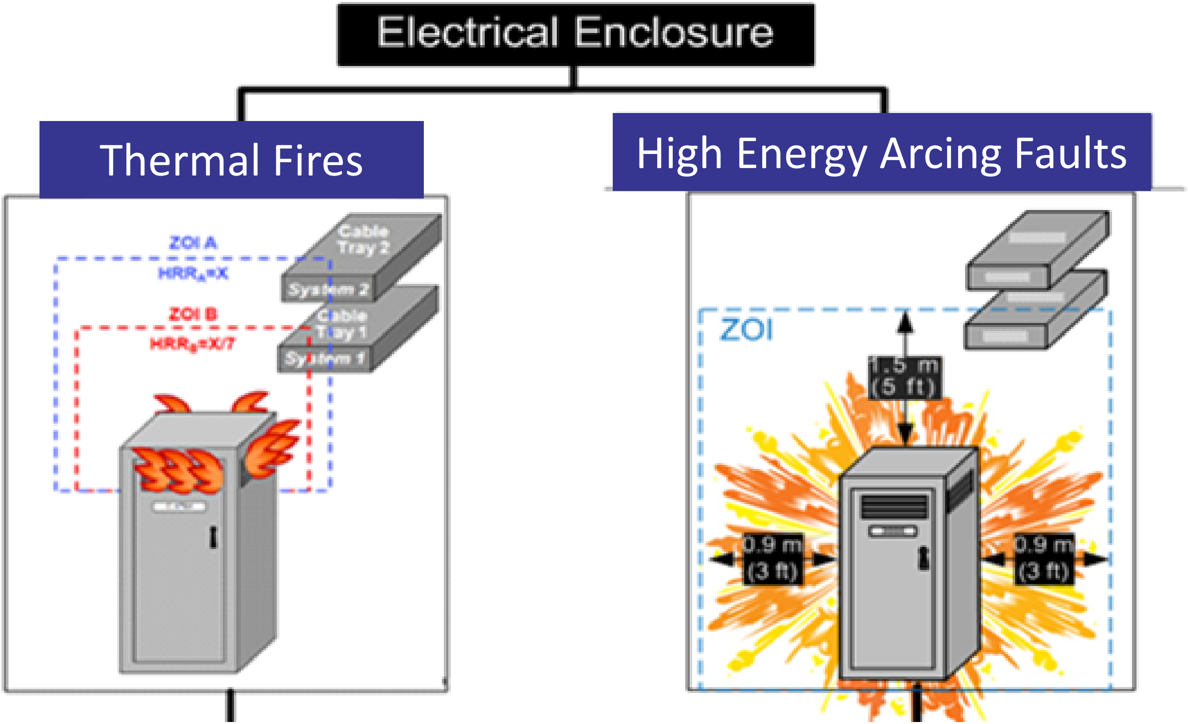
EPRI/NRC-RES
Fire PRA Methodology for Nuclear Power Facilities
Volume 1: Summary & Overview

Electric Power Research Institute
3420 Hillview Avenue
Palo Alto, CA 94303

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/

NUREG/CR-6850 Electrical Enclosure Failure Modes



Electrical Enclosure

Thermal Fires

High Energy Arcing Faults

HRR – heat release rate

ZOI – zone of influence

HEAFs vs Arc Faults

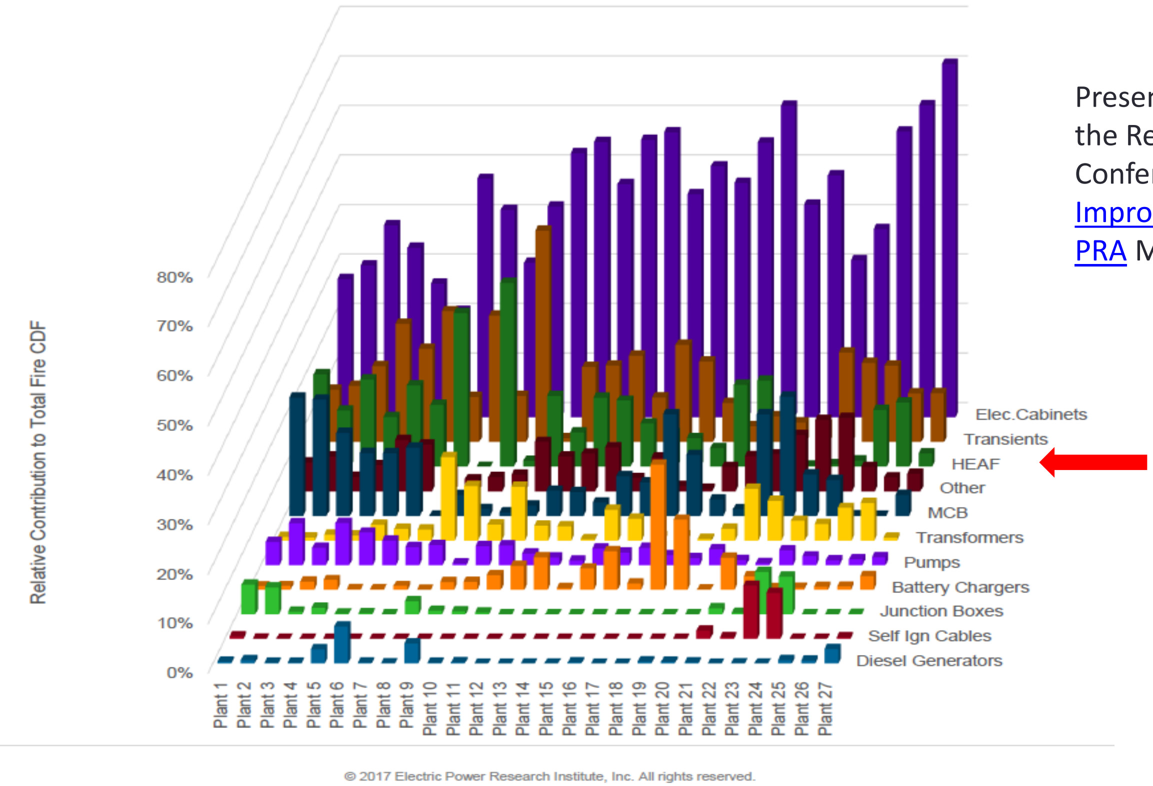
Fire events assigned to the HEAF ignition source bins are reviewed against the following definitions:

Arc flash: An event in which damage is contained within the confines of the component of origin. Minor damage and minimal bus bar degradation occur, and the event does not result in an ensuing fire.

Arc blast: An event in which damage is contained within the confines of the component of origin. The initiating equipment may be damaged through pressure-rise effects but does not result in an ensuing fire.

HEAF: An event in which the component of origin is damaged and breached, with the potential to spread to the surrounding equipment. Pressure-rise effects may damage the initiating equipment. HEAFs in switchgear and load centers are accompanied by an ensuing fire. However, no ensuing fire is necessary for a bus duct event to be considered a HEAF.

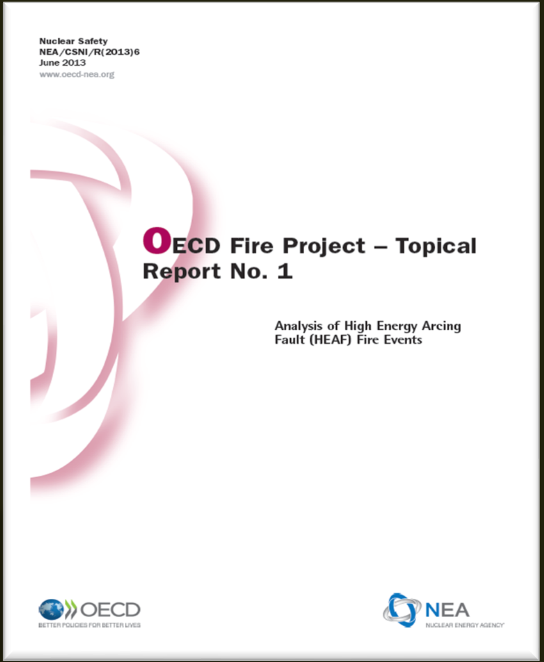
HEAF's Fire Risk Contribution to Core Damage Frequency



Presentation by EPRI for the Regulatory Information Conference [TH30 - Improving Realism in Fire PRA]() March 15, 2018

Background - International Program

- Organisation for Economic Co-operation and Development (OECD) Fire Incident Records Exchange Project (FIRE)
    - *"Analysis of High Energy Arcing Fault (HEAF) Fire Events,"* NEA/CSNI/R(2013)6
- 48 of 415 international fire events represent HEAFs (over 10%)
- The NRC/OECD Phase 1 testing program was initiated as an international cooperative research effort in 2014.
- The NRC served as the operating agent



Nuclear Safety
NEA/CSNI/R(2013)6
June 2013
www.oecd-nea.org

OECD Fire Project – Topical Report No. 1

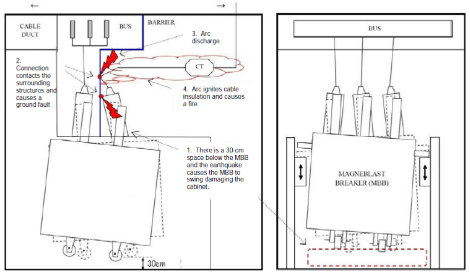
Analysis of High Energy Arcing Fault (HEAF) Fire Events

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

https://www.oecd-nea.org/nsd/docs/2013/csni-r2013-6.pdf

Onagawa – Seismically Induced HEAF Fire Event



Side View

Front View, Door Open

Figure 1.2-2. Onagawa Arching Scenario

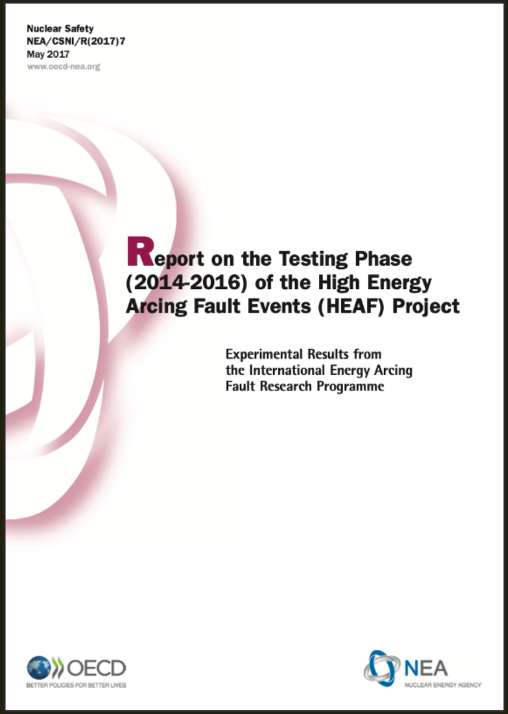
- Fire detected by optical detector, although on-site fire brigade could not immediately identify fire location due to heavy smoke
- Actuation of fixed CO_2 extinguishing system for some rooms after turbine building evacuation
- External public fire brigade called could not support onsite resources because of blocked access ways
- Fire duration of nearly 8 hours
- One safety train lost
- All 10 cubicles completely damaged by fire, left 3rd one mostly damaged because high energy gas in the section where the fire started propagated to other sections

Maanshan HEAF - Fire Event

- March 18, 2001 - fire and station blackout (SBO) due to a HEAF event
- The HEAF event damaged adjacent safety-related 4.16 kV switchgear
- The damage resulted in a complete loss of one safety bus and loss of the capability to feed off-site power to the other undamaged safety bus. This event was complicated by an independent failure of the redundant emergency diesel generator and resulted in the loss of all AC power
- Smoke and CO_2 prevented access to the area for repair and operator actions. The SBO was terminated after about 2 hours when an alternate AC EDG was started and connected to the undamaged safety bus
- **Risk Implications**
  - **CCDP: 2.2E-3**
  - Both safety trains unavailable for > 2 hours
  - The event was a significant challenge to the operators, but their responses were sufficient to maintain the plant in a safe condition

Phase 1 - HEAF Testing

- 26 tests between 2014-2016 conducted under the auspices of the NEA/OECD
  - Participating countries: U.S. (operating agent), Canada, Finland, France, Germany, Japan, Korea, and Spain
- Objective: confirm/refine existing modeling guidance in NUREG/CR-6850 Vol. 2
  - Various equipment classes (donated) tested with different parameters to provide a broad sample of potential results



Nuclear Safety
NEA/CSNI/R(2017)7
May 2017
www.oecd-nea.org

Report on the Testing Phase (2014-2016) of the High Energy Arcing Fault Events (HEAF) Project

Experimental Results from the International Energy Arcing Fault Research Programme

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

NEA/CSNI/R(2017)7

Phase 1 - HEAF Testing

- 2 of the 26 tests produced a damage state that appeared to exceed the existing guidance
  - Both tests contained aluminum and exhibited other effects that suggested aluminum behaved differently than other metals
- Observable differences
  - White (Al) vs. brown (Cu) smoke
- Aluminum oxide deposition on test cell walls

Brown smoke visible from test with copper electrodes

White smoke visible from test with aluminum electrodes

Phenomena Identification and Ranking Table (PIRT)

- Results from phase 1 testing indicated additional research into the effects of aluminum was warranted
- To focus the scope of future research and ensure efficient utilization of resources, NRC/RES hosted an expert elicitation exercise in February 2017
- The countries that sent representatives: U.S., S. Korea, Germany, France, and Japan (2)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG-2218

An International Phenomena Identification and Ranking Table (PIRT) Expert Elicitation Exercise for High Energy Arcing Faults (HEAFs)

Office of Nuclear Regulatory Research

NUREG-2218

NRC/EPRI Joint Working Group

NRC-RES and EPRI formed a HEAF working group in 2018 under the existing Memorandum of Understanding (MOU) for fire research.

EPRI-Affiliated Members	NRC-Affiliated Members
Ken Fleischer (Fleischer Consultants)	Thin Dinh (NRC-NRR)
Jason Floyd/Sean Hunt (Jensen Hughes)	Kenneth Hamburger (NRC-RES)
Ashley Lindeman (EPRI)	JS Hyslop (NRC-NRR)
Dane Lovelace (Jensen Hughes)	Nick Melly (NRC-RES)
Shannon Lovvern (TVA)	Kenn Miller (NRC-RES)
Marko Randelovic (EPRI)	Gabe Taylor (NRC-RES)
Tom Short (EPRI)	Chris LaFleur (SNL)

HEAF HAZARD CHARACTERIZATION

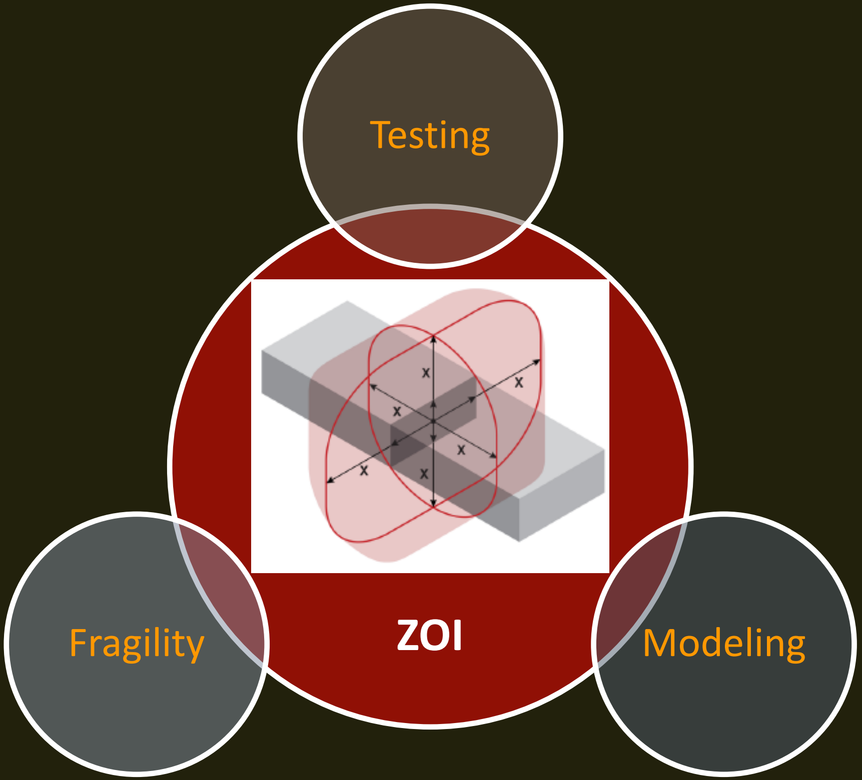
Program Objective

Improved Zone of Influence (ZOI) estimates

Testing – provide empirical data to inform model input and assumptions along with gathering data to inform fragility estimates

Modeling – provide method to simulate large number of scenarios

Fragility – Component functional failure and ignition thresholds

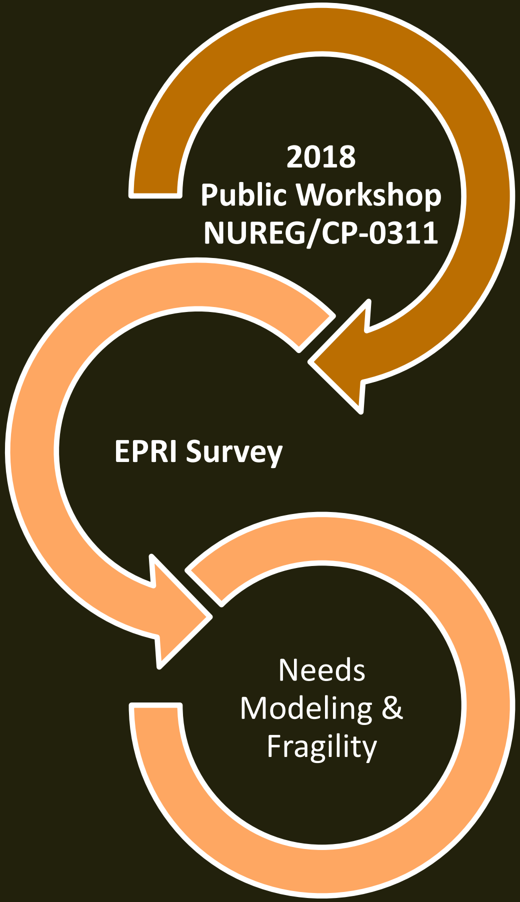


Experimental Planning

Initial plan developed as project proposal to OECD/NEA

Subsequent revisions based on workshop and additional information provided by EPRI via survey and reports

Modeling and fragility efforts identified specific needs

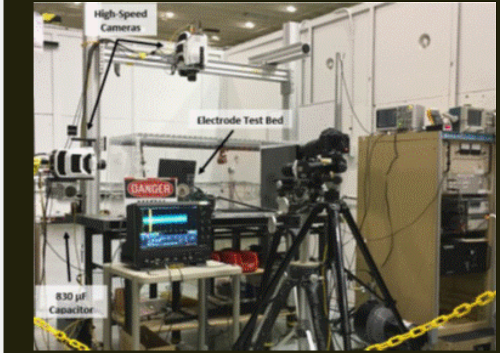


2018
Public Workshop
NUREG/CP-0311

EPRI Survey

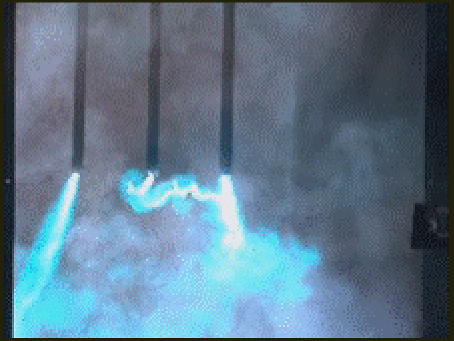
Needs
Modeling &
Fragility

Physical Testing



Bench-Scale

Aluminum/copper particle size distribution, rates of particle production, particle morphology, and oxidation. Informed model treatment of oxidation.



Intermediate-Scale

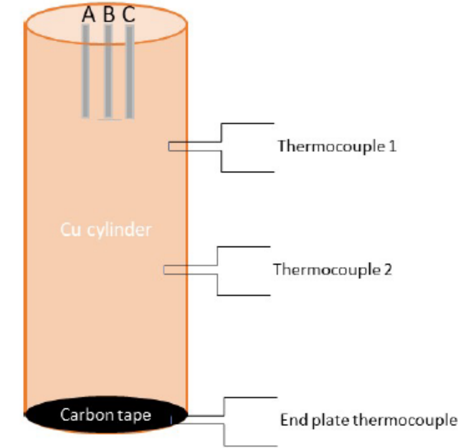
Direct observation of the arc, enclosure breach, material loss, arc spectral emissions. Benchmark for sub-models.

Full-Scale

Enclosure breach, event progression, pressure rise, thermal/visual imaging. Benchmark for CFD modeling.

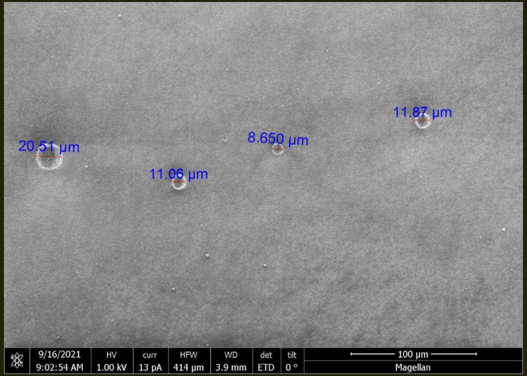
Particle Characteristics

- Full-scale 2018
  - Particle capture at locations surrounding enclosure



- Bench Scale
  - Closed calorimetry
  - Mass fraction (melt vs vaporized)
  - Particle size (SEM)
  - Degree of oxidation (SEM/EDS)

Particle Oxidation Results



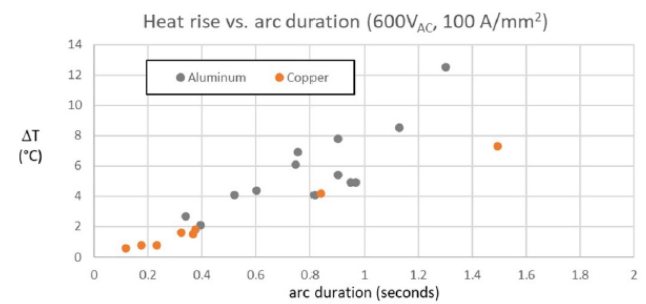
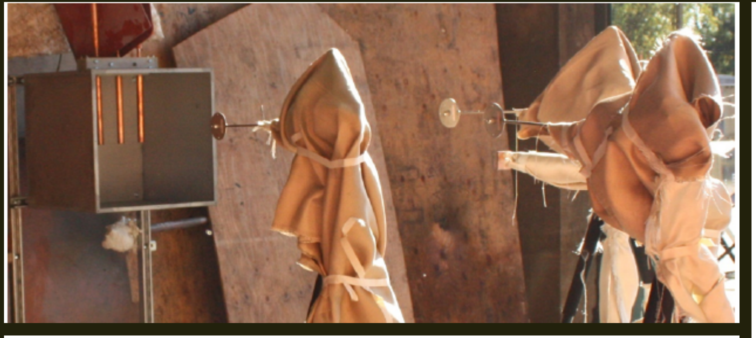
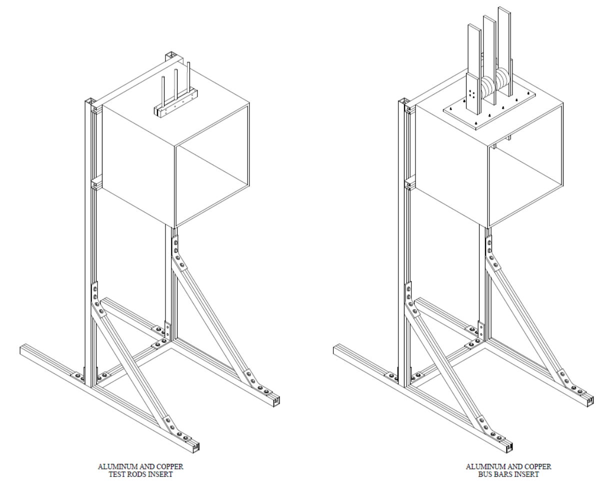


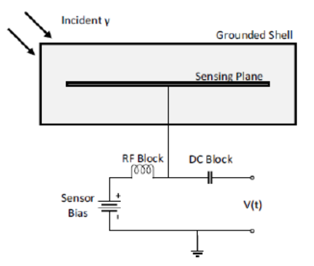
Figure D-8
Summary of measured temperature rise ΔT versus arc duration for all aluminum and copper arc experiments

- Calorimetry indicated larger energy output for Al vs Cu
- Nanoscale drops represent negligible electrode mass
- Large drops have relatively small oxidized mass fraction and tend to drop out of outflow
- Estimated upper limit evolved particle droplet oxidation
  - 75% small Al drops oxidized
  - 50% of small Cu drops oxidized

Intermediate-Scale (Open Box)







Arc Characterization

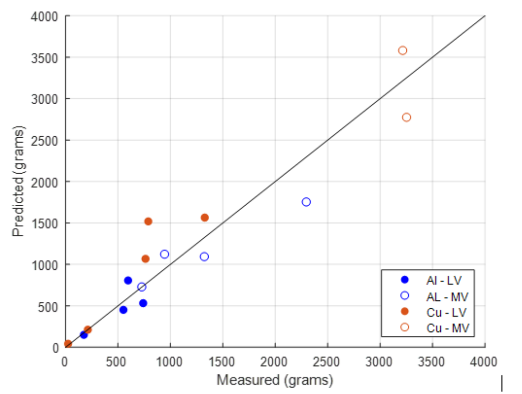


Figure 104. Comparison of Open Box Data to Stanback Jr. Simplified Model for Bus Mass Loss

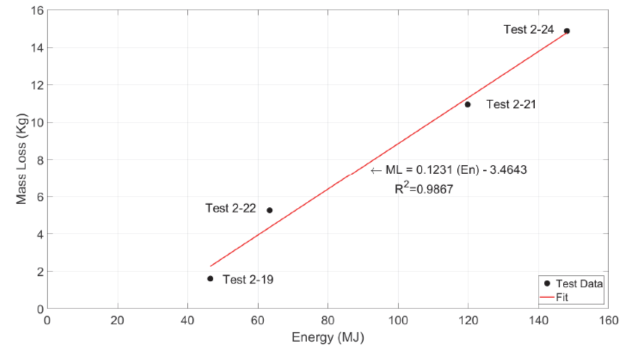


Fig. 89. Electrical enclosure steel mass loss versus electrical generator energy during the experiments.

Arc Voltage
- Numerous models evaluated
- CIGRE model reasonably accurate but may be limited by available information to perform PRA
- Ended up using point estimate 650$V_{L\text{-}L}$ MV, 375 $V_{L\text{-}L}$ LV

Electrode Mass Loss
- Model of Stanback Jr.

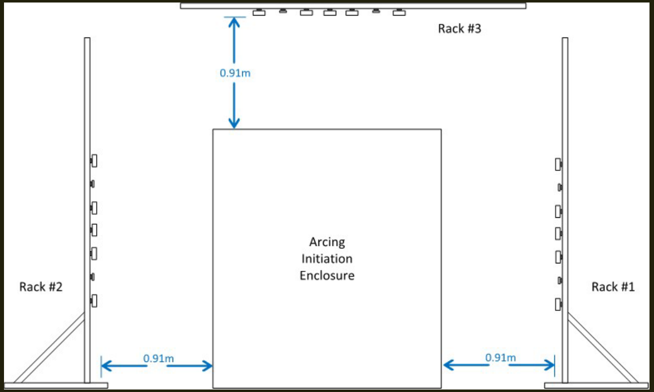
Enclosure Mass Loss
- Empirical evidence to compare with CFD

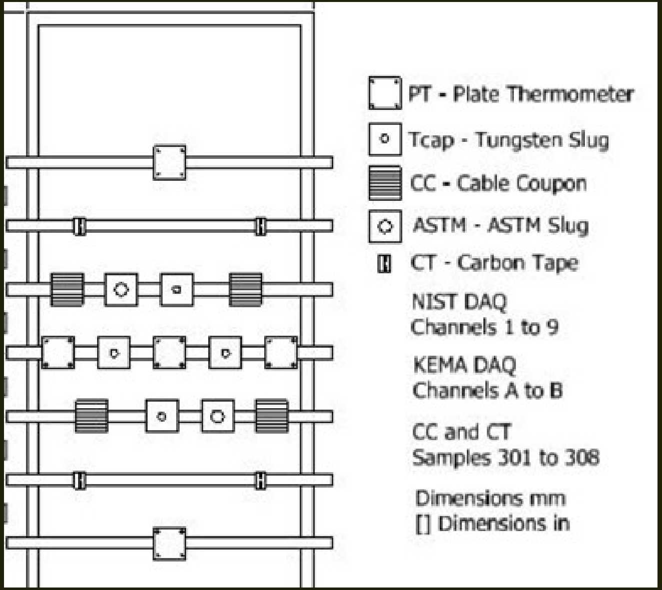
Geometry
- Confirm expected orientation

Intermediate- & Full-Scale Measurements

Measurements	Instrument / Technique
Temperature	Infrared (IR) Imaging, Plate Thermometer (PT), fiber optic sensor
Heat flux (time-varying)	Plate Thermometer (PT)
Heat flux (average)	Plate Thermometer (PT), Thermal Capacitance Slug (T_{cap} slug)
Incident Energy	ASTM F1959 Slug calorimeter (slug), Thermal Capacitance Slug (T_{cap} slug)
Pressure	Piezoelectric pressure transducer
Arc plasma / fire dimensions	Videography, IR Imaging
Surface deposit analysis	Sample collection (carbon tape / aerogels), post-experiment laboratory analysis (energy dispersive spectroscopy)
Qualitative damage	Cable samples

Measurement Approach

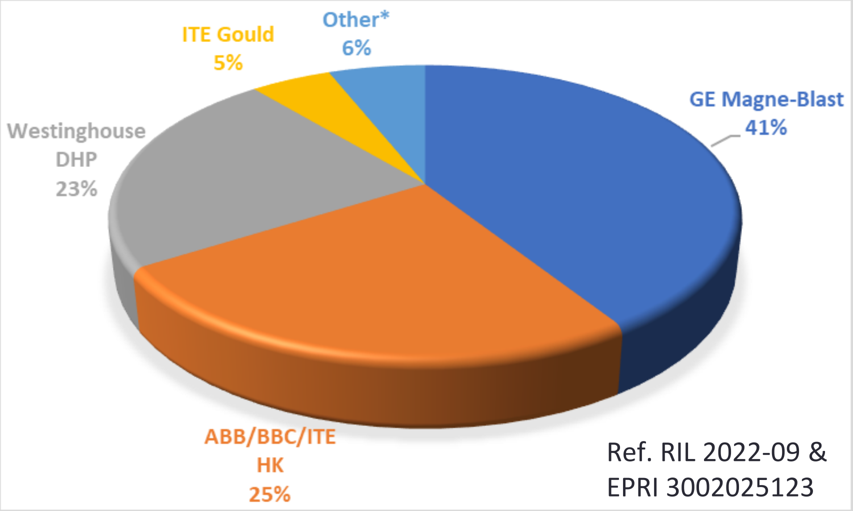




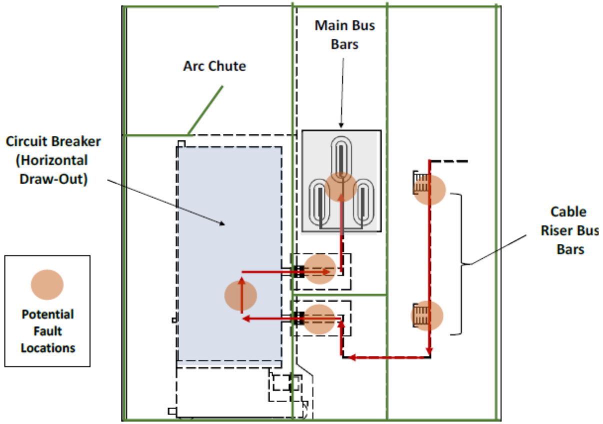
Enclosure Characteristics

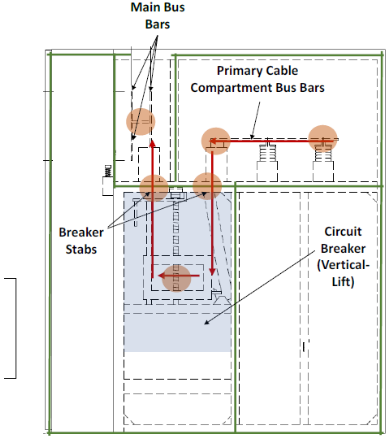
Fault location influences hazard to external targets

- Enclosure partitioning
- Arc direction
- Distance to targets



Ref. RIL 2022-09 & EPRI 3002025123



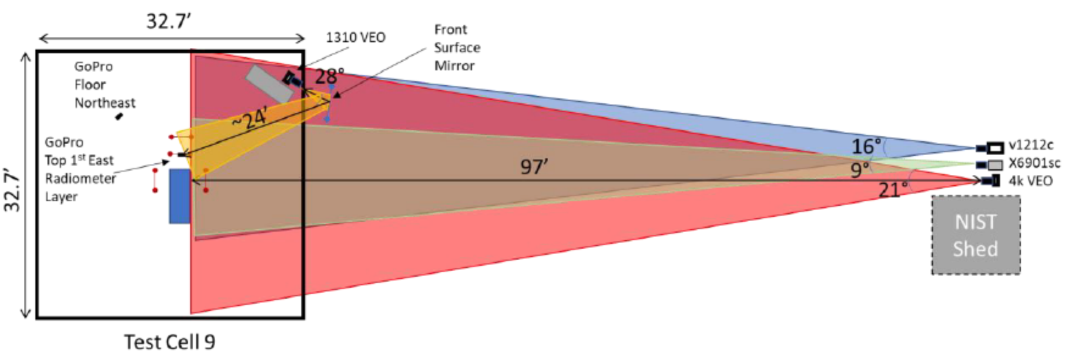


Photometrics

Variety of Imaging Technology

- High Speed Camera (1,000 – 12,000 fps)
- Wide dynamic range
- Varied IR wavelength

Important for understanding event progression and geometry



Cable Fragility Experiments

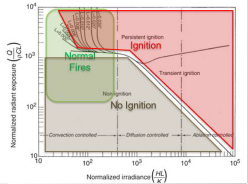
SNL **Solar Furnace Facility**

Heliostat and parabolic reflector, generating up to 6 MW/m^2 over a 5 cm circle

Varied heat flux, duration, cable material, and exposure profile

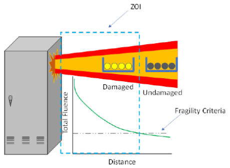
Objective was to develop metrics for evaluating cable failure and quantify threshold criteria

Fragility Working Group Conclusions



Incident Energy

Sustained Ignition



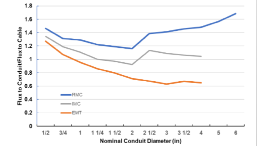


Figure 5-3
Ratios of q''con/q''cab for RMC, IMC, EMT

Protective Features

The threshold for electrical failure/damage of thermoplastic jacketed cables is 15 MJ/m² and the threshold for thermoset jacketed cables is 30 MJ/m²

Sustained ignition is assumed for cables within the enclosure of origin (e.g. internal cables and components within switchgear and load center)

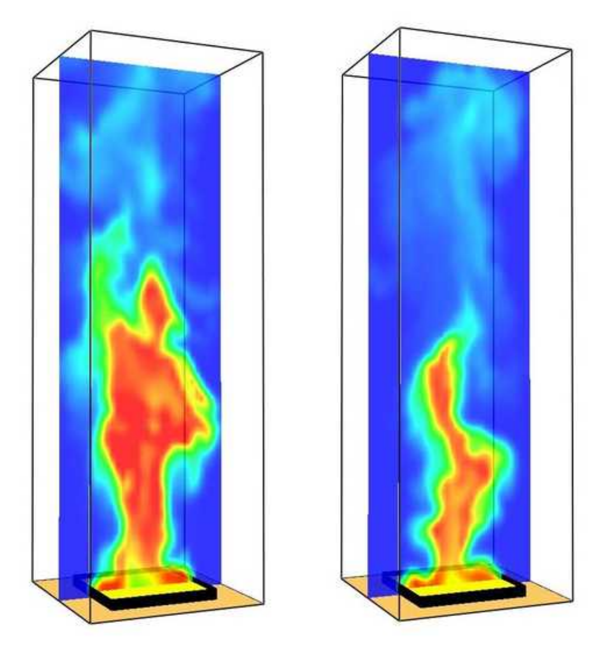
1 hour (or greater) rated Electrical Fire Raceway Barrier System (ERFBS) will prevent ignition inside the enclosure of origin and damage in the ZOI

HEAF

MODEL DEVELOPMENT

FDS Features

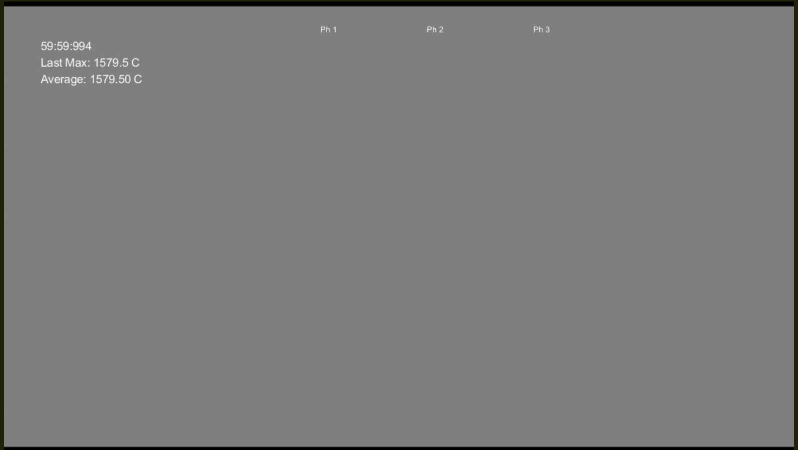
- FDS is a computational fluid dynamics (CFD) code designed to simulate fires
- Low Mach number assumption limits flow speed to about 30% of the speed of sound, approx. 100 m/s
- Gray gas radiation model lumps all radiation frequencies into a single band
- Arc is modeled as a volumetric source of heat with a constant fraction of the energy emitted as radiation
- 1-D surface heat transfer through steel walls of enclosure
- Single step, mixing-controlled combustion of vaporized metal



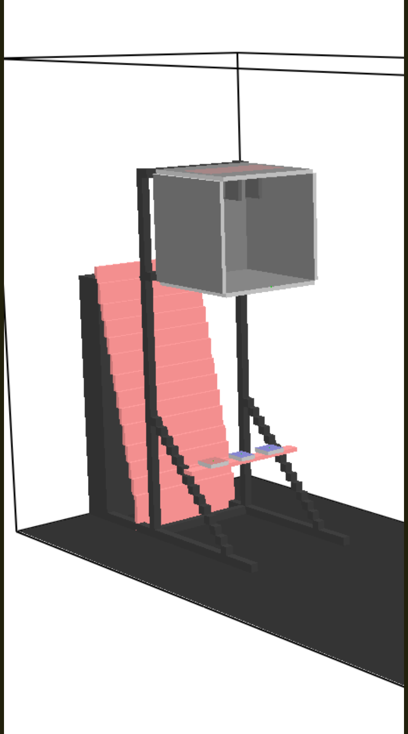
FDS – Fire Dynamics Simulator

Phenomena FDS Does Not Model

- Dissociation of molecules at high temperature and plasma formation. Instead, a fixed radiative emission fraction is obtained from experiments
- Electromagnetic arc dynamics. A constant volumetric heat source is used
- Rapid changes in pressure and flow divergence due to arc cycling. These are assumed to average out over longer time periods

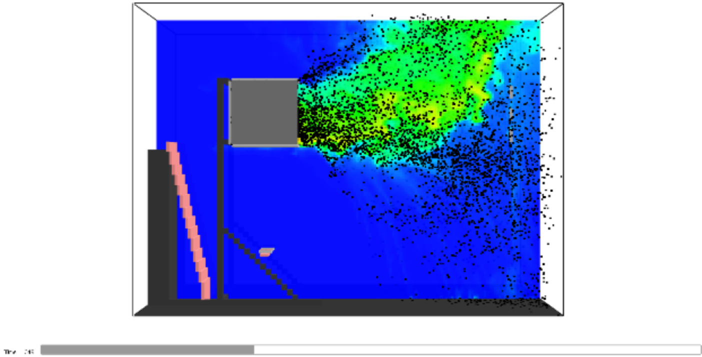


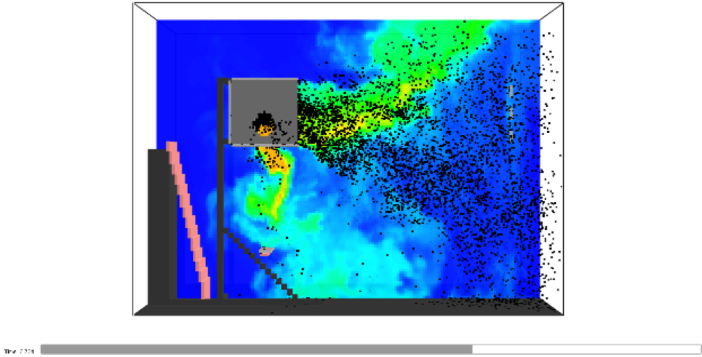
Model Development



- Volumetric heat source (i.e., the HEAF) and combustion (i.e., oxidation of Al and Cu particles)
- Specified radiative fraction corresponding to the volumetric heat source; that is, the fraction of the arc's energy that is emitted as radiation

Typical FDS Results





Typical FDS Results

Difficult to mimic exact temporal behavior, but magnitude of the heat flux is comparable

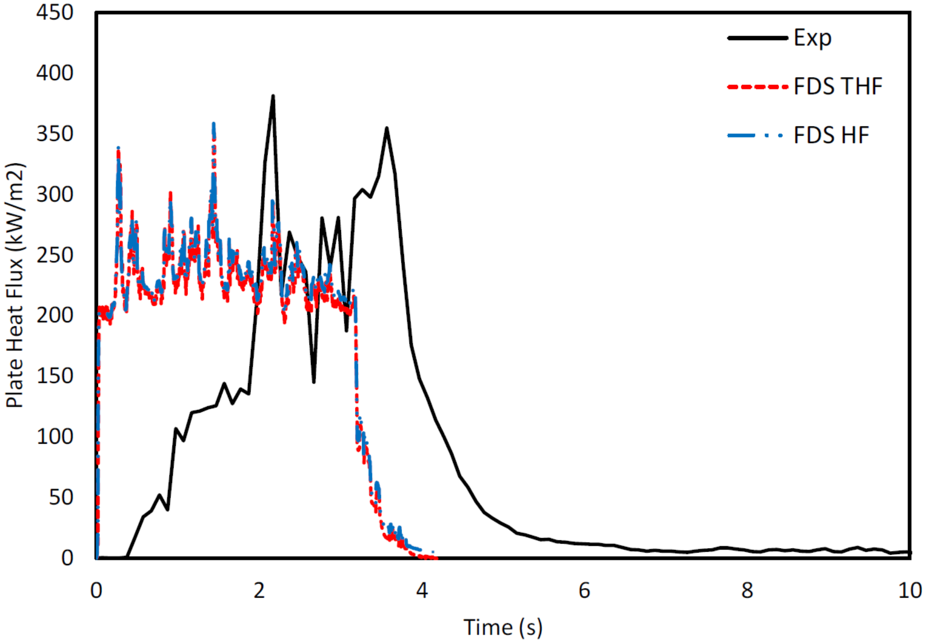
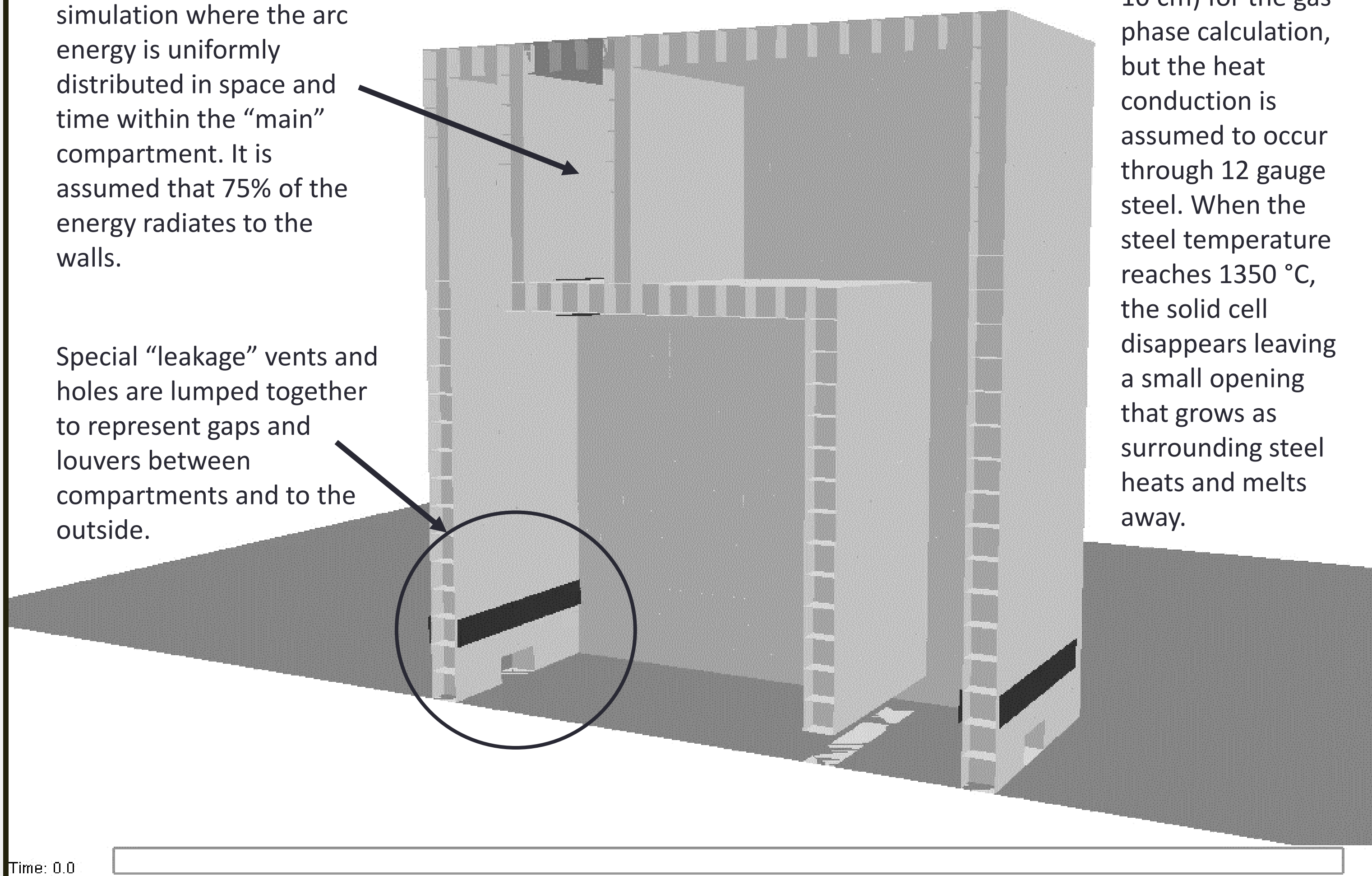


Figure 4-5: Plate heat flux for test OBMV1.



Here is a cut-away of a simulation where the arc energy is uniformly distributed in space and time within the “main” compartment. It is assumed that 75% of the energy radiates to the walls.

Special “leakage” vents and holes are lumped together to represent gaps and louvers between compartments and to the outside.

Enclosure walls are one cell thick (5 to 10 cm) for the gas phase calculation, but the heat conduction is assumed to occur through 12 gauge steel. When the steel temperature reaches 1350 °C, the solid cell disappears leaving a small opening that grows as surrounding steel heats and melts away.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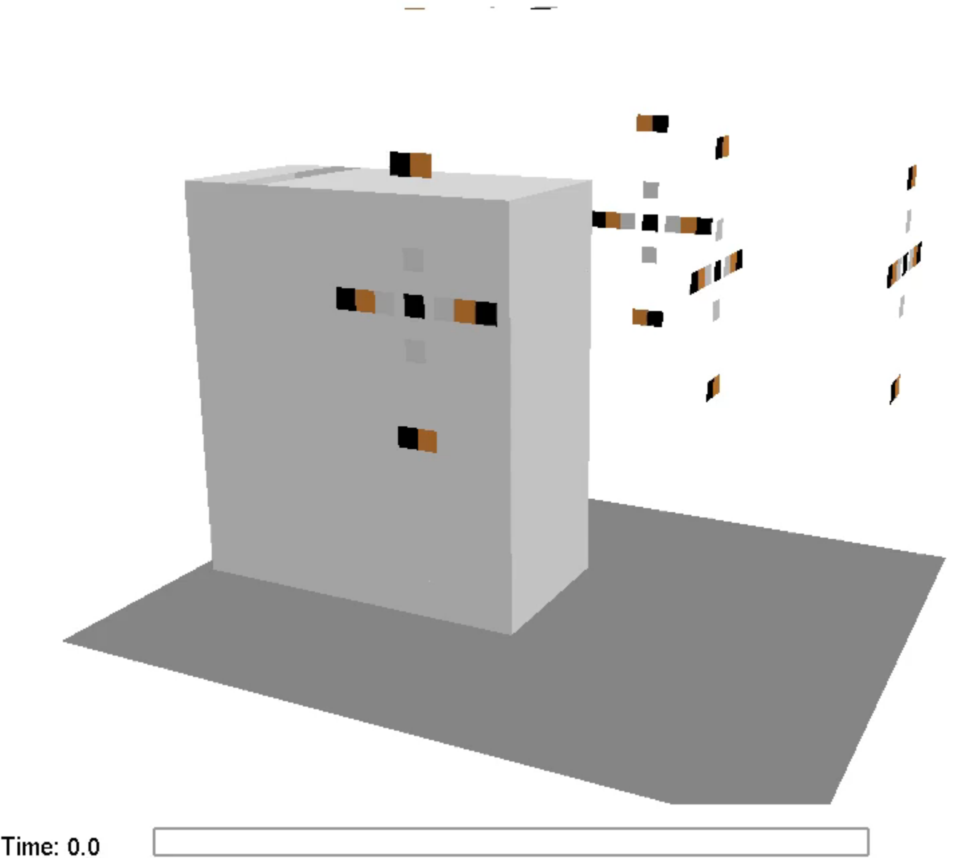
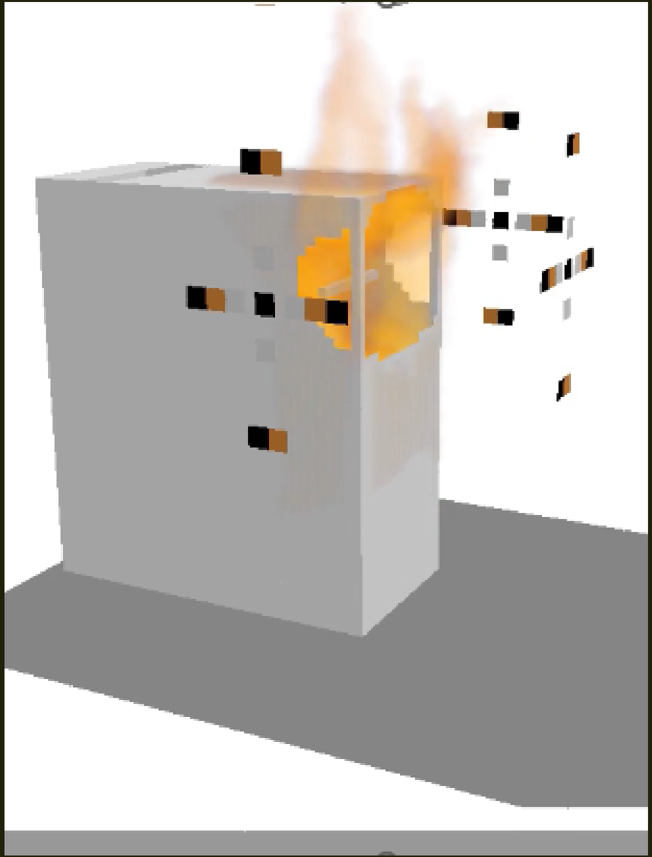
Simulation Results

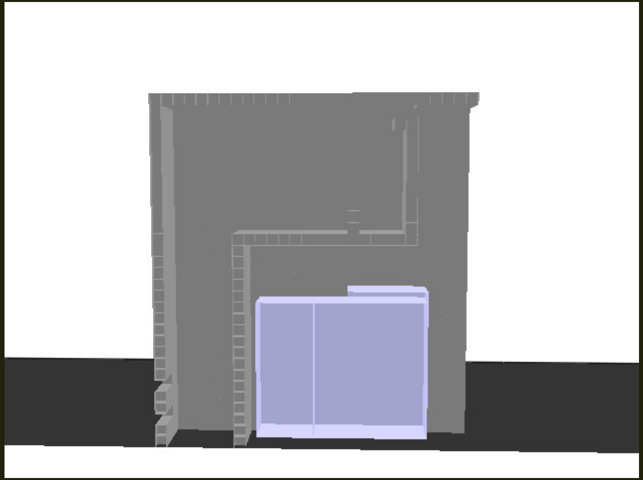


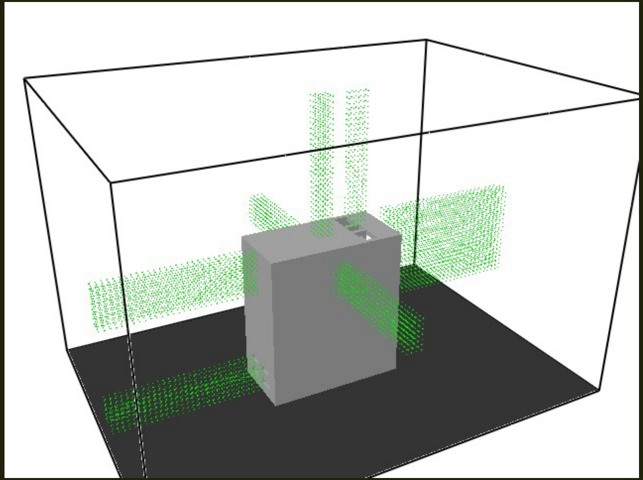
Side by Side Comparison



Grid Resolution and Domain Extent

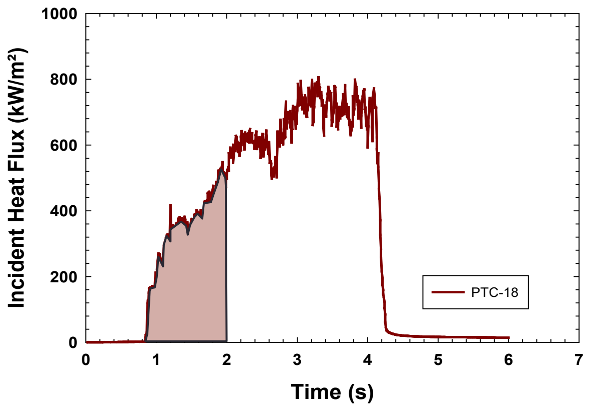
- LV SWGR and MV SWGR use 0.0762 m grid cells
- NSBD use 0.02 m grid cell resolution
- Domain extends 1.5 – 2 m from face of enclosure for all geometries considered

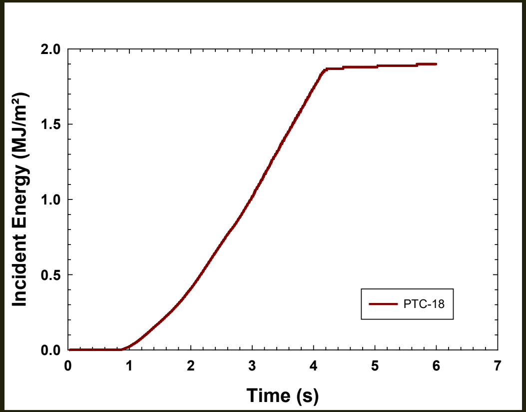




Model Output and Results

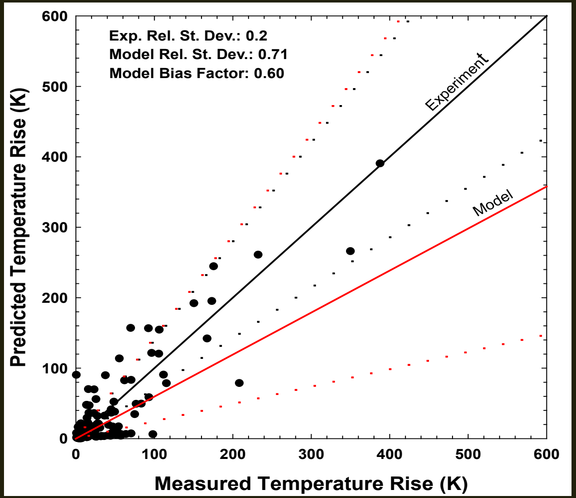
- Calculated model quantity is the gas phase gauge heat flux (incident heat flux) (kW/m^2)
- The incident energy or 'exposure' is the integrated gas phase gauge heat flux over the entire simulation duration (kJ/m^2 or MJ/m^2)



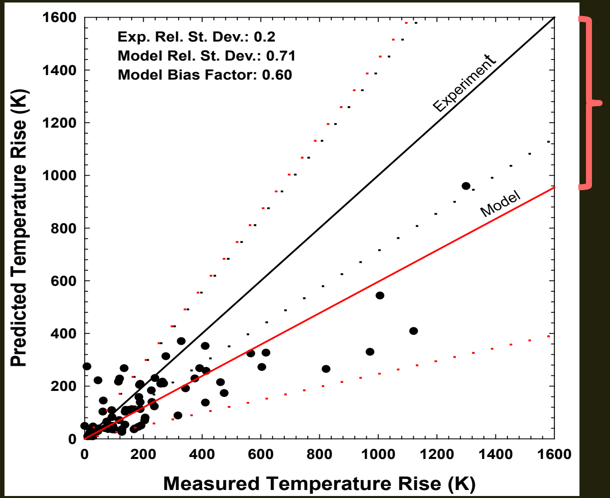


Treatment of Model Uncertainty

- The model bias factor is 0.596
  - Based on results from 4 s tests using racks with the greatest arc exposure
    - The exposure from the 2 s tests is more sensitive to the breach time prediction
  - The model bias is different and typically higher for racks with less severe arc exposure



All racks, 2 s MV SWGR tests



Bias

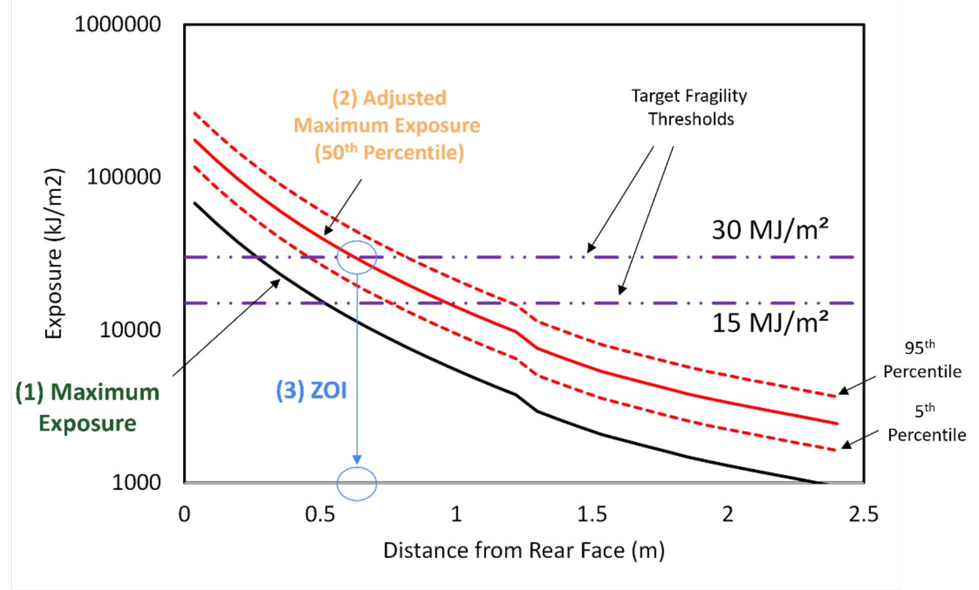
All racks, 4 s MV SWGR tests

Model Output and Results

Find maximum exposure vs. distance among all devices for each face

Adjust maximum exposure using model bias parameters

Determine ZOI from intersection with fragility threshold

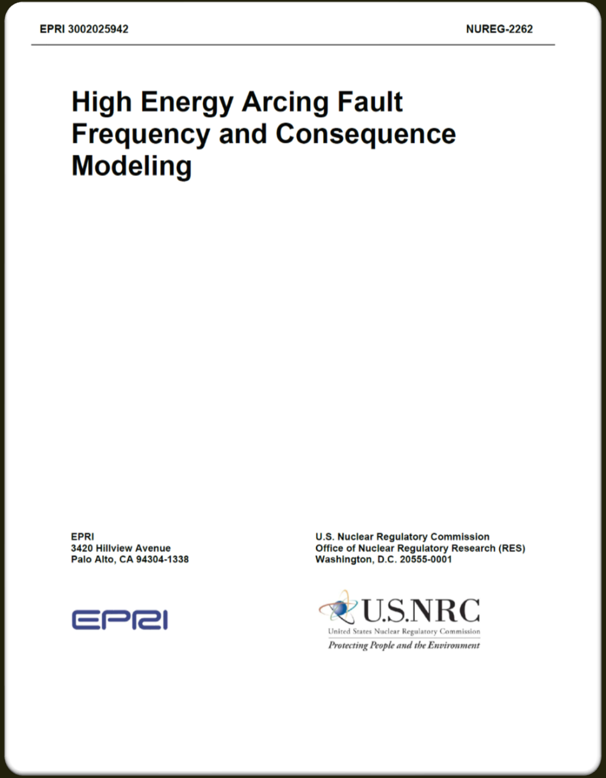


HEAF

PRA ADVANCEMENTS

HEAF PRA Report

- Provides data and methodology for treatment of HEAFs in load centers, MV switchgear, NSBDs, and the iso-phase bus duct
- Updates treatment of HEAFs from NUREG/CR-6850 and NUREG/CR-6850 Supplement 1
- Formally published by both EPRI and NRC
    - Link to EPRI version
    - Link to NRC version



EPRI 3002025942 NUREG-2262

High Energy Arcing Fault Frequency and Consequence Modeling

EPRI
3420 Hillview Avenue
Palo Alto, CA 94304-1338

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research (RES)
Washington, D.C. 20555-0001

EPRI

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

MV – medium voltage
NSBD – non-segregated bus duct

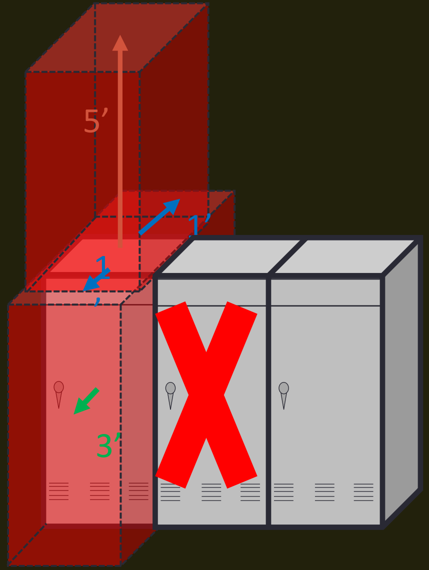
Main Differences between NUREG-2262 and NUREG/CR-6850 Appendix M & Supplement

- Electrical distribution system
- Fault clearing times
- Damage criteria
- Fire frequency
- Non-suppression probability
- ZOI
- Bus duct virtual origin
- Fire propagation
- Mitigation methods (GCBs / ERFBS)

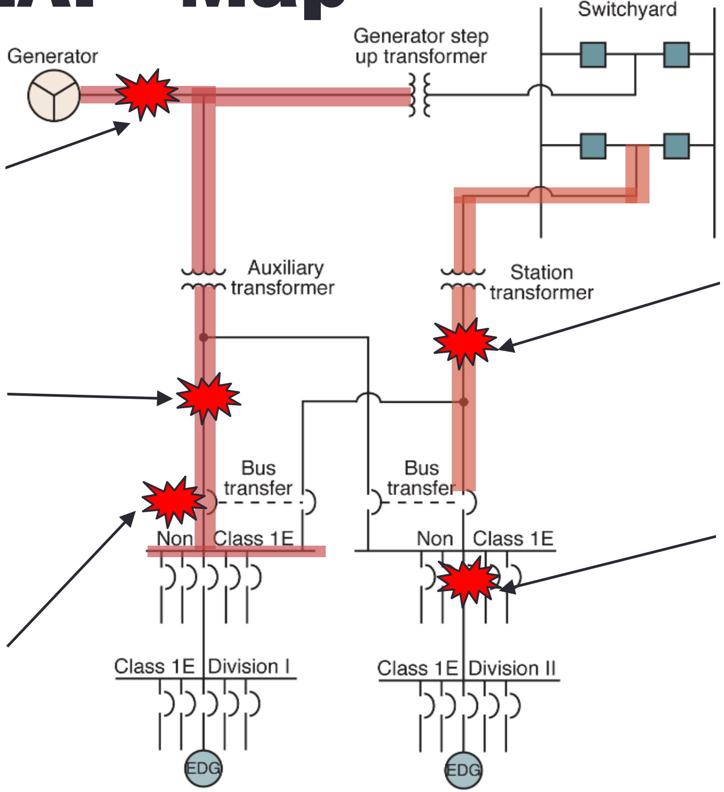
GCB - generator circuit breaker
ERFBS – electrical raceway fire barrier system

NUREG/CR-6850 Appendix M: Zone of Influence

- 1.5 m (5’) vertical (ignition)
- 0.3 m (1’) horizontal above the cabinet (front and rear panels, ignition)
- 0.9 m (3’) horizontal at and below the top of the cabinet (front and rear panels, mechanical damage and ignition)
- Directly adjoining/adjacent switchgear or load center cubicles within the same cabinet bank and in all directions (above, below, to the sides) to trip open



US OE HEAF "Map"



3 IPBD Events [Generator fed fault: 4 to 15 s]

6 NSBD Events [Generator fed fault: 4 to 15 s]

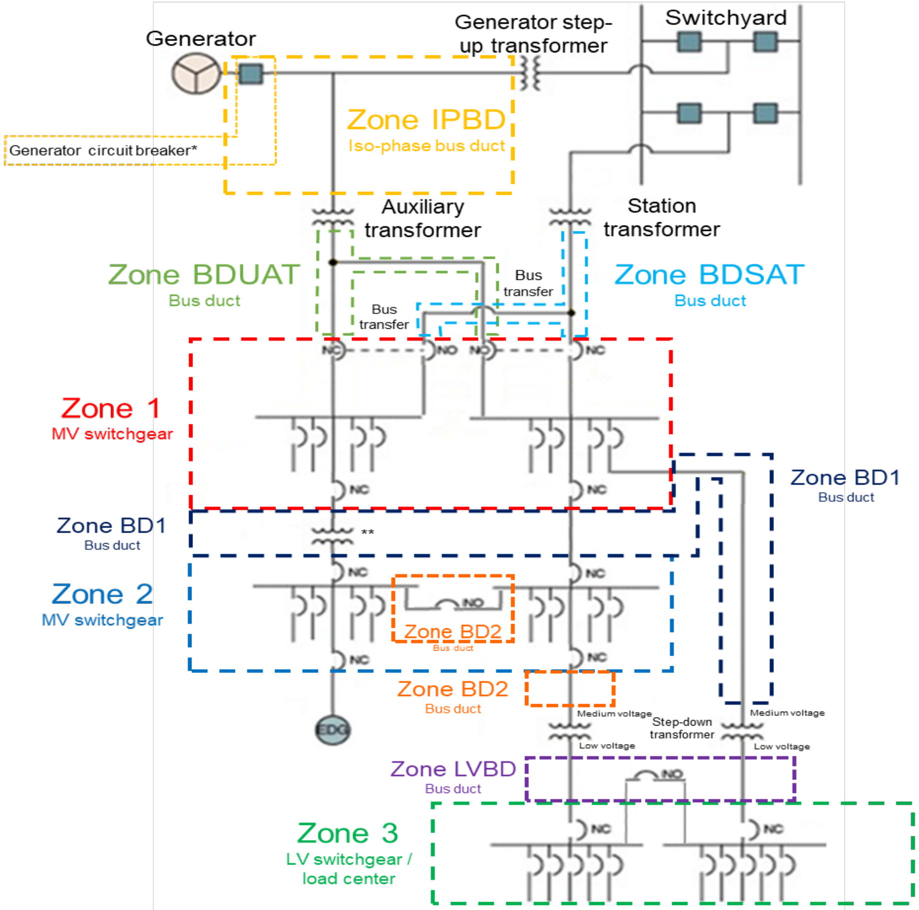
5 MV SWGR Events:
4 at fault at breaker stabs [Generator fed fault: 4 to 15 s]

2 NSBD Events: <2 seconds [Rapid isolation by SWYD circuit breakers]

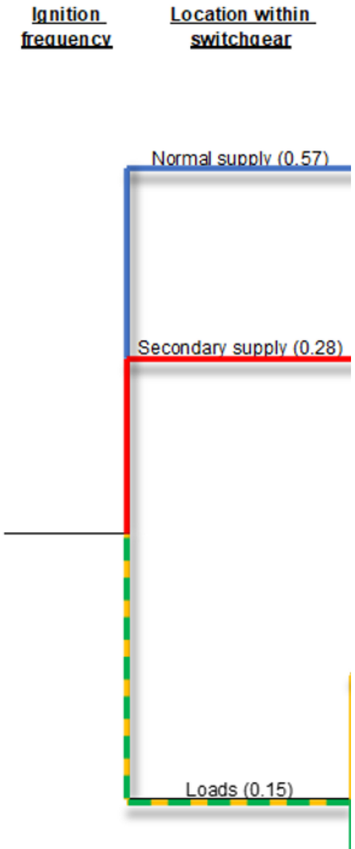
2 MV SWGR Events: Inadvertently initiated from off-site power

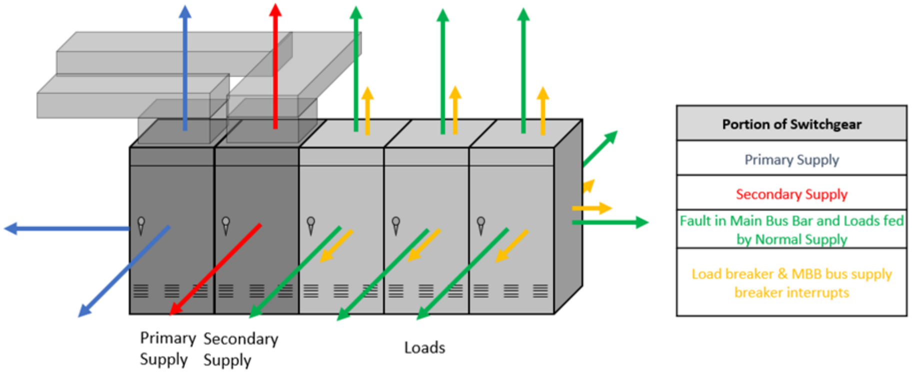
Majority of Severe, Long Duration HEAFs are on UAT aligned portion of EDS (Left Side)

Electrical Distribution System



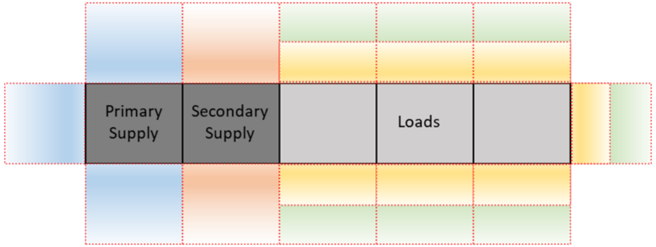
Configuration-Specific ZOIs

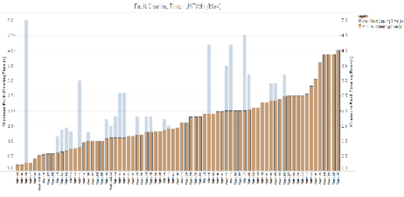




Directionality of Zone 1

Configuration Specific ZOIs

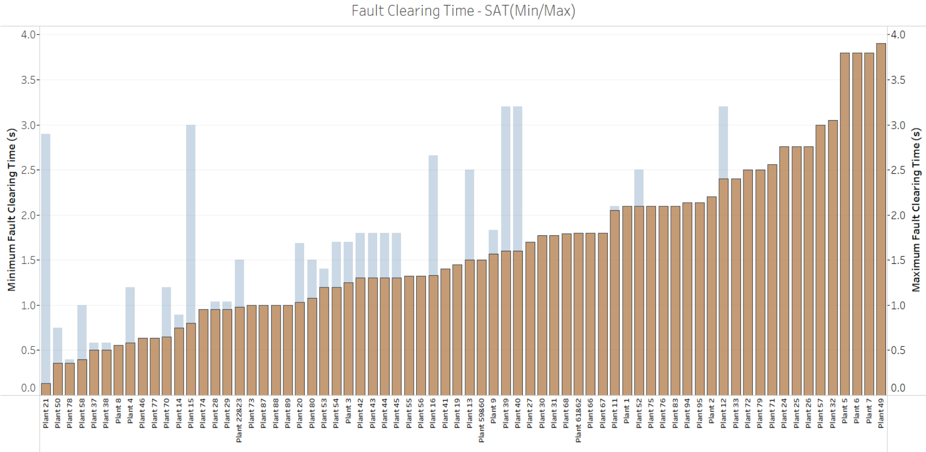




Fault Clearing Time (FCT)

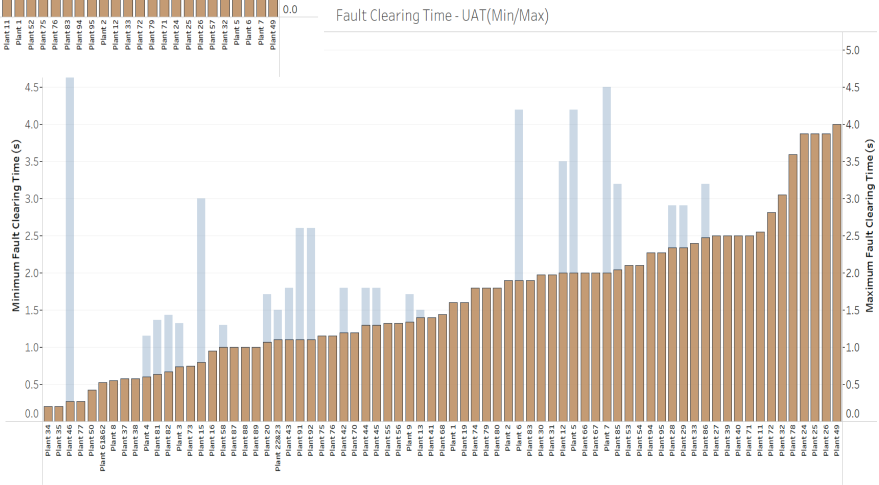
- Fault clearing time (FCT) is the time it takes for the time over-current protection to open the circuit breaker and clear the fault
- Why is FCT important?
  - Fault clearing time is directly proportional to the zone of influence (ZOI)
  - FCT duration typically varies from 0.2 seconds (12 cycles) up to 4 seconds anywhere on the EDS:
- Anything in excess of 4 to 5 seconds of through-fault current can damage transformers (IEEE Std C57.109)
- Load and switchgear protection requirements (IEEE Std C37.20)
- Selective coordination (IEEE Std 242)
- Zone 1 FCT is slower to accommodate Zone 2 primary protection

SAT/UAT Fault Clearing Times



Fault clearing times for station auxiliary transformer population

Fault clearing times for unit auxiliary transformer population



Fire Frequency Changes

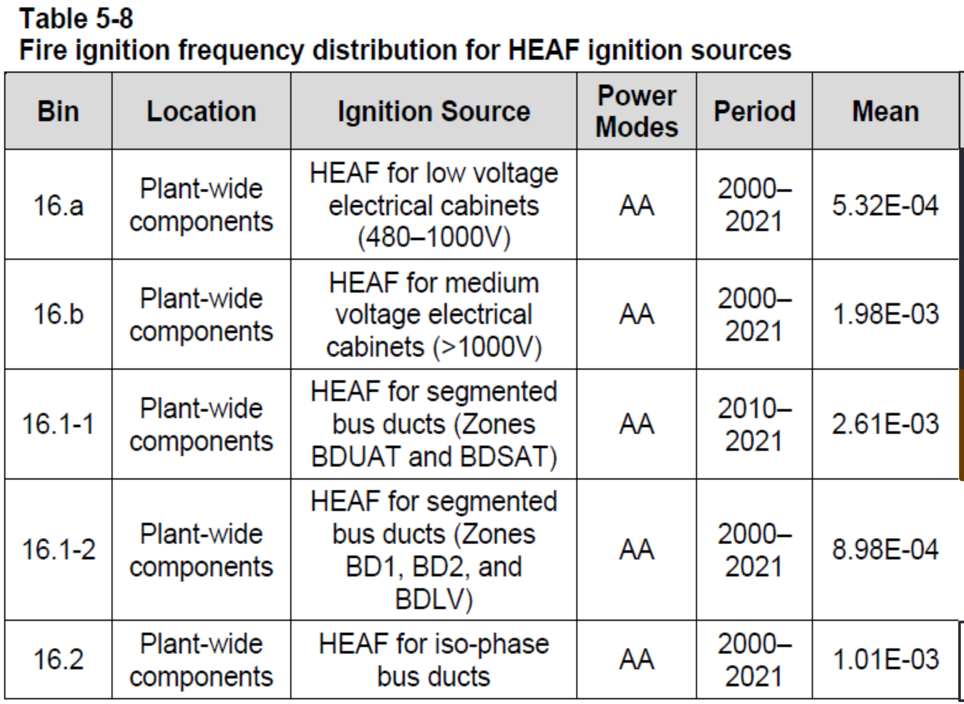


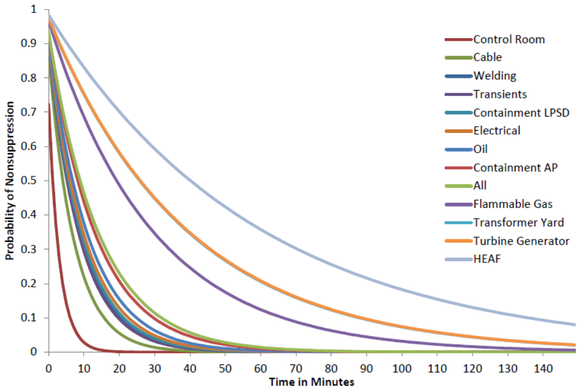
Table 5-8
Fire ignition frequency distribution for HEAF ignition sources

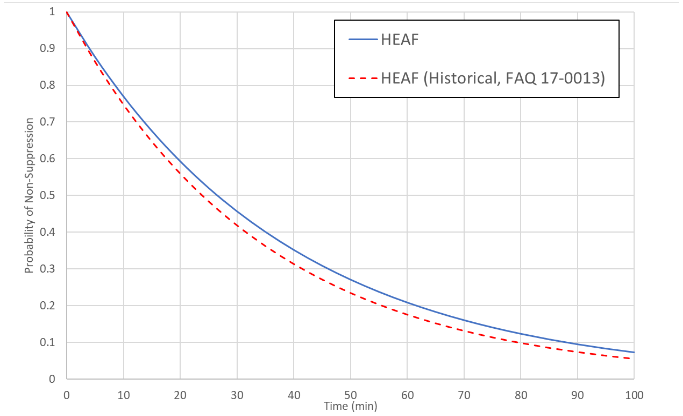
Bin	Location	Ignition Source	Power Modes	Period	Mean	NUREG-2169	
16.a	Plant-wide components	HEAF for low voltage electrical cabinets (480–1000V)	AA	2000–2021	5.32E-04	**1.52E-04** ↓	16.a
16.b	Plant-wide components	HEAF for medium voltage electrical cabinets (>1000V)	AA	2000–2021	1.98E-03	**2.13E-03** ↑	16.b
16.1-1	Plant-wide components	HEAF for segmented bus ducts (Zones BDUAT and BDSAT)	AA	2010–2021	2.61E-03	**1.10E-03** ↓	16.1
16.1-2	Plant-wide components	HEAF for segmented bus ducts (Zones BD1, BD2, and BDLV)	AA	2000–2021	8.98E-04	Bin 16.1 was not differentiated in NUREG-2169	
16.2	Plant-wide components	HEAF for iso-phase bus ducts	AA	2000–2021	1.01E-03	**5.91E-04** ↓	16.2

Non-Suppression Probability

Table 5-10
HEAF probability distribution for rate of fires suppressed per unit of time

Suppression Curve	Number of Events	Total Duration (min)	Rate of Fire Suppressed (λ)			
			Mean	5th Percentile	50th Percentile	95th Percentile
HEAF	15	576	0.026	0.016	0.025	0.038



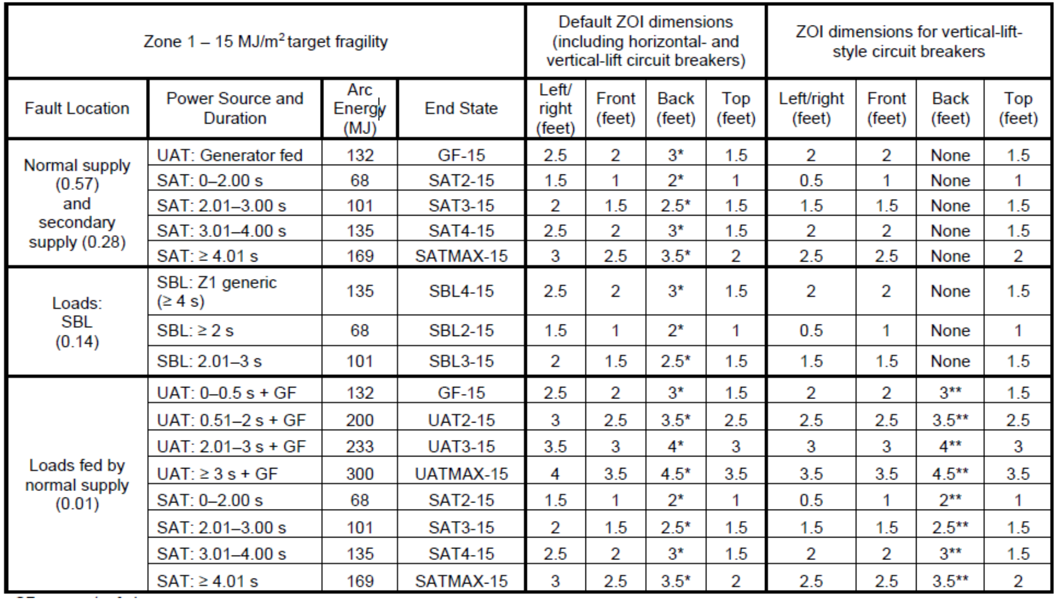


Electrical Enclosures

Screening ZOI
16.b (zone 1)

SAT fault clearing time	SAT arc energy (MJ)	UAT fault clearing time into generator-fed fault	UAT arc energy (MJ)	15 MJ/m^2 target fragility (feet)	30 MJ/m^2 target fragility (feet)
SAT (0–4.00 s)	135	UAT (0–0.50 s)	132	3	2
SAT (4.01+ s)	169	UAT (0.51–2.00 s)	200	3.5	2.5
		UAT (2.01–3.00 s)	233	4	3
		UAT (3.01+ s)	300	4.5	3.5

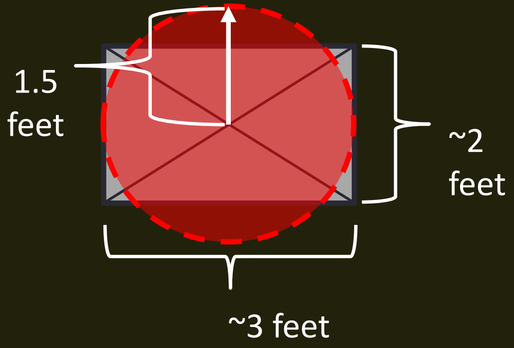
Detailed ZOI
16.b (zone 1)

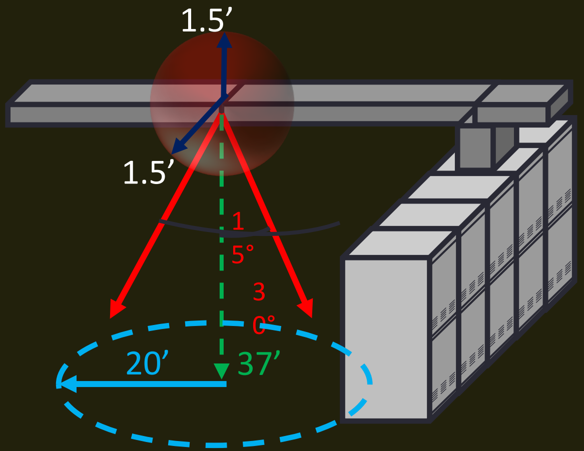


Zone 1 – 15 MJ/m^2 target fragility				Default ZOI dimensions (including horizontal- and vertical-lift circuit breakers)				ZOI dimensions for vertical-lift-style circuit breakers			
Fault Location	Power Source and Duration	Arc Energy (MJ)	End State	Left/ right (feet)	Front (feet)	Back (feet)	Top (feet)	Left/right (feet)	Front (feet)	Back (feet)	Top (feet)
Normal supply (0.57) and secondary supply (0.28)	UAT: Generator fed	132	GF-15	2.5	2	3*	1.5	2	2	None	1.5
	SAT: 0–2.00 s	68	SAT2-15	1.5	1	2*	1	0.5	1	None	1
	SAT: 2.01–3.00 s	101	SAT3-15	2	1.5	2.5*	1.5	1.5	1.5	None	1.5
	SAT: 3.01–4.00 s	135	SAT4-15	2.5	2	3*	1.5	2	2	None	1.5
	SAT: ≥ 4.01 s	169	SATMAX-15	3	2.5	3.5*	2	2.5	2.5	None	2
Loads: SBL (0.14)	SBL: Z1 generic (≥ 4 s)	135	SBL4-15	2.5	2	3*	1.5	2	2	None	1.5
	SBL: ≥ 2 s	68	SBL2-15	1.5	1	2*	1	0.5	1	None	1
	SBL: 2.01–3 s	101	SBL3-15	2	1.5	2.5*	1.5	1.5	1.5	None	1.5
Loads fed by normal supply (0.01)	UAT: 0–0.5 s + GF	132	GF-15	2.5	2	3*	1.5	2	2	3**	1.5
	UAT: 0.51–2 s + GF	200	UAT2-15	3	2.5	3.5*	2.5	2.5	2.5	3.5**	2.5
	UAT: 2.01–3 s + GF	233	UAT3-15	3.5	3	4*	3	3	3	4**	3
	UAT: ≥ 3 s + GF	300	UATMAX-15	4	3.5	4.5*	3.5	3.5	3.5	4.5**	3.5
	SAT: 0–2.00 s	68	SAT2-15	1.5	1	2*	1	0.5	1	2**	1
	SAT: 2.01–3.00 s	101	SAT3-15	2	1.5	2.5*	1.5	1.5	1.5	2.5**	1.5
	SAT: 3.01–4.00 s	135	SAT4-15	2.5	2	3*	1.5	2	2	3**	1.5
	SAT: ≥ 4.01 s	169	SATMAX-15	3	2.5	3.5*	2	2.5	2.5	3.5**	2

NUREG/CR-6850 Supplement 1: ZOI

- The following zone of influence is assumed to originate from a point at the center of the bus duct at the assumed transition point location
- Assume that molten metal material will be ejected from the bottom of the bus duct below the fault point and will spread downward, encompassing the shape and volume of a right circular cone whose sides are at an angle of 15° from the vertical axis (a total enclosed solid angle of 30°)
- Assume that molten metal material will also be ejected outwards and will spread within a sphere of 1.5-foot radius from the fault point. The fault point to be used when applying the **1.5-foot radial damage distance is the cross-sectional center of the bus duct.**
- The cone will expand (height allowing) to a maximum diameter of 20 feet. Beyond this point, the burning materials will fall straight downward in a cylindrical shape. Note that the maximum expansion zone for the cone (20-foot diameter) corresponds to a distance 37 feet below the point of origin

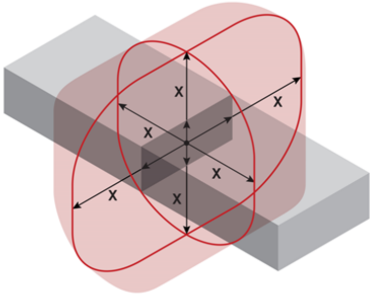




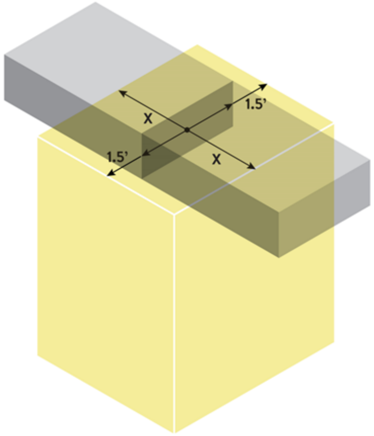
HEAF PRA Report – Totality of HEAF ZOI

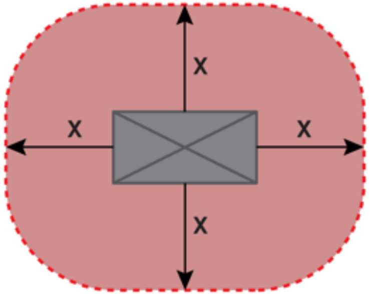
HEAF for NSBDs = Energetic ZOI + waterfall

Along Bus Duct



Waterfall





NSBD HEAFs – ZOIs (in feet)

End state	Power transformer and fault clearing time	Bus duct enclosure material and target fragility			
		Steel enclosure with target fragility of 15 MJ/m^2 (feet)	**Steel enclosure with target fragility of 30 MJ/m^2 (feet)**	**Aluminum enclosure with target fragility of 15 MJ/m^2 (feet)**	**Aluminum enclosure with target fragility of 30 MJ/m^2 (feet)**
BDSAT0.5 BDSBL0.5	SAT: 0–0.50 s SBL: 0–0.50 s	0	0	0	0
BDSAT1 BDSBL1	SAT: 0.51–1.00 s SBL: 0.51–1.00 s	0	0	0.5	0.5
BDSAT1.5 BDSBL1.5	SAT: 1.01–1.50 s SBL: 1.01–1.50 s	0.5	0.5	1	1
BDSAT2 BDSBL2 BDLV	SAT:1.51–2.00 s SBL: Z2 generic* (≥ 2 s) and 1.51-2.00s Low voltage	1	0.5	1.5	1
BDSAT3 BDSBL3	SAT: 2.01–3.00 s SBL: 2.01–3.00 s	2	1	2.5	1.5
BDSAT4 BDSBL4	SAT: 3.01–4.00 s SBL: Z1 generic* (≥ 4 s)	2.5	1.5	3	2
BDSATMAX	SAT: ≥4.01 s	3	2	3.5	2
BDGenFed	UAT: 0–0.5 s + GF	2.5	1.5	3	2
BDGF2	UAT: 0.51–2 s + GF	3.5	2	4	2.5
BDGF3	UAT: 2.01–3 s + GF	4	2.5	4	2.5
BDGFMAX	UAT: ≥3 s + GF	4.5	3	5	3

MV Switchgear HEAFs – Ensuing Fire

This section was revised based on comments received during public comment

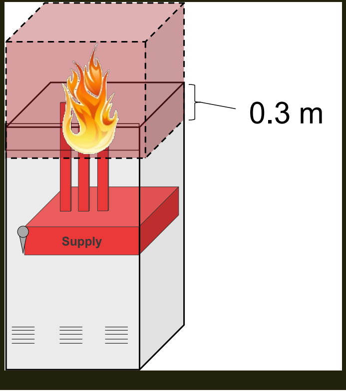
Following the energetic blast, an ensuing fire is postulated

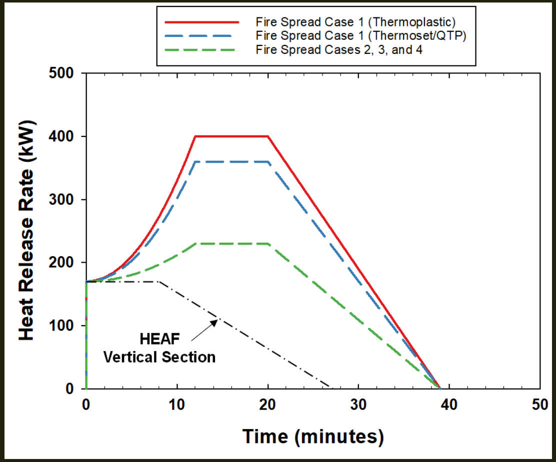
- Ensuing fire HRR: 170 kW with fire base located 0.3 m below the top of the switchgear

Fire timing

- Growth 0 min (none)
- Steady burning: 8 minutes
- Decay period: 19 minutes

Do not use obstructed plume or obstructed radiation





MV Switchgear – Fire Spread to Adjacent Cabinets

- Postulate fire spread to adjacent vertical sections due to the potential for the arc to breach the shared boundary when the arc energy is:
  - ≥ 101 MJ for vertical sections separated by a single steel barrier (single wall construction)
  - ≥ 202 MJ for vertical section separated by two barriers (double wall construction)
- Section 6.5.1 provides the discussion and technical basis

MV Switchgear – Fire Spread to Adjacent Cabinets

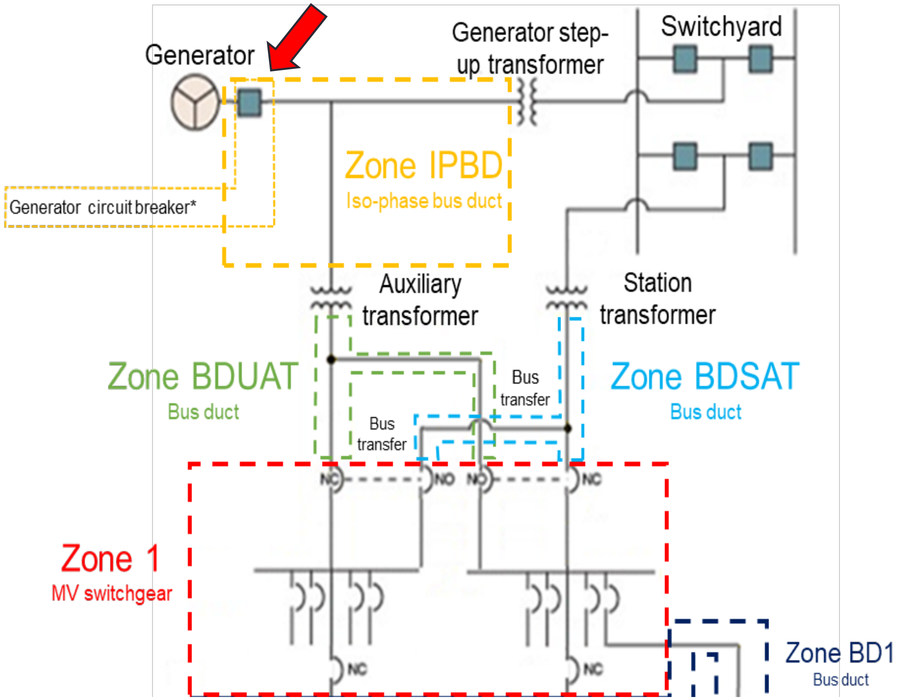
Stiff duration (s)	**Is the stiff followed by a generator-fed fault?**	**Arc energy (MJ)**	**End state**	
			Single wall construction	**Double wall construction**
2	No	68	No fire spread	No fire spread
3	No	101	No fire spread	No fire spread
4	No	135	Use fire spread event tree (Figure 6-19)	No fire spread
5	No	169	Use fire spread event tree (Figure 6-19)	No fire spread
0	Yes	132	Use fire spread event tree (Figure 6-19)	No fire spread
2	Yes	200	Use fire spread event tree (Figure 6-19)	No fire spread
3	Yes	233	Use fire spread event tree (Figure 6-19)	Use fire spread event tree (Figure 6-19)
5	Yes	300	Fire spread to meter and relay cubicle (Figure 6-20)	Fire spread to meter and relay cubicle (Figure 6-20)

Key Findings (Ignition)

- Cables outside the enclosure of origin (but within the ZOI)
  - No sustained ignition concurrent with HEAF
  - Must consider cable ignition outside the enclosure of origin if within the flame, plume, and radiation region of the post-HEAF fire
- Cables inside the enclosure of origin
  - Ignition is assumed (e.g., internal cables and components within switchgear and load centers)
- Based on operating experience and testing

Generator Circuit Breaker in EDS

- GCB can prevent main generator coast-down energy from feeding faults
- CIGRE data used to estimate GCB failure on demand to **3.5E-05**
- Less than 20% of U.S. NPPs are equipped with GCBs

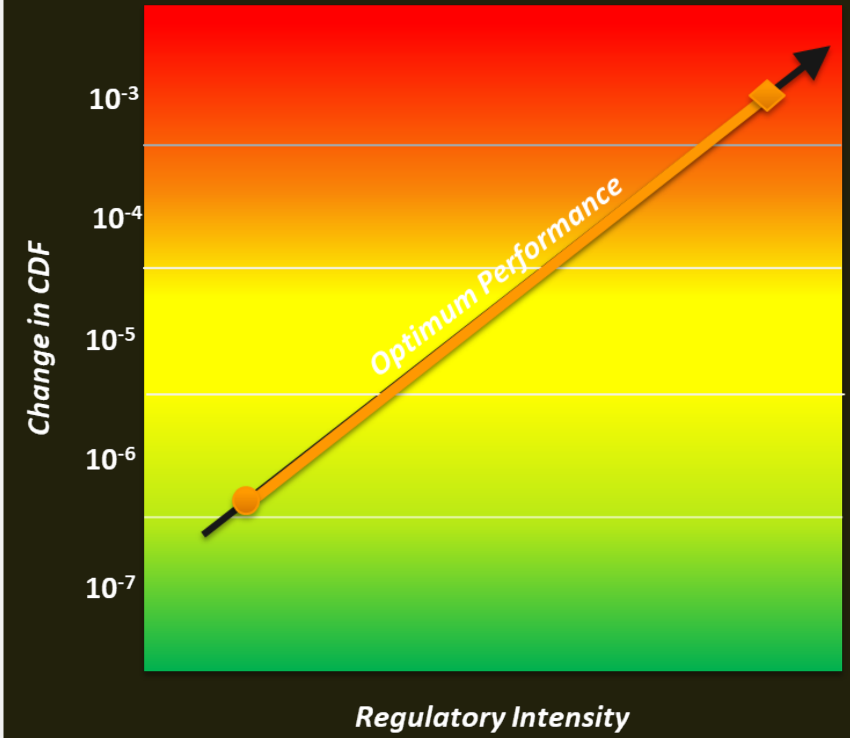


HEAF LIC-504 RESULTS

Background - Integrated Decision-Making Process for Emergent Issues (LIC-504)

- Developed as a lessons learned from Davis-Besse reactor vessel head degradation
- Provides a structured process and expectations to document decisions for issues that may warrant regulatory actions
- Provides guidance to apply integrated decision-making including risk, defense-in-depth, and safety margins considerations
- Has been used frequently for a range of emergent plant-specific and generic issues
- **Not** a substitute for other NRC processes

LIC-504 Graded Recommendations - Examples



Weigh a Spectrum of Regulatory Options

- Immediate regulatory action -
  compensatory measures
- Formal backfit analysis (≥ 10^{-4})
- 50.54(f) letters
- Bulletin
- Information Notice/Outreach
- Smart inspection samples -
  - within baseline program
- No Actions

Use RIDM –
Not numbers alone

RIDM – Risk Informed Decision Making

HEAF LIC-504

STEP 1 – NO IMMEDIATE SAFETY CONCERN

STEP 2 – DETAILED EVALUATION USING DRAFT METHODOLOGY

HEAF LIC-504 – Scope

Copper and aluminum HEAF zones of influence should be treated the same based on the current state of knowledge.

The LIC-504 assessment was then focused on examining the change in estimated HEAF risks associated with the use of the new HEAF PRA methodology.

HEAF LIC-504 – Work Completed

Visited one BWR and one PWR plant

Assistance provided by each reference plant licensee was essential and added credibility and realism to the team's analyses

The team generated risk-informed insights and recommendations

Publicly available memo with WG recommendations was issued on July 22, 2022 (ADAMS Accession No. ML22201A000).

HEAF LIC-504 – Staff Insights

THE RISK OF HEAF COULD BE HIGHER OR LOWER THAN CALCULATED UNDER THE PREVIOUS METHODOLOGY

RISK COULD VARY SIGNIFICANTLY BASED ON PLANT CONFIGURATION

FOR CERTAIN CONFIGURATIONS, THE ESTIMATED RISK FROM NON-ISO-PHASE BUS DUCTS COULD BE NOTABLY HIGHER THAN PREVIOUSLY MODELED

CONCLUDED THERE IS NO SIGNIFICANT INCREASE IN TOTAL HEAF RISK, THAT WARRANTED THE NEED FOR ANY ADDITIONAL REGULATORY REQUIREMENTS

PRACTICAL IMPLEMENTATION OF DRAFT METHOD ALLOWED FOR REAL-TIME FEEDBACK AND IMPROVEMENTS TO FINAL METHOD

HEAF LIC-504 – Recommendations

Issue	Information Notice IN 2023-01 Risk Insights from High Energy Arcing Fault Operating Experience and Analyses
Incorporate	Risk insights into NRR’s ongoing PRA configuration control initiative.
Consider	Integrating risk insights into NRR’s inspection program in accordance with ROP’s change control processes.
Communicate	Risk insights with internal and external stakeholders.

HEAF Research Concluding Remarks

KEMA Labs

Sandia
National
Laboratories

UNITED STATES NUCLEAR REGULATORY COMMISSION

OECD

EPRI
ELECTRIC POWER
RESEARCH INSTITUTE

NIST

FIRE RESEARCH

FUTURE ACTIVITIES

Ongoing/Planned Activities

- Low-power shutdown for non-light water reactors (FY24-26)
  - Identified as a gap for Licensing Modernization Process (LMP)
  - Unique risks associated with new reactors
- Cable Aging (FY24-26)
  - Flame spread and ignition criteria used in PRA based on new cable samples
  - Aged cables may behave differently in fire conditions
- Bulk Cable Tray Ignition Criteria (FY23-25)
  - Reduce uncertainty in technical basis for the guidance provided in FAQ 16-0011
  - Improve modeling guidance for electrical enclosure fire propagation to cable trays

Ongoing/Planned Activities

- Fire Risk for Co-located Hydrogen Generation (FY24-25)
    - RES Future Focused Research (FFR) Project
    - Develop fire risk framework for high temperature electrolysis facilities' impacts on NPP SSCs and infrastructure
    - Update Appendix N of NUREG/CR-6850 "Hydrogen Fires"
- Component-Based Fire Frequencies (FY23-25)
    - Transition from plant-based to component-based frequencies will more realistically reflect as-built plants
    - High priority from 2018 Fire PRA realism workshop, resource limitations delayed execution of project.
    - Update to NUREG-2169

Future Research Activities

- Wildland-Urban Interface Fires
  - Climate change expected to exacerbate frequency of occurrence
  - Evaluate impact on plant infrastructure, accessibility, and habitability
- Molten Salt Reactor Fire Protection Standard Development
  - ANSI/ANS 54.8 “Liquid Metal Fire Protection in LMR Plants” standard inactive since 1988
  - Current efforts in LMP have highlighted the need for updated standards
- Post-Fire Safe Shutdown (Advanced Reactors)
  - Evaluate fire hazards associated with digital systems to ensure safe shutdown capabilities
- Lithium Battery Fires
  - Assess hazard of lithium-ion battery replacements
  - Battery HRRs not considered in NUREG/CR-6850 (currently mapped to electrical motors)