# Official Transcript of Proceedings

# NUCLEAR REGULATORY COMMISSION

Title: Advisory Committee on Reactor Safeguards Structural Analysis/Plant License Renewal Subcommittee

Docket Number: N/A

Location: Rockville, Maryland

Date: September 19, 2014

Work Order No.: NRC1090 Pages 1-600

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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STRUCTURAL ANALYSIS/PLANT LICENSE RENEWAL

SUBCOMMITTEE

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FRIDAY

SEPTEMBER 19, 2014

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ROCKVILLE, MARYLAND

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The Subcommittee met at the Nuclear Regulatory Commission, Two White Flint North, Room T2B1, 11545 Rockville Pike, at 8:30 a.m., Peter Riccardella, Chairman, presiding.

COMMITTEE MEMBERS:

PETER RICCARDELLA, Co-Chairman

GORDON R. SKILLMAN, Co-Chairman

DENNIS C. BLEY, Member

CHARLES H. BROWN, JR., Member

HAROLD B. RAY, Member

STEPHEN P. SCHULTZ, Member

JOHN W. STETKAR, Member

ACRS CONSULTANT:

WILLIAM SHACK

DESIGNATED FEDERAL OFFICIAL:

KENT L. HOWARD, SR.

ALSO PRESENT:

PAUL BROWN, Penn State University

JOHN BURKE, NRR

JEREMY BUSBY, ORNL

MARK FUHRMAN, NRR

RANDY JAMES, VP Structures

MICHAEL KEEGAN*, Don=t Waste Michigan

DAVID KOSSON, Vanderbilt University

H.S. LEW, NIST

MARVIN LEWIS*

JOHN LINDBERG, EPRI

MIKE MARSHALL, NRR

WILLIAM OTT, NRR

JACOB PHILIP, NRR

FAHIM SADEK, NIST

MADHUNITA SIRCAR, NRR

KEN SNYDER, NIST

BRIAN THOMAS, Deputy Director, DE

RICHARD TILLEY, EPRI

*Present via telephone

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P R O C E E D I N G S

8:28 a.m.

CHAIR RICCARDELLA: Good morning. This is a joint meeting of the Structural Analysis and License Renewal Subcommittees of the ACRS. I am Pete Riccardella, Chairman of the Structural Analysis Subcommittee. To my right is Dick Skillman who's Chairman of the License Renewal Subcommittee. Other ACRS members in attendance are Dick Skillman, Ron Ballinger, John Stetkar, Steve Schultz, Harold Ray, and our esteemed consultant Bill Shack.

MEMBER BROWN: And I'm not here. Just pretend I'm not here.

CHAIR RICCARDELLA: Dennis Bley will be here soon?

MEMBER STETKAR: Yes, his bag is here so . . .

CHAIR RICCARDELLA: And Charlie Brown.

MEMBER STETKAR: And it's easy to pretend Brown's not here.

CHAIR RICCARDELLA: Sorry about that.

MEMBER BROWN: That's all right. He's --

CHAIR RICCARDELLA: Today we will discuss concrete degradation and long-term aging effects on concrete. Mr. Kent Howard is the Designated Federal Official for this portion of the meeting.

In brief, the ACRS issued a statement for subsequent license renewal on May 22nd, 2014 and stated the following: We plan to engage the staff and stakeholders in the near future to better understand the technical issues that pertain to SLR: the basis for their identification and prioritization, the status and results of ongoing research and how that information will be included in the regulatory guidance. Long-term aging of concrete is one of those issues.

This topic includes a variety of degradation mechanisms, one of which happens to be alkali silica reaction. This meeting was designed to hear about current research on a variety of concrete degradation issues and, hopefully, learn which specific issues the staff, academia, and industry considers to be the most important to SLR.

Today, we will hear presentations from the Office of Nuclear Regulatory Research, Division of Engineering, and Division of Risk Analysis, National Institute of Standards Technology, Dr. David Kosson and Dr. Kevin Brown from Vanderbilt University, Dr.

Paul Brown from Penn State University, the ANATECH Corporation, and the Department of Energy/Oak Ridge National Laboratory, as well as Electric Power Research Institute.

We've not received written comments or requests to make statements from members of the public regarding today's sessions. The entire meeting will be open to public attendance.

There will be a phone bridgeline to preclude interruption of the meeting. However, the phone will be placed in the listen-in mode during the presentations and subcommittee discussions.

A transcript of this meeting is being kept and will be available, as stated in the Federal Register Notice. Use the microphones located throughout the meeting room when addressing the subcommittee. The participants are requested to please identify themselves and speak with sufficient clarity and volume so that they can be readily heard. I also request that attendees mute their electronic devices, such as cell phones, during the meeting.

Ladies and gentlemen, we have a great deal of material to cover today. Just for the four-hour morning session, we received over 160 slides, which translates into about a minute and a half per slide. In the agenda, I've broken down and allocated specific times for each presentation based on the number of slides for each. I encourage the presenters to focus on their most important slides in order to stay on schedule and allow some time for discussion. But to be fair to later presenters, I'm going to hold us to this schedule. I will advise each speaker as they approach their time allocations. Dick Skillman has offered to be my timekeeper.

We will now proceed with the meeting, and I welcome and call upon Brian Thomas to begin the presentation.

MR. THOMAS: Good morning. So, yes, my name is Brian Thomas. I'm currently the Acting Deputy Director for the Division of Engineering in the Office of Research. With me is Bill Ott, who's the Branch Chief in the Division of Risk Assessment in the Office of Research. The DE staff certainly appreciate this opportunity to come before you and speak to its research concrete degradation program.

As you stated, your request was specific to the subsequent license renewal aspects of concrete degradation, so we will be sure to speak to how our presentation is aligned with requests from NRR with respect to those programs, this subsequent license renewal program. So today we'll here to discuss research that has been done, research that is in progress, and also we'll reflect a little bit on plans for future research, ongoing research.

The concrete degradation program, as you said, there's a significant amount of slides in our presentation. You know, a lot of our work is in response to not only the these requests that's associated with the Office of Nuclear Reactor Regulation but also we have requests that's associated with the Office of Nuclear Material Safety and Safeguards. So as we speak, we'll be talking on degradation studies that are aligned with meeting the goals and expectations of both of those program offices.

So our research goals are aligned with those. And we'll be sure to punctuate those programs as we go through.

Back in April, I believe, we came before you. We spoke of the EMDA program. That was primarily an NRR-driven presentation with respect to subsequent license renewal. Today we'll go into more detail with respect to those issues that were identified as central to that program.

Also, we'll reflect, and it's as shown in the slides, we'll reflect a little bit on the expanse of our program in terms of domestic and international collaborations. There's a fair amount being done with respect to concrete degradation internationally. There's a fair amount that's being done by the DOE and EPRI. All of those different research activities will be taken into consideration as we discuss our plan going forward.

So with that said, I do want to point out, though, that the majority, as expansive as it is, the majority of our research work is confirmatory. It's predominantly confirmatory research, okay? I don't think the staff will be talking about or embarking on any exploratory or anticipatory type research. It's primarily confirmatory.

So with that said, I'll turn it over to John Burke and Mita Sircar to present the first aspects of our presentation.

MR. BURKE: All right. Good morning. Glad to be back. So what we're going to talk about today is the operating experience and research related to concrete degradation. We'll touch on the Expanded Material Degradation Assessment, or the EMDA, NUREG report. You heard a little bit about that back in April when we discussed the SECY paper for subsequent license renewal, in particular the radiation of concrete, alkali silica reaction, and the creep fracture post-tensioned containments.

Other areas are the light water reactor sustainability workshop and roadmap that was conducted at Oak Ridge on non-destructive examination, how the concrete degradation research applies or doesn't apply to dry storage systems for spent fuel pool, and just some overall discussion.

So operating experience and research has shown that concrete structures are reliable and durable, but degradation has occurred. Intervention and repairs are needed at times. And here are some just examples of degradation as occurred in the industry: cracking of concrete for a variety of reasons, post-tensioned anchor head where our concrete walls, where the water has infiltrated through the walls and cracks in the walls.

And I'm sure you're aware there have been several instances of containment liner plate corrosion from the OD of the liner due to foreign material embedded in the concrete. And there's also been issues with the moisture barriers inside containment where moisture has gotten in on the ID of the containment liner down in the joint between the floor and the wall.

Alkali silica reaction is another degradation mechanism that's going to be discussed in quite detail in the second half of the research presentation. Pre-stress tendon anchor head failures have occurred in the industry.

MEMBER SKILLMAN: Could you go back to that slide, please, John? Back one, please. Could you explain how loss of the tendon cap is a concrete problem versus a, if you will, a hydrostatic problem with the grease? I see this image. I know what I'm looking at, but I have a hard time connecting that to a concrete issue.

MR. BURKE: We're looking at both the concrete degradation and the structural integrity. So the tendon failure would affect -- you're right. It would not necessarily affect the concrete or cause degradation to the concrete, but it would affect the structural capacity of the building.

MEMBER SKILLMAN: Yes, sir, I understand that.

MR. BURKE: And in the staff requirements memoranda out of the SECY paper, we were asked to look at both items.

MEMBER SKILLMAN: Yes, sir. Thank you, John.

MR. BURKE: So areas of interest -- there are quite a few inspections conducted at the power plants for a variety of reasons, whether it's the maintenance rule inspections, the IWE or IWL inspections driven by Section 11 of the Code, Tech Spec inspections as part of the Appendix J integrated leak rate testing, or just the license renewal aging management programs for plants that have renewed licenses.

So there are quite a few inspections currently conducted at the power plants. For those plants that have a renewed license, the GALL report, the generic aging lessons-learned report for license renewal, recommends the use of ACI 349.3R for the frequency and inspection criteria.

And then there are -- I guess the last few years have been several information notices that have been published by NRR informing the industry about inspection results. 2010-12 was the information notice about the containment liner corrosion issues. 2010-14 talked about the inspection frequency. In the original maintenance rule guidance documents, a ten-year inspection frequency was accepted. But the ASME IWL code has been updated and now recommends a five-year interval on those inspections. So that's what was discussed in this information notice.

Information Notice 2011-20 notified industry of the alkali silica reaction issues at a plant. 2013-04 discussed the laminar subsurface cracks due to freeze-thaw action. Information Notice 2014-07 informed industry of Leak Chase Channel System inspections as part of the ISI/IWL inspections.

Like Brian said earlier, NRC has been conducting research on concrete for quite a few years. There's a list of some of the reports issued in the last few years. The most recent is the one at the bottom, NUREG/CR-7171. It was a compilation of what has been done over the years on radiation effects on concrete, and we'll then talk about that issue in more detail next. Mita is going to discuss that next.

MS. SIRCAR: Respecting degradation and

going forward, we know for inspection, repair, replacement, reenforcement, and other modifications. But now we've got subsequent license renewal and also storage and transportation.

Based on prior research and knowledge, EMDA panel has identified the gaps for future research. The gaps are, the first one, irradiation effect on concrete for which knowledge is low but structural significance could be very high. Alkali silica reaction is well documented in scientific literature but need to assess its structural significance. Creep-cracking interaction of the post-tensioned containment is not visible from outside, undetectable degradation mode.

The two highest degradation mode that are identified for steel components are tendon steel corrosion and also the liner corrosion. For liner corrosion, absence of current in-service inspection technique is an issue.

First item is radiation. Very little information available. Research conducted in 1960s and 70s are not representative of light water reactor environment. Of interest here is structures that are close to reactor and exposed to radiation. So reactor pressure vessel cavity, reactor pressure vessel pedestal, biological shield wall.

MEMBER SKILLMAN: If I can ask, please, why is the earlier research not valid?

MS. SIRCAR: We'll get to that in a later slide, but I can --

MEMBER SKILLMAN: Later is fine. Thank you. Thank you.

MS. SIRCAR: NRC's current understanding of radiation effect on concrete is largely based on information dated back to 1978 and is based on materials and test condition that doesn't really represent the light water reactor environment.

Here, this log is taken from NUREG-7171, our recent study that was done in Oak Ridge National Lab, and this log is the study of Hilsdorf plot for compressive strength. The problems identified are the temperature range that was used was not correct, and the sample sizes were small. Sometimes, the bending strength was used in place of the compressive strength for this particular one, and then there are shear tension and other mechanistic behavior that were not real representative of LWRS plants.

MEMBER BLEY: Mita, what's the left scale, FCU over FCUO? What are we measuring here? That's not an area I'm real familiar with.

MS. SIRCAR: With the degradation of the property, how it's changing the normalized --

MEMBER BLEY: Normalized what?

MS. SIRCAR: Degradation strength versus the --

MEMBER BLEY: It's the strength?

MS. SIRCAR: Yes, it's the strength. Compressive strength, yes.

MR. BURKE: So FCU would be compressive strength?

MS. SIRCAR: Compressive strength, yes.

CHAIR RICCARDELLA: Current versus original, right? Current strength over the original strength?

MS. SIRCAR: Yes, degradation strength versus the expected strength. This leaves large gap in the neutron and gamma radiation effect on concrete and also quantifying the interaction of temperature and irradiation effect.

The research strategy. Research strategy has characterized the radiation field and determined clearance level for biological shield wall and the RPV support, rear pressure vessel support, for 80 years and more, irradiate prototypical concrete and evaluate, harvest service irradiated concrete and evaluate, determine the effect of neutron and gamma and interaction with temperature, double-up mechanistic understanding of the effect of irradiation of concrete, and then collaborative and leveraging knowledge and capabilities.

NRC identified the need of research in this field since 2008. So it started discussion within NRC among the staff and also with industry, economic representatives, and Japanese researchers. NRC started a research program with Oak Ridge National Laboratory, and we have the results now. Although we did independent research earlier, but future research we expect back will be focused on SLR and mostly collaborative and confirmatory, as Brian mentioned earlier.

This is from our NUREG. Concrete is heterogenous. The picture shows the structure at macro, meso, micro, and nano level. Approximately 70 percent of concrete is applied by aggregate and 30 percent by cement and a large amount of micro holes.

DR. STACK: Just let me go back for a

second. John mentioned 7171, which is a very nice review report. Is that the research you're talking about at Oak Ridge, or is there actually some new work on irradiated material, rather than an updated review paper?

MS. SIRCAR: This is from NUREG-7171, but also research are being conducted in Oak Ridge National Laboratory, what Jeremy will present.

DR. STACK: Okay. But that's DOE research, so that's --

MS. SIRCAR: That's DOE research.

DR. STACK: So NRC is not doing any actual irradiations and measurements?

MR. BURKE: We don't have any right now. We plan on or we're considering collaborating with some international organizations on decommissioned plants. But right now, we don't have anything in place.

MEMBER BALLINGER: What about the Japanese program at Halden?

MR. BURKE: We're aware of it.

MEMBER BALLINGER: But you're not considering, you're not involved in that in any way?

MS. SIRCAR: Not yet. We are not doing

really anything with Halden presently.

The effect of irradiation on the aggregate versus the concrete-based is different, so there would be different mode of degradation. That's also very interesting.

MR. THOMAS: If I can go back to Dr. Ballinger's question just briefly, there are a number of entities in the international arena that have been doing a fair amount of work in concrete for quite some time.

MEMBER BALLINGER: Particularly the Japanese.

MR. THOMAS: Particularly the Japanese. Given some of the programs we have now, like subsequent license renewal and what we're looking into in terms of the extended storage and transportation, we recently started embarking on, recently started trying to establish, look in to establish agreements, international agreements, with some of these organizations to see to what extent we can leverage some of the work they've already done, see to what extent we could align our program with theirs to help foster, you know, additional research that would benefit us.

So from a planning standpoint, there's a fair amount in the whole, you know, research plan going forward that looks at -- you kept hearing the term leveraging resources and capabilities. Given that concrete is such a, been studied for such a long time, such an involved issue, we're really, you know, shaking the trees out there and looking to see to what extent we can utilize what's been done or piggyback on some of their future plans.

MEMBER BALLINGER: And near as I can tell, the only recent data is Fujiwara's.

DR. STACK: All we've seen in these plots, at any rate.

MEMBER BROWN: Why wasn't any of this information needed for the extensions from 40 to 60 years? We've got how many plants that have been extended from 40 to 60? Sixty to seventy plants or something like that. So, I mean, you all didn't -- I'm just looking at the view graph where it says you're starting some concentrated work starting in 2008 and, yet, we made tons of decisions on extending for another 20 years without any other research or other efforts to try to assess this particular phenomena.

MR. BURKE: If you go back to this graph out of NUREG/CR-7171, what that NUREG has pointed out -- and correct me if I'm wrong, Mita -- that at a fluence level of 10 to the 20th is about the exposure where you start to see degradation.

MEMBER BROWN: And this is from previous . . .

MS. SIRCAR: 10 to the 19.

MR. BURKE: Oh, 10 to the 19.

MEMBER BROWN: But prior to when we started the expansions or the extensions for the 40 to 60? I mean, did we have that information when we started that?

MR. BURKE: That was in Hilsdorf, wasn't it?

MEMBER BROWN: I don't know what Hilsdorf means.

MR. BURKE: The 1970 era.

MEMBER BROWN: Okay. So it's the 70s data that you were talking about.

MR. BURKE: Yes, and we don't, plants won't get to that level of exposure at 60 years.

MEMBER BROWN: Okay. So you think that chart, the graph, says there's a minimal degradation.

That's the way I read that --

MR. BURKE: Yes.

MEMBER BROWN: -- that the slope is pretty small, so you don't think that's a critical condition to worry about at the 40 to 60 year point?

MR. BURKE: That's correct.

MEMBER BROWN: Okay, thank you.

MS. SIRCAR: The result from the NUREG-7171 are improve and expand the database of irradiated concrete degradation mode level, resample, and service age to radiated samples, operating testing sample from biological shield wall and RPV support of the decommissioned NPP structures and research reactors, identify neutron and gamma field on NPP structures for 40, 60, 80, and 100, and quantify the interaction of temperature and irradiation effect. And the ongoing research are pretty much aligned to this result.

NRC sponsored a small research study to Oak Ridge National Lab to prepare a report on the latest status of the research and the ongoing work going on domestically and internationally. Research for irradiation is vast, involved, and expensive. So, again, the collaboration and leveraging is needed.

International collaboration on effect of irradiation of concrete structures has been established, and NRC is participating. We are also thinking about potential collaborative effort to develop the computational platform for the evaluation of structural significance of the irradiation effect on concrete.

Other efforts: potential harvest of concrete from decommissioned plant, Zorita, Zion, and others. This picture is, we received that from Spanish regulator CSN. This is their plant of the location from where they are planning to take the cores.

Some more details about the Zorita project that we have received from Spanish regulator. This plant was operated from 1968 to 2006. So effective full power was 26.5 years, and it was 38-year service life.

This has high neutron fluence in a commercial service reactor. Synergy with Zorita Reactor Internals Project, so that may bring some value to it with the prior experience. Decommissioning started 2010, and the harvesting of concrete is planned for March 2015.

The project is fully funded by the Spanish partners. However, if additional cores are required, that would be additional funding.

CHAIR RICCARDELLA: Do we know where Zorita is on that plot on slide 13?

MR. BURKE: No. They're doing those calculations right now on what is the actual fluence level. They expect to have those calculations finished in January.

MEMBER BALLINGER: Are you guys going to be involved with the Zion stuff?

MR. BURKE: We're discussing that with EPRI. EPRI and DOE are the lead on that one. We're involved with other material harvested from Zion, so we're trying to add this one, this project to the other projects we already have.

DR. STACK: In more likelihood, though, Zorita is going to be much higher fluence, I would think.

MR. BURKE: Correct. And I'm pretty sure you've been briefed on the Zorita Reactor Internal Project where we've actually harvested core internal material. Merila's branch, CMV, in research has an active project with the Spanish and EPRI. The core internals are being tested now. And so that project, again, similar to Zion, we hope to build on that partnership that's already established under the ZIPR project.

CHAIR RICCARDELLA: So just in a nutshell, what types of tests are planned on these core samples from Zorita?

MS. SIRCAR: Mechanical and structural properties --

CHAIR RICCARDELLA: But there will be some compressive strength tests?

MS. SIRCAR: -- and the type of degradation that has happened. NRC's informed about the Zorita project through NRC and Spanish regulator memorandum of understanding. Area countries are also informed through the Spanish delegate on the subgroup of concrete of the OECD/NEA CSNI. And also IAEA was informed in the last June meeting. John participated in that meeting.

Research plan. The current status in identifying the gaps, that's our first step; bounding fluence for neutron and gamma; stay informed by participating in the meetings and from the research results; participate multi-lateral collaborations to leverage knowledge and capabilities; harvest service-irradiated concrete; testing of the specimen; evaluate degradation on structural and mechanical properties; computation of framework; and non-destructive examinations. Confirmatory testing and evaluation will be done as needed.

We have a tentative plan for this. The dates are assumed dates, considering that there will be application 2018. But these dates are not taken from any particular research plan from EPRI or NWR. It is expected that the research are ongoing and will go into 2017 - 2018 to support the application.

We already have done the EMDA report. That's the first bar. The second one is also the NUREG/CR that we have published last year. The radiation effect on concrete ongoing research status: that we are working with Oak Ridge National Lab, we have a draft report, and the study will be completed, the report will be completed before March of 2015.

NRC information collection. We are now in touch with international collaboration of irradiated concrete, ICIC, IAEA, CSNI, Zorita Concrete Research, and we have a bilateral with Japan. And we know Japan is doing a lot of work. They are ahead in the game.

Zorita and Zion concrete harvesting. I

have a little dot there in March 2015, so we are planning to collect some samples from there.

Then EPRI research, we have split the whole work in same time frame for the whole EPRI work and also the whole LWRS work, those two black long lines. And the green lines and the blue short lines are the intervals where we plan to review those projects, try to understand what's the latest status, what is the current result, and do we need to do any confirmatory or independent research on those results.

Then those little bars are those time frames where we want to go and review EPRI and LWRS project results. Then I'm going to the lower red bars where we are thinking that there will be some collaborative research with NRC, DOE, and EPRI, the first bar. The second bar is international research on harvested concrete that the current plan is Zorita but also Zion, if possible, or any other prospective plant that NRC considers.

NRC research confirmatory. I have a bar coming from the review line to the little red "I" to the last bar. That means, like, if in that review we find that we need to do any confirmatory research, then we will do a confirmatory research on that. It depends on the review result.

The last line is NRC, CSN, Zorita research under MOU. That is, we have this MOU with the Spanish regulators that whatever they will do, we'll stay in touch and we'll follow their research. That's the last --

MEMBER BALLINGER: With respect to the Zorita thing, Bill was saying that the dose is higher. But what controls everything on the concrete is the aggregate. How close is that concrete to the concrete that we use here? Do you know whether there's going to be a good comparison that we can make?

MS. SIRCAR: That's definitely a very good point, but the whole research is framed, like, different concrete is actually very, I would say, very difficult to say this is the property of concrete. Different places, different concrete, different plant has different concrete. So as much as possible, get the data, get the research result, get a database and normalize the result to have our understanding of what can happen.

MEMBER SCHULTZ: So that leads to my question, and that is, with regard to Zion and Zorita, how well characterized is the concrete? In other words, you're looking at what it appears to be in its strength and characteristics after the 27 years or 30 years of irradiation. How well characterized can you claim it to be to identify, in fact, the differences when you do the testing at this point in time?

MS. SIRCAR: Yes, this is really a very important point, and that's what is in our NUREG/CR-7171 says. Like, test as much as possible specimens, laboratory irradiated and also the service-aged concrete, and try to understand what is --

MEMBER SCHULTZ: The differences there.

MS. SIRCAR: Yes.

MEMBER SCHULTZ: Remember to include the error bars.

MEMBER SKILLMAN: Let me ask this question. I'm curious. You've spoken about Zorita, so we're working with the Spanish and Zion decommissioned plant. I spent years working in Europe, and I'm curious why there isn't information from the RSK or our colleagues in Germany, from our colleagues in Switzerland, from our colleagues in Sweden, because they are facing the same challenges that we are as they look ahead.

And so I'm wondering is there information coming from our international partners or international colleagues that is, in fact, a reservoir of information that will help inform the research that you're doing?

MS. SIRCAR: Correct. And that's one of the goals of the international collaboration of irradiated concrete. And that's a platform to exchange all the information and collaboration, so it has been started. And I think what we're saying, it's going in that direction.

MEMBER SKILLMAN: Thank you.

MR. BURKE: In addition to what Mita said, there are two other sharing forums. One is the IAEA just kicked off a CRP, coordinated research program, in June. And one of the subgroups under that is concrete irradiation, just to share what other countries are doing. And Mita mentioned earlier there's the CSNI organization that also has a concrete subgroup to share information.

MS. SIRCAR: So ongoing planned work. There is a program going on at Oak Ridge National Laboratory and the DOE's LWRS program, EPRI-LTO program, Zorita Concrete Project, and IAEA collaborative research plan, what John just mentioned.

And also we are aware of Halden tests reactor work, research in Japan, research in Finland and Czech Republic.

The next topic identified in EMDA report is alkali silica reaction and assessing its potential consequences on the structural integrity. NRC has began research in NIST and, in the second half, research in the NIST will be presented by -- you or NIST will present it? NIST will present it, I think.

The third one identified is the creep fracture on concrete containment. Creep and shrinkage of concrete, coupled with elastic shortening and relaxation of tendon, can lead to various short-term and long-term losses of the prestressing force on tendons.

So EMDA has identified this gap, also. For the post-tensioned containment, maintaining the prestressing force is very important. Contributors for prestress loss include friction, elastic shortening, tendon relaxation, creep, and shrinkage. Out of this, the tendon relaxation, creep, and shrinkage are related to aging. Sometimes, it is necessary to re-tension the tendons to regain their required level of prestressing. Period re-tensioning may introduce cyclic activation of primary creep and can damage the concrete. Creep fracture could be a potential degradation mode for prestress onto containment.

Creep of concrete and there are complex two-dimensional states of stress may lead to creep-induced heat cracking from combination of vertical prestressing and that evolves with time, sweep cracking or linear may occur during the initial prestressing, during re-tensioning, de-tensioning, repair, and replacement.

Currently, NRC is conducting a study of prestressing concrete containment, but this work is not exactly creep fracture. However, it provides insight about the containment structural response, in-service inspection, and effects of corrosion of tendon.

So there was a round robin study of containment post-tensioning tendons tensioning methods, and it compared both grouted and greased tendon containments. OECD/NEA CAPS started in October 2010. The final report was reviewed by the working group, and it will be now placed for OECD approval.

NRC participated in the CAPS, and we

started a project with Sandia National Laboratory in 2010, October. The main focus of that project was to compare and investigate grouted and greased tendon containments.

There were three tasks. The first one was to study the containment structural response for severe accident and failure modes. The second was to compare the post-tensioning methods and in-service inspections done all over the world and also assessment of the durability and long-term corrosion protection. This NUREG is under review and expected to be published sometime next year.

ISI, in-service inspection, is important for safe operation of nuclear power plants. Review of current ISI methods for best post-tensioning concrete made with grouted and ungrouted tendon and its applicability to newer and higher-strength materials. In this regard, we started another short review project to actually update or revise our Regulatory Guide 1.35.1 which provides the basis for calculation of the losses.

Review of methods of monitoring of the post-tensioned containment by instrumentation. The results of this research will be used to update regulatory guides. The research started March 2012 and is expected to be completed by December 2015.

CHAIR RICCARDELLA: Do any of the plants do any monitoring currently with the pre-tendon tension?

MS. SIRCAR: Yes. Can you please repeat it?

CHAIR RICCARDELLA: Do any plants currently monitor their tension in their prestressing cables?

MS. SIRCAR: With an instrument?

CHAIR RICCARDELLA: Yes.

MS. SIRCAR: Not in U.S., yes. I think EPRI is doing some study they may cover in their presentation.

MR. TILLEY: If I may comment on that.

CHAIR RICCARDELLA: Yes, please. You've got to come to the mike and introduce yourself.

MR. TILLEY: Rich Tilley, EPRI LTO program. We did do some online string gauge monitoring as part of a demonstration project at the Ginna Power Plant. So we did have continuous monitoring of 20 of the tendons over a period of several years. In fact, the monitoring is continuing.

But we did use fiberoptic string gauge technique on these --

CHAIR RICCARDELLA: Thank you, Rich.

MEMBER BALLINGER: Isn't there a requirement with respect to the number of, the amount of tension that's available in the containment for safety reasons for pressurization, over-pressure, and stuff? I think the tension of the concrete, there has to be a certain number of them operative in order to meet the safety. How is that verified?

MS. SIRCAR: With reference to in-service inspection and force, prestressing force in the tendon, that's what you're asking?

CHAIR RICCARDELLA: Periodic full tests --

MEMBER BALLINGER: Okay. So they do that? Okay.

MS. SIRCAR: We do that every five years. This is Section 11, IWL requirement, every five years, yes.

CHAIR RICCARDELLA: Thank you.

MS. SIRCAR: Now we are moving to another topic, non-destructive examination. And this is common and needed for any kind of degradation. Extending plant life beyond 60 may likely increase the probability and severity of the known forms of degradation, and also some new form of degradation may show up.

One of the main objectives of LWRS program is to develop technologies and other solutions that can improve the reliability and sustain the safety over the subsequent licensing period. As a part of that effort, LWRS concrete NDE workshop took place in Oak Ridge National Laboratory July 2012. NRC participated, and a roadmap for future research need was developed under LWRS program. And the report was published in September of 2012. A second report is coming soon, and Jeremy will present in more details.

Methods for detection of degradation. Extremely large size contested with embedded enforcement, accessible from one side only, heterogenous material, prestressing component, all these things makes it very complicated kind of NDE need and that improvements are desired. Whatever is available now may not be sufficient.

The areas are identified. Thick, heavy reenforced concrete, basemat, liner, prestressing components. The gaps that are identified in NWRS NDE workshop are need to serve available samples, techniques to perform volumetric measuring on thick reenforced concrete sections, determine physical and chemical properties as a function of depth, technique to examine interfaces within concrete and other materials, development of acceptance criteria, modeling and validation, need for automated scanning system for any of the NDE concrete measurement systems, and deployment is very important. The structures are large, big area, and sometimes it's inaccessible.

Now John will cover the next part.

MR. BURKE: So like we've been saying, the EMDA report was prepared as guidance on what we need to do for subsequent license renewal. So the revision of the license renewal guidance documents for subsequent license renewal is underway. There are eight structural Aging Management Programs in the GALL report, and Mita and myself are the technical leads for seven of those eight. So the gaps that Mita just talked about are being factored into the revision of those guidance documents.

MEMBER SKILLMAN: John, for the one that you're not the technical lead for, who is the technical lead for that one and is there something that we need to talk about?

MR. BURKE: Well, the technical lead for -- well, that particular one is the Appendix J leak rate testing, and the lead is a senior engineer in the license renewal division.

MEMBER SKILLMAN: Thank you.

CHAIR RICCARDELLA: Is there an AMP for concrete?

MR. BURKE: Yes, there are several AMPs related to concrete. There's one on the overall structural monitoring. There's a separate one for masonry walls. There's a separate one for water control structures. The one for the overall structural monitoring is very similar to the maintenance rule structural inspections.

MEMBER SKILLMAN: Let me ask this question, and it's kind of rhetorical but let me explain the basis. Folks around this table signed a letter on subsequent life renewal, and the question we were dealing with was is more regulation necessary? And we landed on a consensus that more regulation is not necessary, that the current set of AMPs, AMRs, TLAAs are a sufficient tool set to go forward from 60 to 80.

Is it accurate for us to assume that what exists today, plus enhancements or the additional research you're pointing to, will constitute a thorough treatment for assessment to go beyond 60?

MR. BURKE: Yes, I believe it is.

MEMBER SKILLMAN: Okay, thank you.

MR. BURKE: Okay. I got to find the right button here. Okay. So far, we've been talking about operating reactors and subsequent license renewal for the operating reactors and concrete degradation. Well, a lot of the same concerns about concrete degradation in operating reactors can also apply to dry cask systems for spent fuel.

We recently kicked off a project to study concrete degradation in dry cask systems, also. So the two projects are working concurrently.

Now, some of the degradation mechanisms are going to be different and some are going to be very similar. So we're looking at the aging and degradation, what are the inspection frequencies and inspection techniques that could be applied to dry cask systems, the assessment of the adequacy of the concrete to perform its intended function. And that's also a big difference, right?

So the intended function of the concrete in a dry cask system is different than the intended function of the concrete around a reactor. So some degradation mechanisms may affect the intended function, some may not. And the license term is also different.

So the operating reactor research is looking at 80 years of operation. The dry cask storage is much longer-term, most likely.

An expert panel is being formed to look at the concrete degradation for the dry cask system, and the first meeting of that expert panel will be this fall.

MEMBER BLEY: What are their goals? Is this a PIRT kind of thing, or is this trying to actually lay out and maybe quantify, to some extent, the issues?

MR. BURKE: It's a PIRT type panel, but it's not being called a PIRT. It will function similar to a PIRT.

MEMBER BLEY: The goals are to identify the potential mechanisms and what we know and what we don't know?

MR. BURKE: Yes. And here's just a

schematic. There are vertical storage systems and horizontal storage systems. We've talked a little bit about some research that's going on. We're also actively involved in codes and standards and, where it is appropriate, that codes and standards be revised. Our participation in the codes and standards committees to make those revisions a priority is one of our goals. So we're involved in the ASME Section III Division 2 Concrete Containment Committee with the ACI 359; the ASME Section 11 In-Service Inspection; IWE, IWL, IWF programs; ACI 349; the Nuclear Energy Standards Coordination Collaborative; and the American Society of Non-destructive Examination.

Now, some of the -- pardon?

MEMBER BLEY: My understanding was there's a new standard coming out for this. I forget what you folks call it but the steel with poured concrete in the middle construction, like AP1000 shield building. Are you involved in that?

MR. BURKE: Our people in research are, yes.

MEMBER BLEY: Okay. Is that about out now or no?

MR. BURKE: My understanding is that's the

AISC or Standard N690 --

MS. SIRCAR: AISC N690.

MR. BURKE: And there's an appendix to that. We are involved in that code committee, and we're also doing some research with some of the national labs to look at where that standard needs to be improved.

MR. THOMAS: I think for that standard, I think they're looking at, like, a six-month projection for the first issuance of --

MEMBER BLEY: Okay. Thanks.

MR. BURKE: This is some of the international organizations we're involved in. Most of them have been mentioned already. One that hasn't is the second one there. RILEM is a technical committee on ASR degradation.

And that's the end of the presentation. Any other questions?

CHAIR RICCARDELLA: Thank you very much, John and Mita, for the very informative presentation. Anybody else, anybody at the table have any further questions?

MEMBER BALLINGER: I'm assuming that some of the -- I was looking at the schedule -- somebody is going to deal with that so-called Hilsdorf curve in a little more detail during the day?

MR. BURKE: No, I don't believe so.

MS. SIRCAR: Jeremy is going to.

MEMBER BALLINGER: Jeremy, are you going to do that? Okay.

CHAIR RICCARDELLA: Please identify yourself so our recorder can know who spoke, please.

MR. BUSBY: Jeremy Busby, Oak Ridge National Laboratory. And I will cover the Hilsdorf curve and additional data in this afternoon's session.

MEMBER SKILLMAN: Thank you, Jeremy.

CHAIR RICCARDELLA: Thank you. Do we have any comments from the audience or from the people on the bridgeline? Okay. So hearing none, we will proceed with the next presenter, Dr. Ken Snyder. And we are actually 15 minutes ahead of schedule.

MR. BURKE: Division of Risk Analysis and Research has rest of the morning.

MR. PHILIP: Good morning. My name is Jacob Philip. I'm a senior geotechnical civil engineer with the Office of Research, and I'm with DRA, the Environmental Transport Branch.

Just to give you a little bit of

background on what we have been doing in the area of concrete degradation, the two central issues both focus on the materials properties of concrete and basically looking at the service life of concrete structures. We did a lot of work on the long-term performance of concrete waste isolation structures specifically with low-level waste structures entombment and waste incidental to reprocessing. And we also looked at, we are presently looking at waste forms also. This is at Savannah River. And most of this work in the beginning was done by NIST.

We also have a Cement Barriers Partnership program which is through a memorandum of understanding between DOE, NRC, and NIST. And you'll hear about it when -- Dr. Kosson from Vanderbilt will give a talk on CDP.

Under user need, we are doing the degradation of nuclear power plant concrete structures affected by ASR. There are two parts to that presentation. One is the structural engineering aspects and then the materials part. We also did, under the long-term research program in the Office of Research, we did a small research project on NDE for concrete, basically looking at how we could get data from NDE for service life predictions.

Today's discussions will be as follows: current research on ASR; Dr. Ken Snyder from NIST will give an overview of concrete degradation; Dr. Fahim Sadek and Dr. H.S. Lew will talk about the experimental investigations we are doing on concrete structures affected by ASR; and Ken Snyder will be talking about the materials investigations for that project. Professor Kosson will be talking about the Cement Barriers Partnership. He'll give an overview of the Cement Barriers Partnership activities.

This is already been talked to previously. We are also involved with the RILEM technical committee on ASR degradation of nuclear concrete structures. And we also have a partnership with OECD/NEA CSNI which involves many international partners looking at a collaborative program on concrete degradation. And we plan to have a workshop here at NIST in July 2015.

CHAIR RICCARDELLA: Sorry. I missed it. What is RILEM?

MR. PHILIP: It's a French word, but it's actually a standards committee mostly out of Europe. Well known, actually. And with that, I will just ask

Ken to give his talk. And I would also request that David and Fahim, that you could come out to the table.

DR. SNYDER: I think RILEM, it's probably better known among the building community. And it's a pre-standards organization, so it's technical work we could do in preparation for developing a standard. So you won't find a RILEM standard, but you may find a lot of European and American standards based on work that came out of RILEM.

So this concrete degradation, it's certainly worthy of a two-hour lecture. This is just going to be a high level 15-minute discussion. I'm the group leader of the Concrete Materials Research Group at NIST. We look at concrete from a materials chemistry side, not from a structural side. So our expertise covers a lot of the chemistry reaction, including some of the concrete degradation.

So just a quick overview of the high points of concrete degradation. Try to get everything -- what I'm trying to do is provide a context for you so that when you hear other talks going maybe deeper into some of this particular degradation mechanisms you'll understand all that kind of comes with it, the underlying mechanisms, the physical kind of mechanisms. Also, I'll touch upon this very, very briefly: what is the possible side effects of these degradation mechanisms on durability? What are some of our activities we've done with NRC over the years and, finally, just again, just a very high-level discussion of ASR addressing I think one or two questions that someone had.

Let's go to the next one. So to begin, starting with -- let's dig down and take a quick look at a paste. So concrete, water, sand, water/cement/sand aggregate, we're talking about looking right at the water/cement mixture, what we call a paste. If you get down to this kind of SEM kind of level, you see what I'm trying to convey to you is that you're looking at some of these fairly heterogenous, and those black spots you see are pores. So it's not just a gray uniform material. There's a lot of stuff going on in there.

MEMBER BROWN: When you say pores, you mean voids?

DR. SNYDER: Yes, yes.

MEMBER BROWN: Okay, all right. I'm just trying to connect the dots here.

DR. SNYDER: Right, exactly. So that

water is really critical for the hydration reactions to occur. So on the right side, that water plus the cement is going to lead to reaction products. C-S-H is the main binder that holds everything together, which is poorly ordered, which means it kind of comes out as a hump on an XRD and plus another crystal materials --

MEMBER BLEY: Excuse me. Some of us don't know all your acronyms.

DR. SNYDER: Oh, from the federal government, I should know better by now. Thank you, thank you. C-S-H is calcium silicate hydrate. It's a poorly-ordered calcium silicate. XRD, x-ray to fraction, so if you put an x-ray diffractometer, you can identify those crystalline materials. But the C-H-S is going to be kind of a hump.

Those percentages are just ballpark, plus or minus a 120 percent, just to give you an idea. You can see it's a lot of C-H-S, a fair bit of portlandite, but those other ones are fairly minor. On the soluble one, so you've got a lot of portlandite, which is fairly soluble. The C-H-S is not as soluble, much less soluble.

So down at the bottom, what I'm trying to convey here is it's fairly porous. As it reacts, some of the water is taken up in some of these materials. Some of the water gets left behind, but this water is not water. It has a pH of somewhere, it could be 13 - 13 2. It's a highly concentrated mixture. It's a pretty complicated mixture.

So what I'm trying to convey here is this pore solution that's left behind -- in fact, one of the things we'll do to analyze it is put it in a high-steel press, squeeze it out, and analyze that liquid. So we can squeeze the blood from a stone, so to speak.

So when we think about trying to model degradation towards service-life prediction, we think of it as this pore solution is in intimate contact with all the different phases that are there. So now you can -- when I talk about the environment interacting with the concrete, what I'm primarily talking about is the environment ground water or rain water, what have you, working its way, having its effect through this porous system.

MEMBER SKILLMAN: Let me just ask this one question. Is this representative of general concrete, or is this a unique blend specifically for this discussion?

DR. SNYDER: Good question. This was just a mixture of cement and water at about a water-cement ratio of 0.4, which is a good quality. It's the type where you --

MEMBER SKILLMAN: This is the plain jane concrete you get for a normal construction --

DR. SNYDER: If I was making a concrete mix, that ratio of water to cement really kind of starts the ball rolling. That would be the water-cement ratio you'd probably start with for a decent concrete.

MEMBER SKILLMAN: So this is common ordinary cement paste that you get for a normal construction project?

DR. SNYDER: For an ordinary portland cement, which means it's just water and cement. If you go out there now, you're not going to find that, almost certainly. You're most likely going to have limestone in it. You're most likely going to have fly ash in it. Fly ash is much cheaper. It's fairly compatible with concrete, but it's cheaper than cement. Cement is the high-cost component of this.

So you might not, it might be very

difficult to find a, quote, similar kind of image. You'll find fly ash particles in there, and you'll see limestone particles in there more likely. But you will see pores and you will see this heterogeneity.

So some degradation processes. Corrosion of steel you're probably familiar with. You can imagine if I have a road and I'm salting the road, that sodium chloride can work its way through those pores, slowly diffusing through those pores, getting down to the rebar, corrosion, reaction products, pressure, stresses, cracks.

Alkali aggregate reaction. There are a number of different types of alkali aggregate reaction. Alkali silica you've probably heard, we're going to hear probably a fair bit today. There's carbonate reactions and silicate reactions.

Here the alkalinity that's already in the pore solution is going to react with susceptible phases within the aggregate to form a gel. This expands, causes pressure, creates cracking, so on.

Sulfate attack is in an environment where it will have external sulfates, most likely in the ground water. They come in and react with some of those components we have, predominantly some sulfates, creating a high-volume material, expansion, cracking. Freeze-thaw is that liquid that's still sitting the pores. If we don't give it a place to go when it wants to freeze, again, more pressure, more cracking.

You can also have leaching either through just ground water, you know, fairly clean water, or you can even have it as an acid attack. There you're going to lose some material. There can be other kinds. We heard about the neutron degradation. There can be temperature effects, also.

So also what I want to try to convey is if the liquid is going to be moving through those pores, it's going to go at one rate. But if these degradation mechanisms lead to cracking, you're going to accelerate that rate in which things can get through the concrete. So you could have kind of synergistic effects where one thing could be accelerating the effects of cracking for one thing could affect the other.

Let's go to the next.

MEMBER BLEY: After concrete is fully cured, you still have some amount of this high pH liquid trapped --

DR. SNYDER: Yes.

MEMBER BLEY: -- in the structure forever?

DR. SNYDER: If I were to wrap it in plastic, absolutely, yes. If I put it in a humid environment, absolutely, yes. Conceivably, you could slowly dry it out over many, many years or reduce the saturation state. I can reduce it low enough that it's not even susceptible to freeze-thaw anymore because the ice doesn't form enough volume to cause a problem. So yes and no.

CHAIR RICCARDELLA: But you're distinguishing between that water that's there originally versus new water that might come in from the environment.

DR. SNYDER: Right. So when we think about degradation, the first thing you want to think about is, okay, what am I exposing it to? What's it going to come into contact with? How are things going to get in?

MEMBER SKILLMAN: Just for perspective, when you say many, many years, are you talking 20, 40, 60, 80, 100, or more? In terms of your concept of time and concrete, are you talking 20 years when you say many, many years? We need to understand whether you're talking 20 years or 100 years.

DR. SNYDER: I'm trying to remember exactly what I said many, many years -- oh, oh, yes. So the reaction is going to be seven - eight-tenths of the way done in 28 days. So by that point, you're kind of reaching kind of a an equilibrium-ish kind of thing. It's going to be difficult to detect big changes in the composition of that pore solution after about 28 years. Yes, it's going to continue. The hydration goes on, technically, forever. It just gets slower and slower and slower. But at 28 days, you're pretty well there, and that's why you have 28-day strength.

MEMBER BLEY: But you were mentioning wrapping it in plastic versus letting it expose to the -- suppose you're in a desert. How long would it take to lose the pore solution?

DR. SNYDER: That is a matter of knowing what's the transport coefficient, what's my water-cement ratio? So it's not 6, it's not 4.3. It depends.

MEMBER BLEY: Is it years or months?

DR. SNYDER: So if I have -- it's a function of the size. I mean, at the very surface, you're going to slowly dry the thing out. How deep are we going? How thick of a specimen? So it depends. I mean, I'm not trying to evade your question, but to give you a number would suggest that I haven't even thought about all the factors. You know what I mean?

MEMBER BROWN: Can I ask another -- I'm not a structural guy, so this is probably a dumb question. But reactors, containments, and all the concrete structures we have are heated from the inside, and I'm trying to relate your comments to what is the probability of freeze-thaw type phenomena in our structures. Even if you get down to 20 or 30 degrees on the outside, you've still got a lot of heat that's being transported out, and it would seem to me that the freeze-thaw phenomena would be somewhat of a lower order of consideration in our structures than relative to a road or a bridge or something like that.

The other question relative to temperature effects is that, if you look at the external structures, the bridges, buildings, things like that, they're kind of exposed to the environment and they'll -- I won't say uniformly but they go up and down based on the time period that you have low temperatures, but they're kind of uniform relatively. They stabilize over a period of time through the structure.

Here we're always hot, relatively hot, and we have cool. So you now have a Delta T, and I guess I haven't heard anything relative to not just the expansion and contraction but the Delta T change from the internal to the external temperatures and the stress that provides either externally or internally at some point. Again, I'm not a structural guy, but I'm just kind of curious as to the --

DR. SNYDER: My gut would tell me, if you tell me, "Ken, please make a list of all the things we need to really start thinking about inside of a nuclear power plant," freeze-thaw would probably be pretty low on my list, I would agree. Not only do I need a cold temperature, but there's actually a number of cycles. So you could have concretes in Alaska lasting much longer than the concrete in Cincinnati because in Alaska you get one cycle a year and in Cincinnati you might get 30 cycles a year.

And then if you're not even in a saturated state on a vertical surface, well, you've got to keep enough water in there because, over time, even just sitting out, it's probably drying out enough that it's not too much of a problem. So you're --

MEMBER BROWN: Even if you've got a heated interior that's, I mean --

DR. SNYDER: Right. So then you could look at, okay, the elements in the concrete in a nuclear reactor are probably pretty big, and I would think it's the temperature gradient that's going to be. So if I have really hot and really cold and a really thin specimen, all right, I might want to look into that. But I'm talking, you're talking measured by meters in thickness.

MEMBER BROWN: My point is that the external temperatures, it's going to be hard to get that to progress that far into the external structure. That's all.

DR. SNYDER: Right. Nuclear power plants, freeze-thaw would be, yes, way down there. But at the same time, there are thermal effects. So if you do have something like ASR, ASR is going to go much faster in the south of the United States, the southern part of the United States, than it is in the northern parts of the United States because, on average, it's warmer. Therefore, the chemistry is going to speed up.

But I did see in that graph for, the

report on the degradation due to the neutron exposure, I noticed on the far right those temperatures are going to get up to about 500 C, also. If you get up to around 450, you'll start to decompose a portlandite, 450 plus or minus. So those temperatures -- so you're going to start losing water after 450 degrees C. You'll decompose the portlandite into calcium --

CHAIR RICCARDELLA: We don't get close to that.

DR. SNYDER: There are some minor phases you just start losing around 150 to -- I don't know --

MEMBER BROWN: I'm sorry. I didn't mean to push us off the --

DR. SNYDER: That's okay. We'll go after the things you guys are most interested, and we'll just kind of slide by with -- okay. Let's go the next one. So as I mentioned, basically, when we think about degradation, we think about it as, okay, what do you have, where are you, what can possibly come in from the outside? Then these degradation mechanisms we're talking about oftentimes, basically, depend upon this transport: how fast are stuff getting in?

So, basically, the service life of the

concrete for, say, corrosion of rebar is going to be highly dependent upon what my exposure is and what the transport coefficients are.

So this is kind of how I think about it when we come up with the conceptual idea for developing a service-life model, right? So we have external that come in. They also involve expansion. So if something reacts, there's an expansion, and it forms stress. Sufficient stress can then lead to cracks. So the cracks can reduce the mechanical strength. And the cracks, again, if I'm getting cracking due to one thing, it can start speeding up the rate of transport, which can affect other degradation mechanisms.

Next one. So what can we do about it? Well, if that's our conceptual model, what we can do about it is either go to a different location or prevent the environment from interacting with my sample. If I can't do that, then maybe I can reduce the rate at which things can get in by varying the mix design. If I can't do that, then maybe I can slow things down by requiring, say, a higher concentration of rebar before corrosion begins by putting in maybe a corrosion inhibitor. If I can't do that or maybe if it's something else, maybe I can at least eliminate or reduce the amount of reactants. And if I can't do that, at least maybe I can go after it with maybe looking at tougher fibers and stuff like that.

What's important to realize is some of these approaches will kind of eliminate the problem, but others just simply just change the date at which something is going to happen.

So just a really brief kind of quick laundry list of some of our activities. About 20 or so years ago, we started developing this service-life model. And as a proponent of service-life models, I'll be very up-front and very honest. Service-life models do not tell you when the concrete is going to fall apart. So if I have a model for corrosion of rebar and concrete, what I'm probably going to tell you is when corrosion is going to begin under the assumption that if it takes 20 years for the corrosion to begin, from the corrosion to begin you have a really serious problem and it's probably going to be small in comparison to the amount of time it took for the initiation to begin.

Plus, modeling the chemical reactions at the rebar and getting the kinetics is a really tough problem. Then you have to take the reaction products that were created, turn those into stresses, turn those stresses into crack initiation, crack initiation propagation, and so on. That's a really hard problem. I'm not aware of anybody who has done that from start to finish. So when someone says the service-life model, chances are what they're telling you is I'm going to tell you when you have a really big problem.

MEMBER BROWN: So, say, 20 years for the corrosion to start -- no, no, no, no, no. I'm just trying to understand --

MEMBER SKILLMAN: Ken, ten minutes.

DR. SNYDER: Ten more?

MEMBER SKILLMAN: You have ten from now.

DR. SNYDER: Okay.

MEMBER BROWN: Should I be quiet? Twenty years for the corrosion to begin, and then it rapidly accelerates. But you've still got a contained structure. I mean, I'm just trying to think of rebars down inside something, and you've got to get oxygen or something down there to accelerate the corrosion. And so all you've got is a little crack maybe to do that, so I'm trying to get my head around 20 years to start but two years later it's going to be nothing but except a bunch of little rusty crystals.

DR. SNYDER: I carefully evaded, I should have carefully evaded whether it would be two years or three years, but I wanted to imply, the implication or the assumption is that from there on it's going to be a relatively short period. No one knows. No one has a model for, if this is the state at your rebar, how much longer before it falls down because, not only is the chemistry, we haven't even gotten to the point of turning that chemistry into a meaningful impact on the strength of the concrete.

MEMBER BROWN: All right. You said it's unknown, so that's fine. I'm happy with that. Well, I'm not happy with it.

DR. SNYDER: Right. There's just a lot of unknowns, a lot of -- you're hitting, you're exactly -- so we're working on this model. It was basically a transport reaction model. You run the transport in, and then you let the chemical reactions begin. The crux of all these service-life models is that it's all about the reactions, and the reactions are going to change your porosity. Most likely, the reactions are forming, so you're going to fill in your pore space or they're going to leach it out.

So what you have to do is on each crank, as things are changing, you also have to change the transport coefficients based on what has just happened in that pore space. That is a really hard problem. No one has the answer for that. We have approximations and best guesses for that.

CHAIR RICCARDELLA: Well, it sounds like there isn't going to be a single service-life model. There's multiple modules depending upon the type of concrete, the type of application.

DR. SNYDER: Yes and no. Right. So if I wanted to do a service-life model for corrosion, I would look at it as, oh, what I would use is the model that does transport by diffusion and reaction. If I wanted a model for a sulfate attack, what I need is a transport model and the chemical reactions, right? So you kind of see this commonality.

So, effectively, I could have one conceptual model, the transport reaction model. Now I have to build in the specifics of the particular degradation mechanism that I'm interested in. So it's kind of a yes and no.

MEMBER BLEY: The chemistry throughout a structure has got to be, I would think, wildly different location to location because of the distribution of all the stuff you mix together and what the remaining liquid in there was like and what its chemistry was. Is it reasonably consistent, or is it another impossible to know kind of thing?

DR. SNYDER: Well, okay, I'll answer your question. This is how I would go about the problem. You would say, well, I'm interested in knowing if there's going to be a problem. First of all, I'm going to ask where could you possibly get an exposure that's going to be a problem. Oh, here. Okay. But I'm not going to bother over here. I'm going to concentrate over here. Can I simplify this model to the point where we both agree that this is a sensible model? Could I do a 1-D model from that surface to the nearest rebar?

And then all you have to tell me is, okay, tell me as much as you can about the mix design of the concrete. And if you tell me, well, all I know is a type one and a water-cement ratio of this. All right. I can make a reasonably good stab at what the transport coefficients would be, and we have a pretty good idea if you tell me what the starting portland cement is. We can work out that list of portlandite and so on. So we have a reasonably good stab.

We could then possibly then go back and maybe go into the lab and measure the transport coefficients, maybe go in the field and just make sure these things make sense. All right. Now we're kind of off and running. It may not be exactly right, but we're probably close enough to give you a meaningful piece of information.

You say, well, Ken, over here we have high-density concrete. Okay. Well, tell me about this one. So am I answering your question? Rather than trying to model the entire facility, you just take this element and say, okay, fine, what's the mix over here? Does that . . .

MEMBER BLEY: But in a given mix that you bring in and you make a pore, is it pretty much uniform properties throughout? I think it was --

DR. SNYDER: That's kind of what I was --

MEMBER BLEY: And we're worrying about the corrosion is happening in little places down inside where I would think the chemistry could be different because of --

DR. SNYDER: Right. So what we do -- right. So what we're doing is we'll take it from the surface to the location of the rebar and we'll drop it off and chop it up into little nodes. And in each little node, we'll keep track what's the chemistry here, what's the porosity here, what's the chemistry here and what's the porosity here? Because running those cranks and the reaction is happening, and we can change that porosity up and down. Then we have kind of a little heuristic, well, if the processes change by this much, the transport coefficient, this node is just changed by this much. So all these --

MEMBER BLEY: I think you ought to go on.

DR. SNYDER: Okay, sorry. So we worked out this model. We realized the need for NRC, we're growing, and we thought maybe a better way to go about doing this is to move into kind of shift over into more of a collaborative and joint approach, and that's when we started the CBP.

Let's just go to the next one. So let me just, we kind of touched on this a little bit and we'll probably talk a lot about it later. The ASR is the alkali hydroxides. It's the alkalinity reacting with these susceptible phases inside our siliceous aggregates. You can also find this in various aggregates, which is one of the things we worked on, a forensic problem. We did a forensic study for Texas DOT.

So this thing is going to require, you need water and you need alkalinity and you need water and you need reactive phases within your aggregate. Anyone threw those away, and we're done. That's okay.

CHAIR RICCARDELLA: When you say aggregate, does that include the sand, as well as the stone?

DR. SNYDER: That's, in fact, we found it in this forensic thing, but, generally, you're not thinking, oh, sand, that was really odd. But it turned out there was this particular sand that's going to have this silicate phasing. All these aggregates are trying to expand.

Let's just go to the next one. So in practice, what's -- right. So what's the environment? So somehow moisture could have happened in a concrete that's wrapped in plastic. I've talked to people, and they said, yes, it could possibly happen, but, generally, you're probably in a moist environment if you have alkali silica. Transport of the water through, we have the reactants. They result in this gel by kind of incorporating the water. The gel moves out.

The different strategies, of course. Just looking at the conceptual model before, right? Get the water out, reduce the alkalis to a better mix design, maybe reduce the rate at which water can get in by a tighter micro-structure and so on.

Let's go to the next one.

CHAIR RICCARDELLA: Some of the reading I've done, I understand there's a difference between this expansion that gets constrained or not constrained?

DR. SNYDER: Absolutely. Good, good --

CHAIR RICCARDELLA: What do you mean? Could you define what they mean by constrained or not constrained?

DR. SNYDER: So what's happening, if I have just a block, an unrestrained block, this concrete, and I've got this reactive aggregate in it, the alkalis are going to react to those phases inside the aggregate, and those things are going to want to, essentially, each little aggregate is going to want to expand. And so there's, you know, the mechanical restraint of the paste around the aggregate, to some extent.

Now imagine I have the same block, but now inside I've got this cage of rebar in there. So now the same thing is going to happen. My aggregate wants to expand. My paste kind of wants to expand. But now I'm pushing against that rebar. All of a sudden, I'm kind of pushing back against it. So it is inconceivable that you could create enough back pressure to kind of slow down the reaction.

CHAIR RICCARDELLA: Less likely to crack?

DR. SNYDER: Pardon?

CHAIR RICCARDELLA: Is it less likely to crack?

DR. SNYDER: Well, I'll give you my answer but then let a structural engineer pop in. But, basically, what's going to happen is you're probably going to get farther along in the reaction before any kind of cracking occurs. So if you have, if I have this block and only the inside quarter, third, half was inside of a cage of rebar, I could look on the outside and say, oh, it's cracking. Well, that doesn't necessarily mean it's cracking inside because the outside is not restrained.

Next. Basically, that's kind of a quick little laundry test, but, basically, these tests are permutations on -- I could test my binder system that I'm going to use with the reactive sand. I could test my aggregate that's been ground up to a sand and test that with kind of a standard binder. I could test my concrete with the mix, different combinations. I could try it with and without, say, fly ash, which could generally help you but that's not always a certainty there by reducing the alkalis.

So, basically, there are a number of tests out there that work by let's heat the thing up, get it going a little bit faster, make sure we're in a moist environment, and check within a certain given amount of time there's a critical amount of expansion.

What does this kind of look like? There was some question about could the concrete strength increase due to ASR? We don't have any particular data for it, but I think it is conceivable. Let me kind of touch upon why.

So we have this, the gel is expanding. It's most likely going to, at some point, going to penetrate the paste. So you can imagine this gel is going to come out and it's going to go into the paste. Well, what's going to happen? Well, the dynamics of what's going to happen kind of depends on a number of things.

So imagine I have this porous material and I've got this syringe with some gel or something, and I'm just going to start pushing this syringe of gel against this porous material. What's going to happen? Will it crack, or will I fill the pores? Well, that depends. How fast am I pushing on the syringe? How porous is it? How fast can the porous material take this stuff without building up enough stress? How fast am I doing it? What's the viscosity of the gel? What's the porosity or permeability of my surrounding paste? Maybe if I knew all those things, I could tell you.

But, generally, what we see is something along what you see on the right side. This is a piece of chert, and on the inside it's reacting. And where you see the gel is kind of where the gel is kind of ejecting out. And, likely, if you see something like this, I'm going to guess you're probably going to get cracking.

So coming back to this, now, what if it was producing a gel that had low enough viscosity or slow enough that it was just filling the pores? Well, I think, like, random porous media theory will tell you, if I have a porous material where the pores are filled with air, I have one mechanical properties. But if I fill it with a gel, I'm going got have different mechanical properties. Yes, the strength could go up.

Now, if this gel goes out there, will it fill the cracks and maybe seal the cracks or heal the cracks? I made a comment here. I'm not aware of someone who's documented kind of the cementing properties of these gels.

MEMBER BLEY: When you speak of gels here, what are these things like? Are they really viscous? Are they more like the gels we'd see in everyday life? Are they closer to a liquid, or are they closer to a solid that's just moving a little bit?

DR. SNYDER: I think it's kind of -- I look at -- I guess I infer, I would infer it from when you look at this gel. So you could imagine seeing one -- under certain circumstances, you kind of get them when it makes this little rim around the aggregate. Then I would imagine, well, I bet that's kind of a thin, runny syrup. But if I see a gel of very well-defined edges, I'm thinking this is stuff like putty, like a certain putty on a thing --

MEMBER BLEY: It can be a wide range of things.

DR. SNYDER: Yes, the viscosity can be all over the place.

MEMBER SCHULTZ: You have this picture of a gel. Just a quick question. Is this something you look for, look for in the microscope and you find it and you say, wow, I've got one, or is it all over?

DR. SNYDER: It kind of depends. But, generally, from my conversations it tends to be more like you'll see it like little spokes on a bike, you know --

MEMBER SCHULTZ: So one would see enough so you think it's worthwhile investigating its impact on strength?

DR. SNYDER: Well, I think what happens is, typically, you don't bother doing it until you've already seen the cracking. So then you're thinking I wonder what this is doing --

MEMBER SCHULTZ: Why did this happen?

CHAIR RICCARDELLA: Very interesting discussion, but we've lost our 15 minutes, plus 5 now. So we're going to have time for discussion at the end this afternoon. I hope you're still going to be here in the afternoon. And you're up again, too, later. Thank you. So next we have Dr. Sadek.

DR. SADEK: Okay. Good morning. It's a pleasure to be here. My name is Fahim Sadek. I lead the structures group at the NIST, and I'll be presenting our recent or the work that we just start recently with NRC on ASR effects on complete structures. I have Dr. H.S. Lew here, who is a senior research engineer in our group. Both of us are working this problem in partnership with Ken Snyder and his group on the materials side.

So I have some introductory slides on ASR effects. I'm not going to dwell much on them, mainly because Ken covered most of the gel formation issues and how the silica that can exist in common aggregates can interact with the alkali cement base to form the gel and that gel is now expanding or swelling with the extra pressure or strain of the concrete, resulting in significant cracking.

The cracking pattern, as you can see in this example here, it's very random in nature, and you can see this cracking as being parallel to the surface or normal to the surface. And as structural engineers, we, like, don't care much about the details of the gel formation or the chemistry behind it, but we wanted to understand how this phenomena affects the structure performance of an entire containment structure or any structure in general.

So if I go to the next slide, just some data that we collected. Just to give you by way of history, we started working when it was NRC on this problem last year. And in 2013, we developed a scoping study, basically a state-of-the-art report that explains what the issues are, what the research that was done on the materials side and on the structural side, and came up with, based on that literature search, we conducted a gap analysis and basically identified where the gaps in our knowledge are and what is it that needs to be done in order for us to have a little better understanding on the structural behavior of concrete. And that gap analysis and recommendations for further study formulated our current work with NRC that we just started this past June.

So as part of the literature search, I'm showing here some example of testing that I believe was done in France showing as that expansion takes place and cracking becomes visible on the concrete cylinders that you get significant loss of strength in f prime c and also significant loss in modulus of elasticity, which behooves us to look into this, understanding what's going to happen, what's the state of the structure now, the structure that exhibits ASR effects, and what do we expect in the future in terms of residual strength and capacity of structure components and walls and members and things like that.

CHAIR RICCARDELLA: What is splitting tension?

DR. SADEK: What's that?

CHAIR RICCARDELLA: What is splitting tension?

DR. SADEK: Splitting strength. This is like test typical for structural engineers when they have a cylinder and they put it under compression and that results in splitting of the concrete.

So if I go to the next slide, if you are familiar with any of the ACI design documents, everything that structural engineers do is a function of f prime c, the compressive strength of concrete. And once you have that number, based on lots of statistical analysis of data over the years, you can calculate your fracture strength, your tensile strength, your Young's modulus, and also the development length of rebars.

However, we have this information for normal concrete for engineers to use in their day-to-day design of structures, whether it's a nuclear structure or whether it's a bridge or a building. For ASR-affected structures, we do not have this information. If a structure is undergoing degradation due to ASR, and somehow if we can calculate what's the current f prime c that's degrading with time at the given state of expansion, we really don't know how to take these numbers for f prime c and get the Young's modulus, which we use to calculate deflections or deformations in the structure, the tensile strength and fracture strength, which are very important for bond strength of rebars. So we really need to get a handle for the design on some of those issues.

Not only strength, degradation, compressive, and tensile, but also we might have some problems with bond strength. I'm showing here an example of rebar embedded in concrete, and, in order for this cross-section to behave in a fully-composite fashion utilizing the full capacity of the rebar, you have to have a complete bond between the rebar and surrounding concrete. But some of the studies on ASR show that there could be some funny stuff happening around the rebar due to the expansion, in terms of radial stresses around the rebar that can result in some cracks and crushing around the ribs on the rebar that can significantly reduce the bond strength inside the concrete. And this is one of the issues that we really need to address and understand for future evaluation of existing structures.

So based on this literature search, we worked closely with NRC in order to formulate a multi-year research plan to basically give NRC the tools by which they can evaluate the state of structures affected by ASR. And as you can see at the bottom of the slide, the expected outcome from all the work that we would be doing on the structure side and on the materials side at the NIST should give NRC the methodology by which they can calculate the current structure capacity of ASR-affected structures to resist not only static loads due to hydrostatic pressure, whatever it is, or earth pressure as well, but also could resist dynamic loads in case of seismic excitations.

And in addition to that, we would like to also give the tools by which we can estimate what's the future capacity, and that's a very important test for licensing objectives.

I just wanted to make sure that I clarify that, on the structures side, time is meaningless for us. What we do, everything we do is in terms of the expansion. Working closely with our counterparts on the materials side, we will be able to get that expansion in terms of time. So combining the two research efforts and structures and materials, we should be able to give some guidance on what's going to happen in the structure in the future, as the expansion continues.

So on the structure side, the plan that we devised with NRC includes three tests over a span of four years. The first test is to assess the mechanical properties of ASR-affected structures, getting a handle on f prime c, the tensile strength, the Young's modulus, as well as the state of surface cracking due to ASR.

In the second stage, we will be looking into issues related to bond strength of concrete in terms of development length and lap-splice length that might degrade due to ASR effects. And last but not least, we want to look into the seismic response characteristics of ASR-affected structures, mainly looking at the hysteresis shape of concrete structures and understanding how that hysteresis shape or hysteresis loop or energy dissipation mechanisms and the ability of concrete to dissipate energy would be affected by ASR effects.

So I'll just walk you through the first tests, the three tests, and I'll give some details about test one since we have some experimental design that I'd like to share with the group here. So the first task is to assess the mechanical properties of ASR-affected concrete, and the objectives here are basically we wanted to understand the relationship between ASR and concrete mechanical properties. As Ken indicated, we don't know at the beginning of the initial stages of reaction whether we get an increase in f prime c or not. Things like that we really don't understand, especially when confinement is part of the game. And I'll speak about how our experimental work will address some of those issues.

And also we wanted to understand the relationship between ASR, the state of the reaction, and surface cracking of concrete. It's unfortunate that when you go to a site where ASR is taking place that we can only see the concrete from outside. So our hope is to be able to develop a computational model in which you can account for the degradation in ASR and account for whatever loading that exists on the structure and the reenforcement inside the structure providing some level of confinement and be able to come up with a cracking pattern that you can measure against what you can see on the field. And also we wanted to understand the issue that you raised later about the confinement or constraint, how the stresses and the existence of stirrups would affect the behavior of concrete due to ASR.

So the bulk of this work will be experimental work. Basically, we'll be casting four large blocks of concrete. These blocks are not loaded. They are resting on the ground with no loading. But we will use these blocks to extract lots of information about ASR behavior. So portions of this block will have heavy stirrups to get the confinement effect inside the concrete, and portions of it will not be confined at all with no reenforcement.

CHAIR RICCARDELLA: What do you mean by

stirrups?

DR. SADEK: Stirrups are the steel hoops that you can see around -- this is typical for concrete structures for beams and columns. And when you have these and concrete is expanding, they provide lots of confinement and resistance to that expansion.

Some of the initial work with ASR, people basically extracted cores from the concrete and tested them axially. We believe that we can do better because what we wanted to do is heavily instrument these specimens, these block specimens, with what we call tri-axial string gauges. These tri-axial string gauges, as you can see to the right of the slide, will allow us to measure the state of strain inside the concrete in three dimensions.

CHAIR RICCARDELLA: But with no load, just --

DR. SADEK: With no load.

CHAIR RICCARDELLA: -- just due to the ASR. Yes, okay.

DR. SADEK: And then when we extract these cores and test them in our universal testing machine at the NIST, we will put it on a tri-axial testing chamber, applying the same strain or the same state of stress on the cores as we apply the loads to figure out what's the tensile strength and what's the compressive strength.

We will be taking these cores from two directions. One would be normal to the direction of pouring concrete, one in the direction of concrete pouring in order to understand if f prime c will change due to some of these effects.

So the approach that we are taking -- I'm running out of time here but --

DR. STACK: You know, one of the things you said was that, when you went back, you needed a Young's modulus, for example, and how to relate that. But I don't see how you're going to get that out of this unloaded test.

DR. SADEK: We will get it from the cores that we will extract because we will test it in compression, so we'd get the load deformation from which you can extract the Young's modulus. So from these cores that we are extracting from the specimen, we'll be conducting axial tests but under confined state under compression and tension to figure out what's the compressive strength, what's the tensile strength, and what's Young's modulus as the reaction is progressing in time.

DR. LEW: Could I answer this question very quickly? Young's modulus is a slope of a stress-strain relationship. That we all know. So when we do the compression test or a tension test, we will get the stress-strain and the slope of the curve with Young's modulus.

DR. STACK: What always worries me, of course, is you get these local mechanical properties, and then the question is how does that local mechanical property really relate to a concrete structure, which is a very different beast. I see little tests. I don't see any tests that take me to the big concrete structure.

DR. LEW: That will occur in year two and three. That is a beam test we will do.

DR. STACK: Okay.

DR. SADEK: There are three stages to this.

CHAIR RICCARDELLA: And do I understand you're going to take these cores as a function of time --

DR. SADEK: Correct.

CHAIR RICCARDELLA: -- at various points?

DR. SADEK: Correct, correct. And at each time we extract cores, we already have data about the state of strain inside the structure from all these string gauges.

MEMBER BALLINGER: I've got a follow-up to Bill's question. How is this going to be used by the staff? This kind of experiment is fraught with uncertainties and all kinds of scatter you're going to get. Has there been a discussion of, if we get all this data and we get this monstrous uncertainty, and then the staff turns around and says, okay, licensees, use this stuff, I just worry that this kind of experiment is going to end up with so much dependency on aggregate size. You say here three different reactive aggregates. Are they going to encompass the aggregates that are generally used in our applications in the U.S.? I mean, how is this plan worked out?

DR. SNYDER: I guess my question is are you thinking that we would then publish these data and we would use the data? Because our plan is they would use this test.

MEMBER BALLINGER: Well, I don't know what the plan is.

DR. SADEK: I did some of that, also, in

the modeling part of this because, ultimately, we wanted to develop a computer model and we're looking currently at the variety of complete models, discrete cracking models, that would allow us to mimic the behavior that we are observing here.

MEMBER BALLINGER: Yes, I understand what you guys want to do with it. What I'm interesting in is what you guys want to do with it. No, this guy. This guy here, this guy here.

DR. SADEK: I think --

MEMBER BALLINGER: Wait a minute, wait a minute. Did he answer the question?

MR. PHILIP: I think what we're trying to do is to find out the structural capacity of structures subject to ASR. And with this information that we are getting for three different types of aggregates and the testing procedures, it's a detailed list of experiments and results that we're getting which we hope we can use. For instance, we see if there's a structure which has got cracking on the outside, we hope that by having this work where they're going to actually try to relate that surface cracking with what is happening inside, that we will have some idea at least to detect ASR at some point.

And if we have that detection, if we know what the aggregates are and how they're expanding with time, then we can say what the structure capacity is today and what it is going to be in the future.

MEMBER BALLINGER: So that means that the licensee is going to have to go and find out information about his structure in some way, by pores or some other thing --

MR. PHILIP: I would expect that, at least in --

MEMBER SCHULTZ: What I've heard is that what is being developed here is the testing protocol.

MEMBER BALLINGER: I hope so.

DR. LEW: I think that's what we said in slide number six. We want to develop a methodology, and then we'll turn it over to them.

CHAIR RICCARDELLA: I think, in the interest of time, maybe we should move on to task two.

DR. SADEK: Oh, okay.

CHAIR RICCARDELLA: I mean, I think we have a pretty good idea, in general, of what this task one is.

DR. SADEK: So this just shows our environmental chamber at the NIST. We will be casting three specimens that are ASR affected and one normal that is not supposed to exhibit any ASR activity just for comparison. We'll be putting these specimens under controlled humidity and temperature.

And just to show you the plans for the test specimens, these are the blocks. On the right side of the block, this is heavily confined concrete with stirrups that are spaced six inches. To the left side are mildly confined complete. And in the center, this is the area where you don't have any confinement. So we're looking at three different behaviors from these specimens. The specimens are highly instrumented with string gauges, as you can see, in three dimensions and also in the rebars to get a feel for what's the force induced by ASR expansion on these rebars.

And this shows some of the instrumentation that we will have, including on the surface, in order to get a measure of the expansion and cracking. We'll have laser techniques and also what we call the amount with mechanical gauges to measure the surface strain on the outside.

MR. THOMAS: Can I just revisit something that was said? Brian Thomas, the director of engineering. What was said is that we're pretty much developing a test protocol that could be used to provide some sort of an acceptance criteria to licensees, you know, in their licensing submittals. We typically don't do that in licensing space. What we do is ask licensees to demonstrate the safety of the structure, you know, and to tell us what they're doing. And then they could all propose different kinds of test protocols, different apparatus, different testing approaches. And then we do an evaluation. So there's a little bit of a mistake on --

CHAIR RICCARDELLA: That comes back to what you said about it's confirmatory testing.

MR. THOMAS: Right. I just want to clarify that. Thank you.

DR. SADEK: So we can now go to this. This shows the location of the laser tracking and the DEMECS that we're going to use to estimate the surface cracking and surface expansion of these specimens. Again, I want to emphasize the fact that, ultimately, we'd like to have a computational tool, and we'll be looking at the variety of computational tools that are available for modeling ASR behavior. And for whatever methodology out there, validation is always key. And our plan is or our hope is that this experimental scheme will allow us to develop such a tool that can be used for practical assessment.

In task two --

CHAIR RICCARDELLA: Just quickly, I know you have invited ACRS to come over and --

DR. SADEK: Correct, correct.

CHAIR RICCARDELLA: -- visit and witness some of your tests. I, for one, am very interested in arranging such a visit.

DR. SADEK: Sure. Our plans are to cast these specimens early next year. We'll finish the design, and early October we start construction of the specimens and the rebars and all the instrumentation. And, hopefully, early next year we'll be in a position to cast these.

Task number two is to look at the development length and lap splice of reenforcing bars. And, again, we wanted to develop a methodology to assess the effects of ASR on strength through the assessment of lap splices in flexural members and axially-loaded reenforcing bars.

Go to the next slide. So this task will

include two types of testing. The first one is a beam test under the loading conditions shown here. Again, we'll be testing a number of these with ASR and non-ASR concrete for comparison purposes. And there will be a variety of rebar lengths lap splices that we'll be testing here at the center of the beam, and the purpose here, as we are testing a number of these over the span of two years or a year and a half, as the reaction is progressing we will get some information about the rebar lap splice.

Another test that will be conducted under this task is rebar-embedment length where an enforcing bar will be embedded in the concrete. That is, again, subject to ASR effects over time, and we will be looking at various embedment length and looking at the amount of force it will take to break the specimen and break the bond between concrete and steel as the ASR reaction is progressing. And that's what's written in the next slide, providing some additional information about these tests.

And then the last test is looking at, the last task is to look at the seismic behavior of ASR-affected concrete structures. And when we were talking to NRC about this task, the sky is the limit here. If you want really to understand the seismic behavior of these, you're going to look at columns, you're going to look at beams, you're going to look at connections, you're going to look at everything under the sun. But we decided just to limit our scope to testing of shield walls that are loaded vertically with gravity load and subjected to cyclic loading protocol typical to, similar to what's done always for seismic testing, the dynamic type of tests that we'll be doing at the NIST, and, again, similar methodology. Some of this will be ASR-affected concrete walls, and some of them will be normal concrete walls in order to get some insight into the behavior and a measure of how the energy dissipation takes place or degrades for ASR-affected --

CHAIR RICCARDELLA: It's going to be a dynamic load? You're going to shake it or --

DR. SADEK: We do not have the capability to do, like we don't have a shake table, but it will be cyclic loading, and it will give us a measure of the energy sufficient capacity but not as fast as what you would get in beam structures. There are no shake effects.

And with that, I'll be happy to take any questions.

MEMBER SKILLMAN: Now, I would ask a question back on your slide 16, please.

DR. SADEK: Okay.

MEMBER SKILLMAN: If I heard you accurately, you said you were going to do these tests on ASR-affected concrete and not ASR-affected concrete.

DR. SADEK: Correct.

MEMBER SKILLMAN: How do you assure yourself that you have not affected ASR concrete?

DR. SADEK: It comes down to the mix design.

DR. SNYDER: Reactive aggregate or not reactive aggregate.

MEMBER SKILLMAN: Thank you. All right, thank you.

CHAIR RICCARDELLA: Just one general question on your schedule. Year one, is that 2014?

DR. SADEK: For us, time zero was June 2014.

CHAIR RICCARDELLA: Okay. So we're only just barely into year one.

DR. SADEK: Correct, correct.

CHAIR RICCARDELLA: Okay. Thank you. Any other questions from the --

MEMBER SCHULTZ: Yes, I wanted to come back to Brian's comment about what we're doing here because I'm a bit confused. What I thought I understood is this is a very, very complicated issue. And so what NIST is trying to do, as they indicated, they've got testing that they have been done or they work to develop test methods that are considered acceptable for evaluating the degradation, chemical effects and degradation. And now we're hearing about the development of -- at least what I'm getting -- the development of a test protocol that NIST believes is an acceptable way to evaluate the structural integrity of material that's been subjected to ASR. And that's right.

The thing that concerned me was a comment that was -- so then licensees can go off and do whatever they want to do to demonstrate that their concrete is okay. Wouldn't we come to them and say this is an acceptable method, this is a standard that's been developed over the course of five, ten years, standard testing methodology, this is what we want you to use to evaluate and demonstrate that the structural integrity of the concrete that you have in your plant is appropriate? Am I getting it correct?

CHAIR RICCARDELLA: As I understand it, the tests are to develop the properties, not the structural integrity but the material properties that you would then put into a model of some type, right?

MEMBER SCHULTZ: No, I thought we were trying to --

CHAIR RICCARDELLA: I mean, we're trying to understand how to do the testing and that this is a test methodology that one can use to evaluate the properties. We're not testing materials that are in plants. We're demonstrating a way in which to get the properties, but we're not going to tell licensees to go out and run tests like this. I don't think staff plans to --

MR. MARSHALL: Hello. My name is Mike Marshall. I'm the chief of the Structural, Electrical, and Plant Systems Branch in License Renewal, and we're the ones that sent to user need over to research for this work.

The type of way we want to use the work that's coming out of this is basically to put guidance in our GALL document similar to the guidance that we currently have in GALL as far as frequency of inspections, parameters to be monitored. One thing that's really important for us out of this work that was on one of the slides earlier is, typically, you would get your indication of ASR from cracking on the surface. So it's important for us to have an understanding of the relationship of that cracking on the surface to get properties of the structure, and so that's one thing we're looking for to come out of this work. And then we're looking to translate that into guidance that is similar to the guidance we have in GALL, as far as frequencies, parameters to monitor.

Now, if the licensees were to discover that they had cracking of sufficience that they needed to assess their structure, they're free to choose whatever method they want to assess that structure.

MEMBER SCHULTZ: I understand. Thank you.

CHAIR RICCARDELLA: Okay. Thank you. I guess we're back to Ken, and, Ken, you have 15 minutes or as long as you want to go into the break.

DR. SNYDER: As long as I dare?

CHAIR RICCARDELLA: At a quarter of, people can break at will.

DR. SNYDER: I'll know from the fleeing

feet. So this is the materials side of the program. Let's just talk to the second one. So what are we doing here? Well, basically, there are three objectives. One, for concrete, where are we in the reaction? Two, how fast is it going and where would it be, in a sense -- how far is it going, such that we can kind of guess, well, down the road it's going to be such and such a state? And then the other one, the last one, is the impact of the degradation mechanism, the impact of the degradation on other degradation mechanisms primarily through the cracking. How would we go about reevaluating the remaining service life?

They're going to be talking about models, I guess, to manage expectations. Where are we in the reaction? My hope is we can get to the point of telling you which third of the reaction are we in? Are we in the first third, the middle third, or the last third? We will not tell you we're at 23.6 or some of the way through the reaction. That's just not realistic for this scope and this time frame.

How fast is the reaction going? This is not a humongous DOE calculation. This is probably going to be, at best, an Excel calculation, algebraic calculation, order of magnitude. Am I going to have a problem next month, next year, ten years from now time frames.

So those three things are broken into three tasks, tasks four, five, and six. There's task four. Let's go back to the objective. So as I said, basically developing a methodology for walking up to that concrete and guesstimating where are we in this reaction? So kind of come up with a game plan to do that by -- the basic idea is I've got to take a piece of the concrete, and I've got to find the reactive phases, how much do we have, find the react tenths, how much do we have, and relate those to -- basically, the extent of the reaction is basically the extent of the expansion. We're fairly comfortable with that.

So, basically, 4A, 4B, 4C, each of these are about one, each of these are one-year length. So 4A was basically identifying and quantifying the expansive materials. 4B, let's identify and quantify the reaction products. And then 4C is basically confirming this in concrete specimens.

I'm saying it kind of glibly, but identifying these things is not going to be trivial. The last slide in my previous concrete degradation presentation pointed out that the way that we're going to go about doing it was kind of a meat and potatoes kind of way by bicroscopy. It turns out that these gels typically have a tag to them, potassium or sodium. It really just kind of lights up when you're doing an elemental analysis, so we'll see these kind of streams running through that image highlighted and basically start using that as a measure of how much reaction.

MEMBER SKILLMAN: What is the reactant that causes that observation? What is the --

DR. SNYDER: It's incorporation of these alkalis, so it could be incorporation of potassium. In that pore solution, there's a lot of potassium and sodium, and that stuff can end up in that gel.

MEMBER SKILLMAN: Thank you.

DR. SNYDER: Thankfully, this all grabs at potassium. Oh, great, we got potassium because, otherwise, it looks a lot like the C-S-H.

Any questions, just stop me. We're just going to keep on rolling here.

Task five is how fast is it going? So this is kind of, basically, okay, given the time frame that we want to work in, let's think about what are the big factors, what are the things that are really going to drive it? What's going to drive it is basically going to be the temperature and the alkalinity and how much reactive phase you have. So it's going to be, basically, an experimental design of trying different temperatures, different alkalinities, and different quantities, basically exponents, the exponent we need on this kind of thing, that will characterize how fast these are going to go as a function of these primary factors.

And let's jump to 5A. So 5A, here's the primary factors. We're going to try to do it on mortars. We're going to refine that by basically kind of going back and kind of confirming that, as we're watching these expansions going, can we kind of confirm it by doing a little simple small test to show that we're guesstimating pretty well and then finally validate this whole thing on a concrete specimen. So 5A, 5B, 5C are each one year, planned one-year efforts.

And then six is slightly different, and that is, looking at these specimens, we know that the ASR is going to cause, most likely going to cause cracking. That's most likely going to be the biggest impact on other degradation mechanisms. What can we do to kind of get a sense of how we should be re-thinking how long this concrete would have otherwise lasted? What kind of aging factor do we have here.

So six is -- let's go ahead. So six is basically broken down into coming up with a strategy of using -- a really nice way to do this is that the diffusivity, which is the primarily controlling factor in these transport rates, is really well correlated to electrical resistivity, and it's relatively easy to measure the resistivity of a specimen. So we're going to, under laboratory conditions, taking cracked concrete and just monitoring the crack, monitoring the change in the resistivity to show that this -- monitor the change in resistivity and let chloride infiltrate the concrete, cut the concrete, and show that what we're seeing is the chloride are going in that much faster, just like the change in electrical conductivity show, and then, essentially, validate that again.

The primary -- it said on the second slide, I think, and I skipped over it and I really shouldn't have, but the big thing that we're, what we're contributing to in this whole thing is after T equals zero. So if HS have their game plan for saying this is the concrete I have today, tell me what I need to do to learn what I need to know about that concrete today. What I'm trying to do is trying to give them a handle on how can we move forward in time to give the information back to them that they can say, well, Ken, if that's what the reaction is going to look like in, say, ten years, then we're going to run our crank to kind of give you an idea of what the overall structural properties are going to be in the future years. So that's kind of our role is helping the after T equals zero or however you want to define that.

MEMBER SKILLMAN: Ken, on your slide seven, transport of ions through concrete, should we envision that the conducted path is the paste? Because that would give me a mental picture that deep within a monolith the distance, the pH, the surrounding mechanical conditions could explain why at some very great depth there is very little obvious ASR, whereas in current flow, as I get closer to the surface, I might see perhaps an abundance of conductivity, hence a greater amount of ASR.

DR. SNYDER: Let me just restate your question and then answer it. So if I'm understanding what you're saying, if I could imagine a large concrete, it may not have uniform cracking everywhere. The first question was do I imagine that the current cracking is in the paste, and I would say that's the one we're going to be the most concerned about because you can imagine the paste is surrounding each aggregate. If I break the aggregate apart, I still have to get to the paste. So the first answer is, conceptually, yes, we're thinking about cracking through the paste.

And if I understand what your question was, if I put these huge elements in these structures, I've got a lot of cracking here and less cracking here. Would I expect to see possibly more ASR here than here or compounding effects through the ASR and cracking and moisture? I would say yes, first order yes.

MEMBER SKILLMAN: Thank you. It's fine. Thank you very much.

CHAIR RICCARDELLA: Thinking in terms of a real structure, you can walk up the surface and you see a lot of cracking. But chances are, even if you have the ASR deeper, you won't have as much cracking because it's confined, right?

DR. SNYDER: Right.

CHAIR RICCARDELLA: Is this resistivity test something it could do to try to determine that gradient?

DR. SNYDER: One could have, the approach I would recommend is, if we can show that these electrical resistivity methods have worked, then it could be a matter of can I do some sort of kind of CT, electrical CT, on a specimen to get the electrical conductivity as a function of location, and then I can go back and say, well, yes, Ken, it's cracked on the surface, but for the majority of them there's not much cracking in there. We probably don't have a big transport -- there's not a cracking issue here. I said, well, yes, I can't make a strong argument you've got a big transport problem if you don't have any cracking in there.

MEMBER BALLINGER: Some of these structures also use cathodic protection for the rebar and things like that, and also electrodes are hooked up and current is applied and everything. Can you back out resistivity and information using an existing system to assess the degree of surface problems?

DR. SNYDER: I think so because -- I'm not certain we could do it from the data we're getting back from the cathodic, information we'd be getting back from the cathodic --

MEMBER BALLINGER: Well, could you use the cathodic protection system --

DR. SNYDER: Yes.

MEMBER BALLINGER: -- as a means to do this?

DR. SNYDER: Yes. If we can -- which, basically, you're saying we can get access to the rebar, and that would be powerful.

MEMBER BALLINGER: Well, I mean, that's what they're using the cathodic protection for.

DR. SNYDER: They're running it through the electrode, and it's sacrificial, right?

MEMBER BALLINGER: I don't know that it's sacrificial. There's an, it's usually an --

DR. SNYDER: But there could well be.

MEMBER BALLINGER: But the circuits are there.

DR. SNYDER: Yes, that would be a great place to start. And just a quick aside, the relative changes in your transport should be directly proportional to your relative changes in the conductivity. So the sooner you start monitoring that conductivity, the sooner you can start saying, hey, there's something happening. I might not be able to tell you what it is, but I'll tell you if something is happening.

MEMBER BALLINGER: The conductivity is also changing with the degree of hydration.

DR. SNYDER: It flattens out pretty quick. It's going to change -- now, if you have infiltration coming in and you're really changing that -- the composition of pore solution is going to drive it and temperature fluctuations. But I'm in a big structure, and temperature fluctuations really aren't a big problem. If I'm fairly confident I'm not getting a lot of infiltration, then I think we've got something to stand on because if I can get some numbers before there's a problem, then I'm sitting pretty because if I have infiltration I'm going to see it in the conductivity change. I won't have to debate whether or not the pore solution is changed. You've seen a big change in the conductivity. There's something going on here, and we need to look into that.

MEMBER BALLINGER: As you increase the conductivity, the current leakage in the cathodic protective system will change?

DR. SNYDER: I suspect that's going to be the case.

CHAIR RICCARDELLA: As you're starting to put moisture and stuff into the concrete from, you know, outside sources, won't that affect the conductivity?

MEMBER BALLINGER: That's what I mean. Yes, you'll see that --

CHAIR RICCARDELLA: So is your testing going to account for different types of ingress?

DR. SNYDER: So what I would expect to happen is you say, okay, I've got T equals zero. I've just struck the facility. I've started my cathodic protection, and I'm monitoring this. I backfill. Oh, I'm seeing the conductivity is changing a little bit. It shouldn't be changing by orders of magnitude. Okay, fine, it's going to change a little bit. Yes, because moisture is coming in.

If my concrete is intact, it's not going to change fast. I mean, it shouldn't change a lot. When I start seeing changes like powers of tens, it's like, whoa, something is happening here.

So you're right, exactly right. You're

thinking about it in terms of these little nuances that are happening, but I think big problems tend to come up with big changes.

MEMBER BALLINGER: The rebar is about three inches in in these kind of structures, three to four to five inches in. And the ASR is taking place in the first inch.

DR. SNYDER: Well, maybe --

CHAIR RICCARDELLA: It could be 15 inches in there.

MEMBER BALLINGER: Okay, okay.

DR. SNYDER: There may be sufficient moisture in there, and you're just providing more water to just keep it going. Yes, I don't think of ASR, I think of sulfate attack as an outside-in. I think of ASR as an inside-out.

CHAIR RICCARDELLA: Everyone who wants to break can break. Anyone who wants to keep talking, keep talking. We're going to restart at 11 with Dr. Kosson.

(Whereupon, the above-referred to matter went off the record at 10:46 a.m. and went back on the record at 11:00 a.m.)

CHAIR RICCARDELLA: We're missing a few

members, but I think we're going to get started. So next we have the CBP program; is that what you call it? CBP program.

DR. KOSSON: Cannot live without acronyms.

CHAIR RICCARDELLA: My first couple of months here I saw them in my dreams at night. Acronyms flying at me. Okay.

DR. KOSSON: Ready to begin?

CHAIR RICCARDELLA: Yes, please.

DR. KOSSON: Okay. Well, thank you and thank you for inviting us here today. I'm Professor David Kosson from Vanderbilt University. My colleague, Kevin Brown, is with me, also. We work very closely together on this program.

And what I've been asked to do is provide an overview of this partnership's activities, and we're just going to scratch the surface and kind of show you where we're headed and the different types of things that we're doing, and you'll find it dovetails nicely with what you heard earlier from Ken Snyder. And then, at the end, I'm going to talk very briefly about a new program that we're starting up in conjunction with Idaho National Lab, Oak Ridge, and some other players in that.

So next slide, please. The CBP was formed, originating out of the Department of Energy Office of Environmental Management because of the very long time frames that it has to be concerned about with waste management activities, as well as their operating facilities, which are not the reactors typically but are the chemical processing facilities which also rely on concrete structures and waste management relies on concrete vaults.

MEMBER BLEY: Okay. That explains one of the names up there for NRC, but it's surprising to see on this list but it's the long-term waste issue.

DR. KOSSON: Yes. We're a much longer time frames, but also time constants of upset conditions are much slower. So we've put together a team from Vanderbilt; Savannah River National Lab; Energy Research Centre of the Netherlands because of the specific expertise they have in reactive transport; and NIST, obviously -- you heard from Ken's group already -- the NRC and SIMCO Technologies, and you probably see already the link between SIMCO and the evolution of out of the work of NIST that Ken spoke about. He very briefly mentioned the STADIUM, the example there.

So if we go to the next slide, please, there's some things that may be a little repetitive with what Ken said. I'm just going to breeze by those. But the overall goal of the product was to develop a set of tools to predict structural, hydraulic, and chemical performance of these materials when they're used for containment structures, for waste management, or you might think about it as pools and also liquid containment, but also in terms of waste forms because the same properties in a very different application space and the same reactive transport mechanisms impact the overall long-term performance.

So in order to move this forward, we're looking at 100 years for operating facilities as a nominal time horizon for improving estimates, and for waste management you look at a thousand-year time horizon because that's the nominal time horizon for performance assessments in that space.

Trying to bring a mechanistic and phenomenological basis to that, Ken gave a very good introduction to that before. Methods for parameter estimation and measurement. How to think about the boundary conditions which are very different. They're time variant. They are conditions that you're talking about with reactors, and they're very different boundary conditions for dry cask storage.

And when you look spatially where these various materials are placed, even within a structure you have different boundary conditions and exposure conditions that you have to consider. And then looking at the uncertainty characterization, how to propagate that so that you understand what your margins are as you're moving forward. Also to understand where it is best to invest additional effort to reduce those uncertainties. Where you're going to have return on your investments, so to speak.

Next slide, please. The near-term applications that we're focused on are at Hanford and Savannah River where we have single shell tank integrity, which are basically carbon steel-lined concrete tanks in the ground that contain highly radioactive nuclear waste. There are several hundred of them that are way past their design life. Their design was, roughly, 20 years, and that was when they were constructed anywhere from the 40s up through the 60s.

And then for closure assessment, after

they are cleaned out or residuals remain, what are the residual risks that may be there? When it's used as a waste form, a lot of those wastes are destined to go into cementitious waste forms and then go into concrete vaults for, ultimately, permanent disposal. At Savannah River, very similar types of issues that are there. And then nuclear energy because of bridging between the Office of Environmental Management and the Office of Nuclear Energy and also direct linkages between the issues that EM has and what you're talking about: what are the applications to dry cask storage performance and to license extensions? And you'll see me go into that more at the end.

Next slide. Some of the key questions are, for the waste management aspects, what ultimately is going to be the rate of release of radionuclides into the environment? That's not for what you're dealing with here, but that's closely coupled also with what the chemical performance of the material is, as well as the structural performance, because if you have complete structural integrity, you don't have the pathway for the transport of the contaminants or for the liquids. And in your case, if you start having loss of structural integrity, that is also the loss of your service life or the safety role that a particular system is playing.

So often under environmental conditions, you're dealing with the ingress of aggressive species. You've been focusing a lot this morning and today on alkali silica reaction. That's just one of many, and that I think got the most attention because it's manifested itself earliest in the systems that you're looking at. But in other systems, I think you have other types of things that have been manifesting itself or beginning to, in dry cask storage for example. And that is often chloride, depending on the environment, because as it makes its way into rebar and then the rebar corrodes, you have a different expansive reaction; sulfate attack which has internal reactions that cause expansion, spalling, and loss of strength of the concrete; carbon dioxide which is an ingress of a reactive species both through gas phases and through liquid phase and then that changes the pH and the chemistry of the system and, ultimately, when you get to your reenforcement, that changes the passivation mechanisms so that the change in that pH as you reach the rebar, for example, when that goes from strongly alkali to more neutral conditions, the corrosion mechanisms accelerate and then you see the expansive reactions, then you lead to cracking.

So if we go to the next slide, a strategy that we've taken is to develop a series of reference cases and reference materials. And that's important because there is a wide variety of mixtures of materials. You heard a lot about ordinary portland cement today so far. However, let's recognize that, in the construction environment, there is a wide range of mix designs. You have very diverse sources of aggregate and aggregate properties, and you also frequently see the use of coal fly ash in the materials that you're working with, and there is a great diversity in the properties and chemical composition of coal fly ash, as well, depending on its origin. These affect the curing times, the reaction rates, the mineral phases that form, and the mass transport properties, the permeability, the diffusivity within the material or the conductivity, as it was described earlier.

MEMBER BLEY: David, I have a question. When Ken was talking earlier, he talked about a long time until you begin to see corrosion of rebar, for example, and then very quick corrosion. I'm assuming that's related to your quick discussion there of bringing the pH down to something that's more of a --

DR. KOSSON: You've got different mechanisms. Because of the pH effect, you could be safe for the chloride ingress. There are different corrosion mechanisms that can begin. And Ken showed some very good slides or pictures at the micro scale, but you have to imagine this as a very hetereogeneous material in terms of the internal composition that is strongly affected by the formulation of the mixture or the mix design that is there. And at different scales, you have different preferential pathways. Even diffusion pathways in an intact material have preferential diffusion pathways. And then when you get to cracking, you get accelerated pathways above and beyond. So you see these feedback loops in these systems that can start slowly over long time constants but then, all of a sudden, start to accelerate very rapidly.

The other problem that arises is when we talk about modeling these systems we tend to look at continuum models because of the nature of the size and scale that we're looking at. But then that's reliant on how you deal with techniques from the micro scale, looking at the behavior of the aggregate, the gel, etcetera, up through those macroscopic continuum scales. And there has been a lot of work done on homogenization techniques relative to structural performance, so you see that in the literature. There's been a lot less done on homogenization techniques relative to chemical behavior and mass transport properties, and that's a very important thing to recognize going forward. So there are a lot of uncertainties in all of this.

We've been looking at building on existing tools, a microstructure analysis tool that was initiated out of NIST, CEMHYD3D, and evolving into things. We're eager to see them make a lot more progress on that because that helps us with those homogenization and with understanding the microstructure evolution.

Bringing it to continuum scale, we've been using ORCHESTRA LeachXS as a reactive transport code, which takes into account a lot of the major trace phases and some flexibility that you can do there. When coupling --

MEMBER BLEY: When you speak of

homogenization, are you speaking of in modeling or in the actual structure?

DR. KOSSON: No, in the model.

MEMBER BLEY: In the modeling. That's what I thought you meant.

DR. KOSSON: Yes, yes. How do you take this complex, diverse, spatially diverse material and get meaningful properties? And also working with STADIUM for the structural service life of materials, bridging back and forth between the two codes, and certain important areas, ground truthing them against each other so we have some confidence in the codes, you know, independent approaches come up with comparable answers, given all the uncertainties. And then bringing in a performance assessment framework, and the reason for that is just for managing some of the computational uncertainty, managing the Monte Carlo simulations that go through that. And all of this is accomplished with a coordinated experimental and computational program.

So go to the next slide, please. If you take a look at this, this is just -- I don't expect to spend time and details of all this, and there won't be a quiz on it at the end. But this is to illustrate for you the complexity of the scenarios that you're dealing with when dealing with the durability because the behavior of water in these systems is very important, how it moves. The degree of saturation also affects the degree of gas phase transport in reactive species. And that is strongly influenced by temperature, which I don't have here. And I believe that temperature radiance and temperature cycling -- because don't forget these are not stagnant systems. You take them through temperature cycling when you load or refuel and bring them up and down for maintenance, etcetera, and that has certain changes that occur and stresses that are important on the system and also opportunities for measurement, which I'll talk about later, as well.

But looking at the alkali silica reaction, the sulfate ingress, all are different reactive transport things that are important. And then all of these impact the physical, hydraulic, and the chemical processes because they affect the transport rates, the chemistry, what the pH is, at the local scale in these materials and what the expansive reactions are and how that performs relative to the mechanical properties of the materials, the strength properties of the materials.

In the end, in our world, what we worry about is cracking and porosity changes that lead to changes in either the physical structural performance or the hydraulic performance at one side and at the other side the constituent leaching. That's the release of the radionuclides, which is not really in the domain that you're dealing with right now.

The key processes, I mentioned on the right that we've been looking at has been chloride ingress; sulfate attack; carbonation; decalcification -- that's your loss, your leaching of those major species that change your pH, change your chemistry, and the contaminant leaching. And in development right now, looking at cracking, we've made a lot of progress on how to model the effects of cracks if you know what that cracking was. But the evolution of cracking is whole other challenge which we're working on.

The oxidation. A lot of the radionuclides are redox sensitive, and, therefore, that's an important part of the chemistry, how to do the parameter estimation and, obviously, the variability of these systems, the time and spatial variability.

Next slide, please.

MEMBER BLEY: On your previous slide, you had GoldSim. Every GoldSim model is something I can't imagine anybody can -- they use it only when things get really complex. I don't know how you gain confidence in that model.

The picture you had on the next slide, it's easy to understand in terms of physics and chemistry, but it's only a hint, I think, at the complexity of the modeling that must be going on.

DR. KOSSON: Yes. And the reason that -- we use GoldSim as a wrapper around these other reactive transport models. So, basically, to look at distributions of parameter uncertainty and then for it to go and automatically route that through. And we use that as, one, as a tool that came out of a request initially from the NRC in the performance. But in the research domain, we use other tools, as well, that deal with cluster and stuff, computational, etcetera. The key point is understanding the uncertainty and propagating uncertainty is very important of how you think about what judgments you're going to make and the decisions that you're going to make going forward.

One example motivation, and I'm going to breeze through this really quickly, is a --

MEMBER SCHULTZ: Before you go there, David, I just wanted to introduce my concern based on what you've said already, and it goes to the number of variables and the complexity of the problem, as Dennis was describing. And what you showed on the previous slide is a fairly small toolbox, and so my question is do you really feel that you can accommodate this broad range of applications, broad range of complexity, in the overall features that are being modeled with this relatively small set of tools?

DR. KOSSON: No. And I'll use an analogy we're all familiar with. There's been enormous study of a body in medicine. We don't ever rely on the prediction of what our health will be for the next 20 years. We always go for check-ups, diagnostics, and go forward.

I think it's really the integrated behavior of using these tools -- I was going to talk about that at the end -- how you integrate the information you get from these tools from the types of experiments that Ken is talking about. You use that information to focus where you monitor based on your knowledge of the properties of the materials.

We have a challenge with these facilities because we don't know the precise history. We don't know the precise source of the aggregate. We don't know the precise mix that was used for the concrete that was there.

MEMBER SCHULTZ: Right. So first you have to determine, if you knew all that information, what would you be able to accomplish? I'm going to the uncertainty side.

DR. KOSSON: Well, if you went through all that and you ran these models, it would say where in your structure, under which environmental conditions, should you be focusing your monitoring and your diagnostic tools and give you implications for what frequency you should be looking at. What's the rate of change? As Ken was saying, in the first third, the second third, or the third third? These are not linear processes, so being in the first third gives you a much longer time constant to think about things than if you think you're in the second third or, worse, the third third which says degradation processes may accelerate very rapidly.

So I think it's the combined understanding of the material science, what you can learn, and the uncertainties you have about the particular facility and how you integrate that with the diagnostics that you use in terms of non-destruction, destructive evaluation, and even where you apply those tools on the facility itself and when you do. Because, for example, can you take information -- one of the gentlemen here suggested using the cathodic protection system as a diagnostic tool. Another diagnostic tool that you have potentially that we're exploring is the information you can gain from the thermal cycling of the facility because the thermal pathways, the thermal conductive will be different in different areas.

So how do you take different sources of information and bring it together to provide the confidence that you need? I wouldn't rely on any one of them individually.

MEMBER SCHULTZ: I like the pictures you've drawn because if the project is being approached this way, then it gets all of the individuals that are involved talking to each other to address the problems. I'm just concerned about ways in which that can all be brought together in terms of the overall analyses, approaches, and the investigative approach.

DR. KOSSON: I'm going to talk about that as we go through. So if we go to the next slide, just a simple example that's not simple is a concrete waste vault that's been in the ground for now 60 years, coming on 60 years, 50 - 60 years, contained, you know, a million gallons of highly-radioactive waste. You have the exposure conditions from the exterior. Soil gas conditions could have increased concentrations of carbon dioxide. Obviously, your base matter and these facilities are embedded in soils. They have different moisture conditions. You have different moisture transport. So if you're trying to understand the structural integrity and then understand, as the structural integrity degrades with these degradation mechanisms, how does that affect the water ingress for structures that are exposed to the environment and intermittent wetting and temperature and thermal changes?

Next slide. It is necessary that you do some abstraction of the processes and you look at the different layers and sequence of events, and this is just one example of that where we're looking at a buried concrete tank dome into a grouted tank with residual waste on the bottom and soil at the top and how you look at the combinations of advection and diffusion through preferential pathways and orthogonal processes coming from the surfaces. But if you think about a crack, what's happening? That crack is a conduit for liquid. It is a conduit for gas. And the sides of those cracks become reactive, as well. So it's a freshly-exposed surface that suddenly becomes carbonated, so can your reactive front progress much more rapidly so you're not seeing a uniform degradation process but you're going to see localized effects. And one of the questions are, if you see localized effects in different scales, when does that become structurally important for the safety performance of the system that you're looking at?

So next slide, please. One of the things when you do reactive transport modeling is you're starting with a basic assemblage of what you believe are the thermodynamic and chemical phases that are there and the reactants there. This is a representation of the mineral phases in one portland cement mix, if you will. These are represented by the chemical reactions that occur and the thermodynamic constants for those chemical reactions.

Our knowledge of the mineral phases isn't perfect. There are uncertainties associated with those thermodynamic constants, as well. So starting from the very basic understanding and how to propagate that forward becomes important. Some of these uncertainties with certain mineral phases are very unimportant for the overall structural performance but may be very important relative to the chemical performance and vice versa. So there's a lot of knowledge going back from the mix and what you're looking for as to which areas of the uncertainty, even the basic thermodynamic formulation of it that you need to be thinking about.

Next slide, please. So then as you integrate this to a system, again, different level of conceptualization of each of the different layers and how you can apply different models to different layers sequentially or in a feedback situation. This was a combination of carbonation leading to structural degradation, infiltration, then carbonation, and, ultimately, change in pH that could result in release of the contaminants of concern.

Next slide, please. At the different scales, one of the challenges with a complex computational platform is how do you deal with transport and reactions in crack media and the changes there. So here we do a transform, if you will, from the picture on the left, which is a crack matrix, to conceptualizing it as a series of different-sized spheres and flow around it because you maintain the crack interface area the same, you can have your distribution of diffusion distances, and it becomes a two-dimensional system, as opposed to a three-dimensional system, so that order reduction helps you computationally. Just one example of the approaches taken.

Next slide. And then bring it together. You have to worry about the stochastic parameters: how do you think about crack spacing, how do you think about infiltration rate? Fortunately, it doesn't rain everyday, but also, fortunately, it rains some days. How do you deal with the differences in the porosity of the material and how those properties evolve, as Ken spoke about. And then where is your composition and where you all recognize there's uncertainty associated with the structural properties of the material, that being the modulus that you have there on compressive strength, and how do you propagate that because that's part of your damage mechanics integration with the changes of the chemistry.

Next slide, please. So you bring all this together in a model of the different systems. I'm not going to spend much time on this because I really want to get to some of the end stuff, and I know we're short on time today.

Next slide. And what you come out with is a coupled analysis, and you have a mean and uncertainty bands that come out of it from your Monte Carlo simulations that are reflective of your understanding of the uncertainties and the distributions of the underlying parameters. And then you can couple that on top of with model uncertainty because, for example, which of those reactive phases are important or where you can test the impacts of alternative conceptualizations of these interactions.

Next slide, please. To do all of this, you also have to understand the changes of materials. A lot of reactions in concrete take place in 28 days with simple concrete. However, with these more complex mixtures, especially with fly ash and the like, these reactions are ongoing over time. With your porosity measurements, here you don't see much change. You get a fairly tight coefficient of variation. These are two different formulations over two years of study.

Let's go to the next slide. If we start looking at diffusion coefficient measurements and a central transport parameter in these things, and this is a technique that SIMCO uses coming out of work from NIST initially for an electrical conductivity transport migration tests and the variability that you can get with different materials and how you do that over short-term testing of materials that have been aged over longer time frames.

Next slide, please.

MEMBER BLEY: The various covered terms with different materials?

DR. KOSSON: They were different times on the same material.

MEMBER BLEY: Different times on the same material.

DR. KOSSON: Same material. So at 28 days up through two years, how were these changing?

MEMBER BLEY: No, I mean the different colors.

DR. KOSSON: Yes. The red was at 28 days --

MEMBER BLEY: Oh, I see.

DR. KOSSON: -- fairly rapid. The black was at two years of aging of the material. Next slide, please. So if you take a look at this, the diffusion coefficients, which are then integrated and reflected here as an average tortuosity, change by an order of magnitude over two years with your starting point being that 28 days. And that's assuming none of the reactions that are coming from aggressive species or other things are implicated with this and there's no cracking. So I encourage you not to think about these things as static materials after 28 days. I think that's very far from the reality.

Next slide, please. So also permeability measurements which are important because of the ingress again or release and also vapor transport. You can see here again significant changes from 91 days. If you went to 28 days, then changes would be even greater out to two years.

Another aspect of this is understanding integrated measurements of the ingress and release or leaching of reactive species. And we've borrowed tools that we've developed for EPA in terms of standardized testing methodologies because they also are very helpful in the reactive transport. It also, for the waste management area, provides some consistency about how two different regulatory structures are viewing the integrity of these systems because, ultimately, there's more than one regulatory structure that's brought to bear in the impacts to the environmental performance.

So next slide, please. So a summary for what we're doing in CBP is down in the lower right. You'll see experimental data; a methods, parameters, and verification, both laboratory and field verification where we can; bringing that to parameterize and including the uncertainty parameterization of two key models: STADIUM for the longer-term structural performance; LeachXS and ORCHESTRA for understanding the chemical evolution and leaching. And then using GoldSim as a wrapper to do the uncertainty analysis and how to propagate it.

We've gone through different levels of development, from arranging a proof of concept right now to integrated demonstrations that have actually been used in applications, such as for sulfate attack and for chloride reactivity. And the uncertainty propagation, we've demonstrated everything from proof of concept and how to do it from the thermodynamics uncertainty up to the model uncertainty, but we don't have the full-scale integrated tools yet to bring it from one to the next. Those are things that we're working on.

MEMBER BLEY: I can kind of see how you put all this together and get a hint of its complexity from the all the pieces you've talked about. With this complex a model, with so many different possible reactions and other things going on, after you get results, can you untangle this to figure out what's important?

DR. KOSSON: Well, let me show you -- you're a great straight man today, Dennis. I appreciate it.

MEMBER BLEY: The next slide.

DR. KOSSON: The next slide. Okay. Given this challenge -- and, Mr. Chairman, if I may take just a few more minutes. I won't go very long.

CHAIR RICCARDELLA: Yes, you recovered very well.

DR. KOSSON: I'm trying. A new initiative that I've just started over the past few months, working with Idaho National Laboratory, the Department of Energy, Oak Ridge National Laboratory, and looking to engage others, as well, is to develop a concrete structural health monitoring framework that integrates between the damage modeling, the mechanistic work that I've been showing you here, with monitoring: how do you think about your non-destructive sensor evaluation, the specific techniques, and other issues or approaches that are emerging that may come to bear, such as embedded sensors and full-field monitoring, take advantage of big data analytics that are evolving out of other fields, and uncertainty quantification that comes from all of these different things, ranging from the basic thermodynamics and models up through the non-destructive evaluation, and bringing it together using a Bayesian formulation to basically provide what we euphemistically refer to as a digital model of a concrete structure at a facility that would be the basis for ongoing performance health monitoring or structural health monitoring of that facility.

So it's not using a single technique but using one technique to inform where you should be using the other and those feedback loops across between the basic modeling and the NDE and what you do know or the uncertainty in what you know relative to the mix designs and your environmental exposure conditions to say, ultimately, where should you be focusing your effort and with what frequency and when do you get to the point that uncertainty is too great/

So next slide. This is just a quick summary of the different types of uncertainty that need to be considered, the natural variability. And part of that is homogenization issues that I talked about, and the other is really understanding the system cycling and how it was constructed or what the exposure conditions will be. You've got all the data and the model uncertainty and then using a Bayesian network to provide all that uncertainty integration.

Next slide. So the path forward with this is assembling different techniques for looking at the different damage mechanisms and models. ASR has been chosen as the first one to look at because of its prominence right now for integration. Consider the impacts of multiple damage mechanisms and these feedback loops and then look at integrating the simulations that we were talking about, that Ken was talking about earlier, for field imaging and all these different pieces into a risk management framework.

And we're going to be having a workshop on this in early November. I've spoken with Jake about it, and I look forward to and hope that we have NRC participation and participation by others that bring appropriate expertise and needs and problem definition to the table.

So thank you. And I hope I helped you recover some time, and I hope I got across the key messages.

CHAIR RICCARDELLA: Thank you very much. Do we have any other questions?

MEMBER BLEY: The key message is really good. The work left to do, this is a really complex thing. You make it sound easy and tractable. We'd really like to hear more because it's a bear of a problem.

DR. KOSSON: It is a bear, but you have to have a concept or a vision of how you're going to bring it together because, otherwise, you may be hitting your head against the wall endlessly or you may put in undue effort into micro aspect of that problem when it may not be what's driving your overall concern or where your greatest risks are.

MEMBER BLEY: It's too easy to spend all your money where you know what you're doing.

DR. KOSSON: Yes.

MEMBER BLEY: This will make you spread it out.

DR. KOSSON: Thank you for the opportunity to meet with you today.

CHAIR RICCARDELLA: Thank you. So do we have --

DR. STACK: Just a quick question. ASR, you know, seems like a problem that civil engineers should have fixed. Their bridges, presumably, have less structural margin than our biological shields do. Does STADIUM, when you say it does structural stuff, does that come out of the civil engineering world?

DR. KOSSON: That is a coupling between the reactive mass transport and the structural world. That is a very evolved thing for other systems that are not, I would say, with the same degree of safety significance. For example, it's being used for peer design. It's being used for the Panama Canal extension. It's used for standard designs for the U.S. Navy, etcetera, even though it's a Canadian --

MEMBER BROWN: What do you mean by U.S. Navy? I don't know of any ships made out of concrete yet but --

DR. KOSSON: I do think you realize that the ships require ports.

MEMBER BROWN: No, I understand that.

DR. KOSSON: Oh, yes, very much so.

MEMBER BROWN: The pier structural integrity and --

DR. KOSSON: Yes.

MEMBER BROWN: Okay, all right.

DR. KOSSON: Naval engineers are responsible for that.

MEMBER BROWN: Well, Naval facilities engineering is fundamentally the ones who do that. But when you said Navy, I wanted to make sure I categorized it. Thank you.

DR. KOSSON: I couldn't avoid a little tongue in cheek there.

MEMBER BROWN: And there has been a concrete ship. He's right.

MEMBER BALLINGER: They used to make ships out of what's called ferrocement.

DR. KOSSON: And a traditional civil engineering exercise for undergraduates is an annual concrete canoe that every department in the country does.

MEMBER BROWN: But what you're saying is it's not really good for, it wouldn't work very well for a bridge where you have high cyclic loadings and long-term --

DR. KOSSON: You have better inspection. You have less demanding service, if you will.

MEMBER BROWN: A bridge does or we do?

DR. KOSSON: You have more demanding service because you don't have the observation capability. You --

MEMBER BROWN: I agree with that.

DR. KOSSON: -- can observe the degradation and make repairs much more easily, as opposed to what I believe is the case with the nuclear systems.

MEMBER BROWN: All right. I got that.

DR. KOSSON: The other thing which -- you know, you talk about civil engineering, but my own background is from chemical engineering and I chaired a civil engineering department for 12 years. One of the things I learned is that the majority of civil engineers go into civil engineering to avoid chemistry. So this marrying of chemistry and structural analysis is really important, and I applaud

NIST and other groups that are bringing us together and your interest in bringing us together because that's really the underlying mechanisms that control the ultimate performance. But it's also really a frontier research. Thank you.

CHAIR RICCARDELLA: Okay. Thank you very much, David. Dr. Brown? We will work to give you your full hour, Dr. Brown.

DR. BROWN: Okay, thank you. My name is Paul Brown. I'm from Penn State University. I'm primarily, however, going to talk today about work I did as a consultant on behalf of an organization called the Union of Concerned Scientists, and that activity permitted me to review a variety of correspondence involving a durability issue at a particular nuclear facility, as well as some other correspondence.

I'm primarily going to discuss concrete not from the perspective of a structural engineer but from the perspective of a material scientist. I'm probably going to be telling you things which are fairly obvious, one of which is concrete is truly not in equilibrium with its surroundings. And those surroundings, in some cases, even include the aggregate. In fact, one of the things we often wish to do is to avoid to the establishment of that equilibrium because if we did, as you heard in a prior presentation, we would wind up primarily with calcium carbonate, hydro silica, and some other odds and ends. We wouldn't have a true cementitious system.

We typically rely on diffusion control that interfere with those degradation processes, particularly for things which are coming in from the external environment and interacting with the concrete microstructure. The exception of that are things like purely mechanical processes, like freezing and thawing damage.

But having said that, we also need to understand we're dealing with a system which is inherently flawed. The concrete is, by its very nature and as Ken Snyder showed you earlier today, contains porosity. Concrete, by its very nature, will also contain cracks.

In terms of -- concrete is kind of like our spouses. We tend to take it for granted or them for granted unless a problem shows up. So unless there's evidence of deterioration, concrete, I think, gets ignored. And that usually means there's a significant time window between 28 days, or the end of the curing period, and the time where a problem emerges, and that can be years and years and years.

So, typically, what happens is someone finds evidence of some form of deterioration and then an assessment process starts, typically associated with a visual assessment, typically associated with taking cores and doing strength determinations. And I want to actually spend some time talking about what strength means because strength, you get a number, but, actually, the interpretation of that number is not necessarily unequivocal. Then, depending on the situation, hydrographic analysis and other non-destructive analyses will be carried out.

Generally, the parties involved have no dispute in terms of those activities. When we get to this slide, this is when the adversarial activities tend to show up, and it has to do with arguments of whether or not the mechanism is still active, whether or not, okay, I see deterioration, but is that deterioration phenomenon really going to compromise the integrity for the serviceability of the structure during its design life? If it is, what kind of repair is reasonable? If it isn't or if you're uncertain, what do you actually do? How do you anticipate what's going on in the future? What kind of schedule for future inspections should be maintained?

You heard a lot about this before, and so I'm going to kind of go through this, but I tried to separate these things which can possibly deteriorate concrete with respect to their genesis. And so, for example, mix design where the selection of concrete materials can affect things like the occurrence of alkali silica reaction, the occurrence of carbonate reaction, strengths and permeability parameters. Placement and curing processes will also significantly affect strength and will affect permeability.

And I'll show you as we go through that, talking about concrete variability, take exactly the same concrete mix and you can vary its physical properties by 50 percent merely by the way it was cured. And you'll see, in terms of mix design, as well as placement and curing procedures, both strength and permeability show up in both places.

In addition, the presence of cracking. Concrete is going to be cracked. There is absolutely nothing that can be done about it. It's a phenomenon inherent to the way concrete behaves. So cracks are going to exist. The question is what is the genesis of those and how concerned should we be about them? And then also things like certain durability factors are affected by the curing process, as well.

There's a phenomenon known as DEF, delayed ettringite formation, whereas in structures which are either steam cured or they can act as bath which are large enough that internal heat by the hydration process stays within the structure can affect the early hydration processes such that, when the concrete is placed in service, a chemical reaction called internal sulfate attack occurs and that can result in expansive reactions.

And then the third area of factors which can affect concrete aging is the service environment itself. We've heard a bit about carbonation. We've heard about leaching, freeze-thaw, two forms of sulfate attack, both of which have their genesis in sulfates coming in from an external environment, corrosion of embedded steel, and then alkali silica reaction. And someone asked, I was sitting in the audience, someone asked, well, how long should concrete go without it corroding? As long as the internal environment within concrete is not being affected by carbonation passing in front of the steel or by ingress of chlorides, essentially forever, certainly intergenerationally and probably well beyond the design life of the structures you guys are concerned with today.

And then you'll see ASR again popping up in the service environment. ASR, even if you have susceptible aggregate in concrete, again, it will be dependent on the service environment to establish whether or not the phenomenon is going to manifest.

Let me talk for a bit about strength, if I could. This is a fairly sophisticated group, so this may not be relevant to you. But when people talk about a 28-day strength, this is not what they're talking about. They're not talking about the mean strength as shown in this slide. They're talking about the minimum strength which is expected after 28 days, and that's shown here.

So when someone subsequently goes in and does physical testing on a structure, and in this example the specification called for a 28-day strength of 3,000 psi, and that's what they found after 20 years, I think that's a problem. Even though it's above the so-called 28 design, that's, I think, truly indicative of a degradation phenomenon occurring. In the litigation, we see that over and over. People will say, well, wait a minute, it's still slightly above its design strength, what's the problem? In fact, I think, typically, there is one.

In terms of things that affect long-term strength, I want to talk about these four factors here, the mix design, how the concrete was cured, how the actual cores were handled, and then the presence or absence of a degradation phenomenon. Air porosity doesn't contribute to strength. Concrete only needs a water-to-cement ratio of about 0.3 or so to provide sufficient proportion of moisture to support the hydration events going to completion. Any amount of water proportion above that is going to result in porosity. Porosity doesn't actually contribute to strength. And if we plotted the compressive strength versus the water-cement ratio, this is the sort of curve we would generate. And this is -- I don't want to imply every concrete is going to exhibit that behavior, the precise behavior, but the generic behavior I think is typical.

Here we see the effect of curing. And, you know, the duration of curing means providing sufficient moisture so that the concrete doesn't dessicate. Going from three days to 28 days and then the samples got broken after anywhere from 28 to 180 days.

And if you look at comparing three days of curing, which is not atypical in structures, if true care was taken and the concrete was maintained in a continuously moist condition for about half a year, you can see the strength varies by a factor of about 50 percent. And this is for a fairly typical concrete, a water-cement ratio of 0.5.

If we go to the next one, we see something which is sort of unusual, and that is when the curing was stopped after 14 days the concrete was actually stronger when it was broken at 28 days had the curing continued continuously for that period of time. And what this speaks to is the testing conditions. Concrete which is tested after it's been allowed to dry is going to present a different set of mechanical properties than concrete which has been tested when it's maintained in a moist state.

CHAIR RICCARDELLA: What do you mean by break on those slides?

DR. BROWN: We do a compressive test and

establish --

CHAIR RICCARDELLA: When it breaks?

DR. BROWN: When it breaks, yes. And here you can see the effect of just handling the cores. For a lower-strength concrete, you realize a relatively higher benefit by allowing it to dry than you do with a higher-strength concrete. But you can see there can still be significant variability in the mechanical properties of a concrete, merely depending on how not only the way the cores were handled but how big they are, the length-to-diameter ratios, whether or not they were capped, whether or not the material was sliced from the ends. So there are a whole variety of factors which can affect the strength of a concrete that's being hypothetically removed from a deteriorating structure that will affect the data which is obtained.

And, again, this is some of the questions that arose earlier this morning. What are the mechanical effects of deterioration associated with expansion on structures? And this, I think, is a fairly reasonable plot. The black line is strength obtained compared to some reference strength with continuous moist curing, as opposed to a strength associated with a degradation phenomenon. And as you can see, there's a period of time during which the strength of the structure or the concrete which is being subjected to deterioration actually sees that of the unattacked concrete. And then as the process proceeds, eventually the expansive process then starts to mechanically, the benefit of pore failing is diminished, the effect of the expansive reaction then occurring within the porosity is manifested. And concrete is, of course, generally designed to resist compressive loads. It doesn't do so well when it's a tensile load, even when that tensile load is internal. And then you see the deterioration in the mechanical property.

CHAIR RICCARDELLA: What is the time scale?

DR. BROWN: Oh, that's just a hypothetical. I just --

CHAIR RICCARDELLA: Are we talking years, decades, days?

DR. BROWN: Well, it's going to depend on the specifics but -- I'm a very strong advocate for concrete petrography because --

MEMBER SKILLMAN: For concrete what?

DR. BROWN: Petrography. Actually cutting it open and looking inside of it. Because it's unclear to me when people use the term "crack" what they're actually meaning. And in a restrained structure, you can have very extensive cracking, but it's micro cracking, which is going to significantly compromise the properties. And if you look at the structure you just don't see it. And so it's for reasons like this shown in this slide, that micro cracking leads to that sort of phenomenon.

If we were to look at -- you can go to the next one, Jake. And so the question then arises, well, what can we do? Okay. If we can't simply rely on someone giving us some compressive strength data to really understand what's going on in the structure, what alternatives exist? And one of those, and I think H.S. Lew kind of spoke to that earlier today, do both compressive testing and do splitting tensile testing of some sort. And you can see then in the black line highlighted by the dash lines sort of the column of uncertainty with regard to comparing tensile and compressive strengths --

CHAIR RICCARDELLA: Normal concrete? The black curve is normal concrete?

DR. BROWN: Yes, the black curve is normal concrete and the dashed lines reflect the sort of the uncertainty which emerges as the strengths go up, as compared to what happens when a deteriorated concrete is characterized both for its compressive and its tensile strength.

And you can understand it fairly simplistically. If you take a solid metal object and you just squeeze on it, you take a roll of quarters and you squeeze on it, the mechanical properties in compression may not be significantly compromised. But if you try and do a tensile test, you'll see a very, very different set of results.

In terms of the presence of porosity which has to do with the fact that it's very, very difficult to actually constitute a fresh concrete with only sufficient water that you would need to allow the hydration process to proceed, so the extra water present is there because it's needed to support the mixability of the concrete when it's in a plastic state. That water gets consumed -- and I'm just using hydration, and I apologize for the chemistry. I'm just showing the hydration of tricalcium silicate in which the tricalcium silicate molecule winds up consuming seven molecules of water, producing something called calcium silicate hydrate and then some calcium hydroxide.

If we were to sum the molar volumes associated with those processes, we'd, in fact, find that the total volume of the system actually decreases. If you take the volumes of the reactants and compare those to the volume of the products, the system shrinks, called autogenous or chemical shrinkage. However, the concrete gains strength as a result of this process because, if you look at the volume of solid reactants as compared to the volume of solid products, that increases dramatically. But the net volume reduction in concrete does have a tendency for it to crack, regardless of how good the installer or how good the process is.

And I, again, show you that graphically here. We start off with volumes of water approximately three times or so that of the volume of the cement itself. The volume of the cement diminishes as a consequence of the hydration process. It produces hydration products. It also produces hydration products containing a type of porosity called gel porosity, and that porosity is not really responsible for bulk transport. It doesn't support the movement of a species from one place to another within the concrete. However, the capillary porosity does. And so this is just a graphic where I attempt to show those volume changes.

I actually got this from the W.R. Grace Corporation, and this is part of their advertising. They're attempting to show the benefits using shrinkage-compensation admixtures. And this is a plot showing the dimensional change with time, showing that initial period of shrinkage, then followed by a period wherein there are dimensional changes associated the expansion. And the reason for that is concrete, the binder in concrete is primarily a gelatinous material which is generally in the field of space available to it. And that's what's happening in the early stage. Then as time goes on, crystalline materials are forming, and those tend to be more choosey about how they fill space, and the formation of those crystalline products then tend to cause the concrete to expand slightly.

If we superimpose on that, as shown in the next slide, the range of tensile capacities, and I took this from one of Neville's books, the range of strength capacities that concrete can stand before it starts to crack, you can see that even a typical concrete is showing some evidence of cracking associated with those dimensional changes. Then the concrete dries out, and we actually see a strength regression. There's a plot showing the relative strength as compared to the strength of a concrete which has been subjected to continuous moist curing, and you see that the bottom curve reaches a maximum, and then you get mild regression in strength. Again, that has to do with the fact that dessication reduces the dimensions of the object, and that can lead to initiation of cracks which then, ultimately, compromise mechanical properties.

The understanding of these dimensional changes in cementitious materials, however, is rather complex. And here this is a mortar. This shows a dimensional change as a function of relative humidity. And the thing is why on earth would it shrink down to relative humidity of 50 percent and then between 50 and zero or lower? And we can deconvolute that by superimposing the two phenomena which are occurring. One is drying shrinkage, and second is carbonation shrinkage. Carbonation shrinkage dies out when the concrete gets sufficiently dry and there's not a medium through which the CO2 can get into the concrete, enter the pore solution, and cause the chemistry. So even phenomena which are, you know, classically fairly simple, if you probe the chemistry behind them, they can start to look rather complex.

In terms of the permeability as a function, again, of water-cement ratio, and, continuing this theme, I just took that 3,000 psi concrete and superimposed a water-cement ratio that's slightly above 0.7. It's probably, realistically, somewhat lower than that. But there are, there is a well-defined relationship between the water-cement ratio of concrete and its permeability.

And if we turn to the next slide, you can see the influence of water-cement ratio on the presence of that capillary porosity, the porosity through which aggressive species can move if that's the issue.

MEMBER SKILLMAN: Dr. Brown, what establishes the correct water-to-concrete ratio for an optimum structural outcome?

DR. BROWN: Well, the National Ready Mixed Contractors Association will tell you there's never a good reason for making concrete with a water-cement ratio above 0.5. Now, that doesn't always happen, and it's very dependent on the geography. In the southwest, where there's no concern over freezing and thawing for example, it's routine to see concretes with water-cement ratios much higher than that. However, that makes that concrete susceptible to things like sulfate attack, chloride ingress, and things of that sort. So there's really no clean answer, but perhaps the next slide will speak to that.

If we look at the permeability as a function of water-cement ratio, it's not a linear scale. The permeability is fairly insensitive to water-cement ratio until you get about to 0.6, and then it increases dramatically. And at least at Penn State, one of the things we try and teach them is avoid working in a window where one critical parameter depends really strongly on a second one. And you can see, considering the inherent variability in concrete, if you're using concrete with a water-cement ratio of, say, 0.65 or so, if you do permeability testing in one part of the structure, as opposed to a different part of the structure, how you can get very, very different permeability results. Here, you're looking at a couple orders of magnitude.

And so one of the things about concrete is the worse it gets the worse it gets. In other words, the higher the water-cement ratio is, the more variable it tends to be and, at the lower end, the more susceptible it tends to be to deterioration phenomena.

CHAIR RICCARDELLA: So you say at the low end it's tends to be less variable spatially?

DR. BROWN: No, no, low end it tends to be far more variable. In that L-shaped curve I showed you, that one gets smaller and smaller and smaller the better the concrete is.

CHAIR RICCARDELLA: By low end, I meant the low end on the water-cement ratio.

DR. BROWN: Oh, yes, the lower in the water-cement ratio, it tends to be less -- yes, it's better and less variable.

I'm not going to reiterate these. You've heard about those already. But let me just spend a little time on the phenomena themselves.

A reasonable concrete will carbonate to a depth of somewhere between a half a millimeter and a millimeter per year. If the depth of cover is, you know, three to four inches, it's probably not a concern. It, however, can become a concern if the structure is cracked and those cracks intercept the embedded steel because then it doesn't really matter how deep the carbonated front is. Now you have the concrete in a moist environment which is not being protected by the elevated pH of the pore solution.

Leaching and chemical attack are, again, probably boutique issues depending on site-specific conditions, and they're not of generic, tend not to be of generic concern. Again, freezing and thawing, I think someone said before these structures tend to be warm. Is there really concern over freezing and thawing? Again, that's going to be structurally dependent.

The thing to remember about freezing and thawing is it tends to be relegated fairly close to the surface for two reasons. The water in the porosity close to the surface is more like regular water. The further you get in, the higher the pH, the higher the ionic strength of the water is, and that depresses the freezing point the same way throwing salt on your pavement does. So, you know, again, this may be an issue in some locations but certainly not a generic concern.

I already mentioned delayed ettringite formation. I put these on the same page because DEF and ASR share features in common in that both of those phenomena tend to result in homogenous or near homogenous expansion of the concrete. The phenomena, as long as there's moisture, the phenomena are occurring, more or less, uniformly throughout the concrete. And I'll come back and revisit ASR at the end and tell you a little bit about some strategies maybe to deal with it.

Sulfate attack and physical salt attack have more to do with an aggressive species entering the concrete from an external environment at one location and then being transported through the concrete to another location where there's an evaporative front. Along the way, some chemistry can occur associated with the formation of expansive sulfate-containing solids and sulfate attack ettringite. However, even if there's no chemistry occurring within the concrete, as these species approach evaporative fronts, the loss of moisture can result in crystallization events occurring. Those crystallization events are damaging to the concrete the same way any other expansive event is, and that leads then to spalling and loss of concrete and regression of the original surface going back in.

In the right climate, that can occur, a physical salt attack can occur over some inches in a decade or so. So you can, while these phenomena can be regarded primarily as surficial, under the right set of circumstances they can proceed in pretty quickly.

Corrosion of embedded steel, again, as we heard before, the pH which is typical of a core structure of concrete protects the steel from corrosion, even though those pores are full of water. The pH is such that the passivity, a passive layer forms on the steel, and then the rate of corrosion is so slow it's not a concern over the design life.

That changes very, very significantly in the event of chloride ingress. Chlorides have the capacity of so-called depassivating that passive layer. They disturb that passive layer and pretty much, regardless of the internal pH, the corrosion of the steel can move forward.

ACR is kind of an unusual reaction and has to do with certain aggregates which contain magnesium becoming expansive, and it's not something one sees all that commonly. And then if I attempt to kind of group these into what's going on, we can talk to things which tend to be locally expansive associated with the conditions: freezing and thawing, sulfate, physical salt, and corrosion, and then reactions which occur more globally throughout the entirety of the concrete structure. Of course, one I think which is of primary interest is the occurrence of the alkali silica reaction.

CHAIR RICCARDELLA: What about the effect of constraint? I understand the ASR, I understand from what I read -- I'm not an expert in it -- that there's a big difference in the expansion you get from ASR if it's in a constrained part of the structure versus unconstrained.

DR. BROWN: That will be true of any expansive reaction, any of these expansive reactions. The constraint can redirect the orientation of expansion. So if you have two mats of reenforcement, it can redirect it, so you wind up bifurcating the structure and you wind up with two separate structures with a crack running down in between. And so if you wish to understand the mechanical consequences of these things, yes, you really have to look at it with respect to the nature of the reenforcement, the way in which a structure is reenforced.

So we're faced -- you know, and I guess the concern here primarily is, you know, high-value structures, what can be done to ensure that they're going to continue to serve their intended functions for their design life. And so if one is faced with a durability issue, you know, I think it's important to ask yourself, you know, what's the objective of the repair? And as you can see, this is simply restore the damaged area. Let's restore the damaged area and then establish if there's a mechanism by which we can interfere with subsequent damage, or sometimes you want to do both.

In terms of repair methodologies for in-situ concrete, the list looks fairly similar as you walk down. It's typically removal and replacement of the affected area, and that applies to carbonation, leaching, etcetera, etcetera, if corrosion of embedded steel where the objectives are remove the concrete and then clean the steel and recast concrete around the present steel.

However, when you get down to DEF, ACR,

and ASR, there is no generally-accepted repair methodology. The one thing I might point out, and I think there was some discussion about corrosion in metals, there is a technology where you can apply to a concrete surface something called a penetrating corrosion inhibitor in with the objective of that corrosion inhibitor then migrating through the concrete to the location where the steel is corroding and it subsequently interfering with the corrosion of the steel.

MEMBER SKILLMAN: What is the time dynamic for that particular application?

DR. BROWN: A penetrating corrosion inhibitor?

MEMBER SKILLMAN: Yes.

DR. BROWN: Again, I know you guys are looking for specific answers, but there never is one. And it's --

MEMBER SKILLMAN: Well, it's got to be months or years.

DR. BROWN: Oh, yes, it's not going to be -- well, yes and no. But I would think, yes, primarily in that time frame. The more damaged the structure is then the more quickly these things are going to find their way in, but then the question is is the structure worth saving in the first place?

But, yes, we're not talking in time frames which are short.

MEMBER SKILLMAN: Thank you.

DR. BROWN: The rest I'm going to speak to is really ASR. Certain siliceous aggregate, if they contain amorphous silica or if the silica is strained, are susceptible to dissolving in high pH solutions.

MEMBER BROWN: What do you mean by strained? That's sand, right?

DR. BROWN: Well, certain strained ports, yes. It's actually physically strained.

MEMBER BROWN: Oh, okay, you're talking about an internal strain --

DR. BROWN: Within the mineralogy, yes, yes.

MEMBER BROWN: All right, okay.

DR. BROWN: And the question came up before, well, does sand cause, can you really get ASR in sand? A lot of sand is actually manufactured. It's not the sand you run into at the beach. It's sand that was produced by chopping up or grinding up coarse or aggregate. So, you know, if the large aggregate is susceptible to ASR, sand manufactured from that large aggregate is also going to be susceptible to ASR.

But, essentially, what happens is calcium, sodium, potassium, silica gel forms, and that gel is expansive and causes the sorts of damage you saw in the overheads that Ken Snyder showed you.

In terms of a practical repair method, there is no generally-accepted repair method. In terms of a theoretical repair method, sure, there are a variety of things one can think of, all of which, however, must involve contriving to establish a set of conditions within the concrete where the occurrence of the phenomenon is unfavorable. We can do that today in new concrete by adjusting the chemistry and incorporating fly ash which acts as a source of reactive silica, putting in lithium which interferes with the expansivity of the gel. But the issue is what do you do when you have an existing structure which is suffering from the phenomena? And people have been promoting various things, particularly associated with the use of lithium as a means for interfering with ASR. And I'll speak to that in this next series of slides.

One of the things one can do is attempt to deprive the concrete of moisture. The thinking is ASR really doesn't proceed unless the relative humidity within the internal porosity of the concrete is above about 80 percent or so. So if a strategy can evolve by which that can happen, then at least there's a basis of interfering with subsequent damage to ASR.

And, in fact, technologies have emerged. This one is developed by the Army Corps of Engineers, and it has to do with attaching electrodes to the reenforcing steel, driving cathodes into the ground surrounding the structure, and then applying electrical pulses. That was developed for basically wet basement cement with subterranean structures. Whether or not you can drive the water content of the porosity within the concrete down to the requisite low level, I just don't know. But, at least hypothetically, there's a basis for at least one technology. Some of it has to do with figuring out how to dessicate the structure without the need to excavate clean off the surface, the soil-facing surface, and then trying to put some barrier material there. This is something which apparently works for in-situ structures.

Introduction of lithium salts and the thinking there is the ionic radius of lithium is sufficiently smaller than the ionic radii of sodium and potassium, that the lithium can intrude, the expansive ASR gel changes alkali-silica ratio and therefore render it non-expansive. And lithium well and truly does work. The problem is, when you have an existing structure, how do you get it into any depth? There have been various studies where they've applied it to pavements and so on, and those studies seem to support the fact that it works. But how you do that with a structure which has, you know, a meter or more of wall thickness becomes an issue.

Hypothetically, at least reduce the pH of the pore solution. I think Ken Snyder said pH's run from in the high 12's to the mid 13's. If you can reduce the pH below around 13, generally, for most aggregates, the problem with ASR is gone away. And I'll speak to that in a minute, but let me enumerate the other two things.

The other thing you can do is affect the alkali-to-silica ratio itself. So rather than putting in an ionic species that would depress the pH, put in a species which elevates a silica. And, in fact, there's a technology available for that where, in fact, one adds a liquid form of silica, allows it to intrude the core structure and that affects the alkali-to-silica ratio, and the process stops.

And then, finally, deploy some modification of electrical chloride extraction, ECE. And that's shown in my final slide.

There are technologies out there, again, by which you electrically connect the embedded steel to an anode made out of a metal which won't erode. You apply a potential, and, essentially, you drive the chloride out of the concrete. In this case, you wouldn't want to do this for an ASR-affected structure because you could draw alkali in. But one can think of other scenarios where you would change the species in which are trying to intrude to the concrete to do one of those two effects, either lower the pH or change the alkali-to-silica ratio.

CHAIR RICCARDELLA: Is the chloride related to ASR, or this is just --

DR. BROWN: No, this is just an example of a technology which is used in an attempt to reverse the susceptibility of structures which are exposed to chloride to the embedded steel corroding.

CHAIR RICCARDELLA: So this is for the corrosion of the steel you --

DR. BROWN: This is for the corrosion of steel, but I think one could think of technologies where you could attempt to do the same thing, except introducing ionic species that would mitigate the effects of the ASR.

I think that's all I have to say. Oh, we have a summary.

The one thing I do want to draw your attention to as I run out of time is the definition of a crack may mean very different things to very different people. And I think this speaks to something you had asked me about before. If you simply have an absence of macroscopic cracks because of constraint, does that mean there's no damage? And, unequivocally, the answer is no. The way in which expansive reactions tend to manifest themselves in highly-restrained structures is networks of microcracks form. And, essentially, what happens then is, rather than having concrete which has reasonable mechanical properties on each side of the crack, you have no crack but you have concrete which is in the process of turning to mush. And so you get a significant regression in the mechanical properties which is not associated with the presence of macroscopic cracks.

And I think one more slide reiterates what I mentioned before regarding various strategies to attempt to deal with ASR.

So thank you very much. And I guess I have a couple minutes for questions if . . .

CHAIR RICCARDELLA: I mean, is there a way, in your opinion, of evaluating an ASR in a structure to determine its effect on the structural capacity? I mean, that's what I think the morning presentations were all about.

DR. BROWN: Well, I was very, very impressed with the NIST work because I think that offers the opportunity to do that because they're looking at the progression of ASR in a bulk structure, but the way in which they have established their program is they can remove smaller samples from that structure. They can then subject those smaller samples to accelerated ASR, and then that gives them the basis for a predictive tool to go back and see how the bulk structure is going to respond to that. And then once you have an accelerated test that you can link to the performance in a real structure, then you have a reasonable basis for producing a, I don't like to say a predictive tool but providing a lot more guidance than we presently have. So, definitely, I think that work is going to be very beneficial in that regard.

CHAIR RICCARDELLA: So it isn't a go no-go. I mean, it isn't, well, I've got ASR, so my structure is no good.

DR. BROWN: It's not like falling off a cliff, yes. It's like cancer. Early detection, you really benefit from it because then you can think about what you might do. The other thing early detection benefits you is you then can start establishing, over time, the response of your structure as a basis for extrapolating out into the future.

MEMBER SKILLMAN: Dr. Brown, you made the comment just a minute ago that it is the network of microcracks that could point to your concrete turning to mush. That suggests to me that a program of taking some selected deep boat samples and analyzing them would be basis for a licensee to say, for the structures about which I'm concerned, this is the present state.

DR. BROWN: I think that makes a lot of sense.

MEMBER SKILLMAN: I would think that would be quite convincing.

DR. BROWN: That makes a lot of sense. If you can show us through petrographic means that your structure is not being presently damaged, that would be a compelling argument.

MEMBER SKILLMAN: Or even if it is damaged, it's in an early state and there is a predictable 10, 20, 50 years remaining for the time it took to achieve that level of degradation.

DR. BROWN: And the other thing is these structures are not subjected to the same moisture environment everywhere. There tend to be areas where you could extract cores as sort of a control situation where the probability of ASR occurring is very low. Then you'd have a basis for establishing how that concrete looked in comparison to concrete, which --

MEMBER SKILLMAN: Let me ask, if I may -- I might be asking you to step out on a limb, but I'm going to ask you to do that. If you would opine, current state of moderate degradation, whether it's

ASR or ACR or whatever the degradation might be, and impose on that radiological effects, fairly high neutron to gamma, what might your thought be about that sample of concrete?

DR. BROWN: Well, you cut off the limb behind me because I don't know what the effects of radiation would be.

MEMBER SKILLMAN: Okay. Thank you, thank you.

CHAIR RICCARDELLA: So, you know, the samples that you were talking about, core samples or whatever, that's somewhat destructive. What do you think the prognosis is for non-destructive means of monitoring this?

DR. BROWN: I'm a very strong advocate of coring. In terms of destructiveness, I think it's minimally destructive, as long as you're not impinging the steel. It's done routinely. It's very inexpensive, and you can set up a program that would permit you to establish performance for time.

But I think you're right. It makes sense to couple that with NDE methods, but it's always nice to have some understanding of what the NDE data are telling you with regard to the concrete looks.

MEMBER BROWN: Where are you putting the core after you've taken part of the structure out? What do you fill it, backfill it with?

DR. BROWN: You fill it with high-strength --

MEMBER BROWN: So you just refill it with what? Steel or concrete?

DR. BROWN: Concrete.

MEMBER BROWN: Okay. Do you take rebar out with that or --

DR. BROWN: It depends on what you're looking for. If you're concerned about the condition of the rebar, I do half cell determinations.

MEMBER BROWN: What's that mean?

DR. BROWN: You measure the corrosion potential of the steel in place, so you don't have to take it out.

CHAIR RICCARDELLA: The idea would be to miss the rebar.

MEMBER BROWN: The idea would be to take the core and miss the rebar.

CHAIR RICCARDELLA: Well, you might use the NDE to find where the rebar is.

DR. BROWN: Yes, there are fairly

sophisticated metal detectors now where you can map out --

MEMBER BROWN: How big are the cores? Core inch diameter? I'm just trying to get a calibration. I have no idea. That's why I'm asking --

DR. BROWN: Depending on what you're doing, you can use a very long barrel and you get a whole series of cores and you can actually structurally interrogate the structure as you go near the middle as you go further out.

MEMBER BROWN: Could I ask one technical question that I didn't quite -- everybody talked about expansive, the ACR being an expansive process. Or ASR. Excuse me. And I was trying to calibrate myself what that means. That means there's internal tensile forces being built up as a result of the expansions inside? That's what -- okay, all right. I understand.

DR. BROWN: Yes. Either the aggregate itself is expanding and pushing against the cement base or the gel is getting --

MEMBER BROWN: But you're introducing the compressive nature of the overall, the overall structural capacity by the internal tensile --

DR. BROWN: Yes.

MEMBER BROWN: -- forces? Okay.

CHAIR RICCARDELLA: It could also be trying to push, you know, stress against the rebar, right?

DR. BROWN: Oh, yes. Oh, sure.

MEMBER BROWN: Got that. Got that.

DR. BROWN: And there was one study cited in Japan, and maybe you guys are more aware of it than I am, but where that happened. The ASR actually blew the rebar.

CHAIR RICCARDELLA: Yes, I think one of the NIST presentations showed that, showed the rebar, the cracking of the rebar. Well, thank you very much.

DR. BROWN: Thank you.

CHAIR RICCARDELLA: We appreciate the presentation. Before we close the morning session, are there any comments from people listening? We have to turn it on. They can hear, but they can't speak. Are there any comments from anyone in the room?

MR. FUHRMAN: My name is Mark Fuhrman. I'm a geochemist in the Office of Research. And this was alluded to a few times in the presentations, but I think it might be important to point it out again that you may have an individual degradation mechanism, like ASR, causing cracking. But depending on the environment you're in, that cracking then can lead to compounded degradation mechanisms. Enhanced chloride penetration, for example.

So it's very important to keep in mind that the rates may change very, very rapidly, and the mechanisms may change very rapidly over time. We don't know how that would work out, but it's something to keep in mind.

CHAIR RICCARDELLA: Thank you. Is there anybody on the bridgeline? There's nobody on the line, so I guess there's nobody with comments. So we will adjourn the meeting until 1:30, and we'll reconvene at 1:30.

(Whereupon, the above-referred to matter went off the record at 12:27 p.m. and went back on the record at 1:29 p.m.)

CHAIR RICCARDELLA: Okay. So we'll reconvene the afternoon session, and we're going to hear from industry, plus Oak Ridge. Our first presenter is Randy James from ANATECH Corporation. So go ahead, Randy.

MR. JAMES: All right. Thank you. Good afternoon, everyone. My background is structural engineering. Our niche is kind of performance-based analysis for concrete structures. So I thought I would just talk a little bit about a project that illustrates how, once a structure is known to have aging problems, how we can do an engineering assessment of that to look at the functionality of that structure.

I won't spend too much on this. I just want to mention that the way I define aging is that it's really a changing behavior over time. So if you put a stimulus on a structure today, you'll get a different response for that same stimulus in the past and a different response in the future. That means it's inherently nonlinear, and you kind of need to use nonlinear performance-based assessments.

There's lots of examples of aging structures here in the U.S. for civil structures. And we'll be talking about some navigational locks and dams today. Fewer examples of aging concrete in nuclear plants. I think that may be just the higher standards for concrete design and construction in the nuclear industry. It could be just simply that the relative ages and the number of these nuclear plants don't match the ages and the numbers of all the other civil infrastructures, so maybe we'll find out.

I do think that we need assessments for several reasons, like when specific issues arise. So like an ASR issue may be found at Seabrook will be an example. Maybe assessments to help understand possible future issues. An example there might be what are the radiation effects on concrete long term. There's not a lot of data, but there is some information. Maybe given some limits, you could do assessments to see if it is an issue or not.

And then it seems that we may need assessments where we modify older structures. An example of that might be a Crystal River type situation where an older structure that had aging issues, you know, try to do some major modifications to the structure. So what I'm talking about is determining if the structure still meets this design function is one part of an assessment.

So aging is definitely a complex issue, and simulation is pretty difficult. The good news is that concrete structures are pretty resilient to damage. We've all seen structures that have pretty good cracks in them, and they're still performing well. But the bad news is that, generally, when the limit is reached, the failure in the concrete can be sudden and catastrophic. So it's good to do an assessment to know how close we're getting.

So the assessment -- I guess methodology is maybe a little too great a word. It's more of an engineering procedure that was developed, and it's basically, you know, set out with these types of steps. Obviously, we need to collect a lot of material properties. But in addition to that, we really need to know the structural state, the current structural state and how that state is changing, and I'll get into that in a second.

And we need to have an adequate concrete material model that can not only look at time-dependent properties but also have interaction and progressive effects of the cracking. So when cracking does occur, redistribute stresses in the right way and we'll get the right stress within the structure.

So the idea is that we look at the macro effects of the aging. For ASR, it might just be the expansion of the concrete. And we put that in the model, put whatever material data we have in there, and then we perform an analysis of the whole structural history of that structure, the important parts of the structural history, until we can match the current structural state. So the example I'll show is how we indicate that we think we have the current structure state captured in our baseline model.

And once you have that model benchmarked, we think we can use that to assess the current structural state. For example, you can take a load and design basis, apply it in the current structural state and, for example, increase up that load until you find failure to get a margin of that load on the current structural state. And then, obviously, you can continue the analysis in time and look at potential limit states, what's really going to happen with that aging mechanism.

There is a lot of uncertainties in all this, so we always like to kind of look at assessment of uncertainties in lieu of probabilistic --

MEMBER BLEY: Randy, can I interrupt you at that point? I read the paper that got sent to us. From what you just described about the model assessment process you're doing, it sounds to me, we heard that presentation by Dave Kosson this morning about the Cementitious Barriers Partnership where they're developing a very integrated model of all the corrosion and physical mechanisms. But it kind of sounds like when they, what they get out is a state of the concrete, and that's where you start. It's from the current state of cracking and all of that but then see, if those same processes continue, what might happen in the future. Do they fit together at all?

MR. JAMES: Well, I didn't -- I apologize I wasn't here this morning to hear that --

MEMBER BLEY: Well, I don't know if you know that group, the CBP group, what they're up to.

MR. JAMES: I'm not trying to capture the details in my consistent model about the aging mechanism itself.

MEMBER BLEY: So you take what is the state right now.

MR. JAMES: I take the effects of that --

MEMBER BLEY: So the physical state?

MR. JAMES: Yes. And then put it in. And then because I calculate in time to get to the current state, you know, I think I show that, whatever I put in there, the macro effects of the chemical reaction and all that stuff that's going on, you know, I've captured the structural macro effects of that because the structure is now under the same state that it currently is in the field.

DR. STACK: But if somebody could give you a mechanistic model of the expansion, I mean, you could put it into your model.

MR. JAMES: We can definitely put it into the model.

DR. STACK: I mean, you could integrate them that way.

CHAIR RICCARDELLA: Yes, yes, I think there will be a lot of data coming out of the NIST program in the next two or three years that feed into this methodology. It will probably reduce the uncertainties.

DR. STACK: It gives you more predictive -- I mean, the problem you have is you're very good at predicting the current state because you're backing up, I mean you back up to it. But then to project what's going to happen, you really are either extrapolating or you need a more mechanistic model to describe the expansion.

MR. JAMES: So I'm trying to get the rate of the structural change correct in my model and then project that on out and then do uncertainty band around it.

CHAIR RICCARDELLA: But if there's a nonlinearity somehow where it all of a sudden, you know --

MEMBER BLEY: We won't get that.

CHAIR RICCARDELLA: -- the hockey stick --

MR. JAMES: That's why we do the uncertainty assessment. We take, you know, ASR produces an expansion in the structure, so we benchmark it to an expansion rate that varies over the structure. It doesn't have to be constant. And then we look at plus or minus 20 percent of that expansion to see. There definitely is some nonlinearities when you just do it that way.

So the example, the project we applied this to was a lock structure. And you see here it's a fairly big structure. There's a person right here doing some examinations on a steel gate, so this is the miter gate. This is a series of monoliths that are placed side by side to form a chamber, and there's a culvert down the middle of it and outlook ports where the water is flushed in and out to lower and raise the chamber.

So this is showing some cracking down at these outlet ports here. So the foundation is pretty rigid, and the swelling in the concrete is pushing either upstream or downstream, and you get these kind of shear-looking formation of cracks. And there's cracks in the corner of the culverts. So over the years, they've mapped out all of the cracking in the structure. In some places, there's cracks big enough to have kind of a waterfall coming through the concrete wall, which is not good.

MEMBER BLEY: I don't want to see that at a nuclear plant, I don't think.

MR. JAMES: This concrete, of course, doesn't have all the enforcement that nuclear structural concrete has in it, so you're likely not to see this. This is a pretty extreme example of what AAR can do in a concrete structure.

But the monolith that we were worried about is called this miter gate monolith. That's where this big steel miter gate is hung and swung from, so it's got anchorages in this miter gate.

MEMBER BLEY: Just to give me a feel for it because I haven't seen these things for real, and I don't know how much of this is out in the real world. But when you get a situation like this, it's obvious. Are we close to a complete failure, or are still far from that? Can this leak this way for years?

MR. JAMES: Well, that was, that was kind of the objective of this project that we did for the Corps of Engineers. They wanted to know, you know, kind of a cost-benefit thing, can we continue to repair it, you know. They tried repairing it with block anchors that drill down in the foundation here, and they tried to stop these cracks with these pins. The idea was, you know, what's really going to happen, what's going to be the failure, how long can we maintain it, or is it better to put it into the line item budget to re-do it, rebuild it, which is what they wound up doing. They got funding through Congress to replace this lock.

So basic to your question is, these horizontal cracks aren't really the problem. It's a gravity structure, so each block is kind of made so it won't, you know, shear off. But it was this crack here that was of concern because that's where the anchorages are and that's what we came up with. That area is very congested and hard to repair.

CHAIR RICCARDELLA: And this is -- how old was this structure?

MR. JAMES: It was in early 60s, I believe. I don't remember the exact --

CHAIR RICCARDELLA: Sixty years old.

MR. JAMES: So when we started looking at it, you know, the difficulties of trying to capture that in the constitutive model were significant at the time. And I call it lack of constitutive relations. There's a chemical reaction that causes the gels that cause it to expand. And even if you know the reaction rate, you don't really know the expansion rate because the expansion rate because the expansion rate is a function of the stress, which is also a function of creep in the concrete.

So this data here, this is some specimens that have a different applied stress, and they have, you know, the AAR in it. So you can see that some higher stresses cause different rates of expansion of that, and this is measuring the expansion of the sample. So throughout the whole structure, the expansion rate itself, if it affects the cracking, then it can be different.

MEMBER SKILLMAN: How was that data

obtained, Randy?

MR. JAMES: I think they just put samples that had the susceptible aggregate, you know, that was going to have ASR in it and then had different samples under continuously-applied stress and just waited and measured the expansion of that sample.

CHAIR RICCARDELLA: This is from this 1988 reference?

MR. JAMES: This is from Hobbs, I believe, yes. So the higher stress keeps it, you know, there's a period where it won't do any expansion and then the rate of expansion changes with the amount of stress that's on it.

So, you know, even if you measure the reaction rate, which I think you can now, in the concrete, you still have to relate that to the actual structural effect of expansion in the concrete itself because the stress state can change.

So our approach was to take a concrete material model that was developed in the late 80s and early 90s to look at construction, constructability studies of concrete, where we want to track the concrete from half a day old placements all the way through the construction process. And the idea is to simulate the actual construction sequences, placement temperatures, the environment, and include the hardening and the aging of the concrete and the shrinkage and the creep in the concrete and try to minimize the potential for cracking on these mass concrete structures. So this is a Corps of Engineer procedures or like a reg guide, you might say, that's called NISA, nonlinear incremental structural analysis, that they like to do on some of their big, massive concrete structures.

So the model has a shrinkage term, which is volumetric shrinkage during the hardening process. So for the ASR expansion, we just reversed that term and made it grow. And then if there are modulus degradation that you get from test data, you can put that in the model.

And as I was saying, to do this, you really need a concrete model that can capture when cracking occurs, where it occurs, and how it redistributes to stress as cracking develops. So this particular model has a crack initiation interaction diagram that looks like this. It's time dependent because the slope of this is really the modulus. So early concrete has a soft modulus. As it ages, you change your cracking criteria and so forth, and it can capture split cracking when you have high-compressive loads on your free surface.

And the important thing is how the stresses get redistributed when you have shear across an open crack. So if you have a tight crack with lots of reenforcement, you can carry shear across that crack. But as the crack opens, then you can't carry shear, and the shear capacity will be creased with crack-opening strain.

So we go to global model of the lock wall. Actually, this is a half model because the data showed that it was pushing itself both upstream and downstream kind of from the middle. Again, this project is 12 years old or so, so at the time we were a little stretched for computer resources, so we thought we had to have a little fine mesh, you know, local model of this modulus that we were interested in because we were going to do a lot of probabilistic assessments, a matrix of calculations of different variations. Nowadays, I think we can model this thing and further refine the whole lock and do all the calculations.

But it just illustrates that the effects of one component is not only dictated by the expansion in that component due to its aging, but it's affected by the upstream part of the lock pushing on it and the downstream part of the lock, you know, kind of resisting that expansion. And so you might notice that this downstream part is not symmetric, you know. As it pushes on that upstream part, you get kind of a torsional load on the top of that monolith.

So here's an example of benchmarking the field data. So they took measurements on the top of the lock for vertical and longitudinal displacements over a number of years. And you can see that, you know, it is moving a fair amount. The joke at the time was this is a 600-foot lock, and we said, well, if you guys will just keep watering it, it will turn into a 1200-foot lock. They didn't think that was too funny.

CHAIR RICCARDELLA: That's displacement in inches.

MR. JAMES: Yes, displacement in inches. So they had monuments up on top here, and they would measure those in intervals. And this is the cracking, you know, actual crack patterns that they determined in the monolith through some drilling to find, you know, the extent of the cracking. And then here's our calculated cracking.

So it's easy to make a structure move the way you want to by putting alpha delta T or some swelling in it. But unless you're getting the stress right, then you don't really have the current structural state.

So the stress in the structure is something that you can't really go measure, but the cracking patterns is really a nice signature of that stress state. So if you match the cracking patterns, we think we captured what that structure went through in its history to get to the current point.

So then, you know, based on that, then we started running the analysis in time and looking at what was the true limit state of this. And that's when we decided that this crack up here is going to cause the ultimate link of the structure. So what we're applying is the strain normal to that, and this is showing different concrete strengths that, you know, have been arranged. And we would include the repairs.

These are grouted pins that they drill in, put a pin in and grout it to try to control the cracks, so it changes the slope but, eventually, you keep expanding that crack. And the reason that's a critical area is because these are the big steel A-frames that are embedded in that concrete monolith that hold the miter gate. So here's the crack patterns and the strain from the crack patterns that are this, you know, this crack here. That's the longitudinal crack.

So we modeled a local model, took the boundary conditions from the global model that we benchmarked and looked at and tried to decide what the limit strength really was, how much motion you could have. So the idea of the limit state is that, if the miter gates are on miter and you have some movement in the anchorage, you can slip the miter and you can lose the pool. So that was what we considered the limit state of this structure.

And then, again, there is uncertainty, so we tried to look at some of the core samples that were taken. And we set up our growth rate based on a distribution and expansion from the foundation up, kind of a linear distribution. As you get higher and higher, you have less stress so you have more growth, as a benchmark. So we took plus or minus 20 percent, and, you know, various things that were key in the assessment, and we'll do a matrix of calculations. So what we're plotting here is like a factor on that strain that's normal to those miter gate anchorages.

So we'd look at the different parameters that affected that and calculated out these factors and then do, like a probabilistic sampling of the different factors to try to get a little probabilistic of, you know, the current state of the structure.

So I've got another example here, if we have a couple more, a few more minutes in time.

CHAIR RICCARDELLA: You've got until 2:10, so we got about 15 minutes, 10 or 15 minutes.

MR. JAMES: So we need more questions. So another example is, rather than the AAR, is a thermal cycling and a freeze-thaw damage. So this is another lock structure in the Pittsburgh area that has the usual freeze-thaw damage of spalling of the concrete in the chamber. So here we're locking through some coal to a coal-fired plant in the picture.

But the surface freeze-thaw damage, you know, wasn't the real issue. Inside these monoliths again, they had this pretty significant structural crack that was running longitudinally down the monolith. And so the project was to understand what was causing this cracking and, again, project it and see, you know, what the ultimate limit states might be.

So for this modeling, it's basically tied to the use modulus and tensile capacity from the outside in. So we have water that gets into the pores, freezes, and works its way inside. It was clear that all the operating loads themselves were certainly not responsible for that cracking that they were observing down the link, so it had to be some kind of an aging, summer-to-winter thermal cycling that was causing that crack.

So in this case, we had different rates of degradation based on where the surface was. If it was in the chamber exposed to filling and emptying. It was wetted and then dry during a temperature cycle. So that would be the highest rate of degradation and so forth in interior galleries or exposed just to air, so they would have less degradation. Again, an iterative approach to get those rates of degradation so that we match the structural history over time.

And I just have a few results to show here. Here's a model with a section view, so that's the crack that they were seeing. That picture, we're standing in this gallery looking at the crack on the wall. And what you didn't see in the picture was a crack all along the floor of that gallery that extended down into the coal room. So this is where the water flushes in and out through this culvert. So when they would flush it, water would come up into the gallery.

And they had took measurements over the years and knew that the crack started from one end of the monolith, each end of the monolith, and worked its way toward the middle. And, you know, our model was able to benchmark that and looking at the width of the crack. So we felt that we had set up the benchmark sufficiently so that we had the mechanism in there that caused that cracking, and then we would project that on out in the future and try to -- in this case, it was really just that crack that would cause issues with their operational procedure, and they could repair that.

DR. STACK: Now, with a smeared crack model, when you changed the stiffness matrix in the element that's cracked, the crack just propagates because you then recompute the stresses with that new stiffness matrix, and you see what happens in the adjacent element?

MR. JAMES: Yes, correct. It can propagate or rest, you know.

DR. STACK: Yes. I mean, but it's just the stress, the change in stress as you change the stiffness in the cracked element, then you just look and see what happens --

MR. JAMES: Some stress, stress in the element. And if that exceeds the limit of the material, like the cracking stress, then we have to take that stress off. And so it has to get redistributed somewhere else. If there's rebar or something that can take it, then it usually stops. If not, you know, that will propagate on. So that's an aggressive type calculation.

CHAIR RICCARDELLA: For your model on slide nine, the one -- you don't have to go back. That one?

MR. JAMES: Yes. You know, so this is the guy that -- we don't preset any of these cracks anywhere. It's just a fully, you know, virgin material. And when we start out, we look at principal directions and find where a crack will start based on this crack initiation criteria. And then apply, you know, the stress, take the stress off normal to the crack and we reduce the stiffness in the shear direction because now you're looking at aggregate rock. You're not looking at solid concrete. So there's still some stiffness, but we reduce the stiffness in that direction.

DR. STACK: And that's the magic sauce, so it's zero in the tensile direction and some magic formula for the shear.

MR. JAMES: Yes, and that's the key, I think. Most concrete structures tend to fail in this shear mode when they just can't carry anymore stress across that normal -- they're parallel to the crack surfaces.

CHAIR RICCARDELLA: You do that element by element?

MR. JAMES: Element by element, yes. So if the crack goes to progress, you know, on the next element, we'll get the same thing.

MEMBER SKILLMAN: Randy, on slide 15, please, what is effectiveness grouted pins between one and ten? What does that mean?

MR. JAMES: So they repaired these cracks, these longitudinal cracks in this monolith with what's called grouted pins. They drill in and they put a steel bar and they grout it to kind of hold it. So since that was the critical area and that was the limit state, we needed to understand the effectiveness of that repair. So that was based on some data from the Corps of Engineers, you know, how long does that repair usually last? You know, pretty soon, the grout degrades and you get water in and you start degrading the steel bars.

So the factor, we did some runs to look at how big that strain would be in the monolith based on how soon those grouted pins would degrade. And so this is just a factor that -- we have this curve as a parameter in our probabilistic model, so we would go pick, you know, random selections of the different parameters and whatever factor we would pick off would get multiplied times that strain.

So this was, you know, kind of a key thing. It lasts for 25 years without a lot of issues, but, you know, after 25 years, that grouted pin is going to not be able to keep the crack together. So this is just like a factor that was calculated from a series of, a matrix of calculations to understand the effect of that on that strain.

CHAIR RICCARDELLA: It's really ineffective.

MR. JAMES: Yes.

CHAIR RICCARDELLA: Ten is bad.

MR. JAMES: And here's some of that really nonlinear stuff, you know, that you kind of brought up earlier. This is a factor on that strain based on a 20-percent increase in the AAR growth rate, so you might say, well, how come -- you would think a 20-percent increase would give you a bigger factor all the time, so there is, in effect -- this was kind of tracked down to the fact that, if you get to a certain state, you have enough cracks where it kind of relieves the stress, and so the expansion can continue easier. In fact, some dams that have AAR, they go in and they just saw a slit in the dam that relieves all the stress. But it increases the expansion rate, but it, you know, it takes the stress away that's causing the cracking.

So in this case, the cracking that was developing was at a point such that it kind of relieved the stress. If you had a lot of AAR growth rate early, you know, it didn't have much an effect later, until much later.

MEMBER SCHULTZ: But that's for a time, and then you have an increased slope.

MR. JAMES: Yes. Well, I guess I'm at my summary, if there are no questions.

DR. STACK: Just one more. You know, when had the expansion, so you have an expansion model, but you didn't try to get very sophisticated about the stress dependence, from what I sort of took on your comment that you did some sort of linear gradient of that thing rather than actually having a constitutive model that said the expansion was such and such that was a function of stress. You just sort of linearly did it.

MR. JAMES: Right. So, you know, the reaction rate is something, but the actual expansion rate is something else. And so rather than trying to have a model that would tell me that interaction, I just assumed the interaction until I got the structural history and structural state to --

DR. STACK: Okay. But you couldn't, like from that Telford book, there wasn't something in there that you could write a constitutive equation for expansion as a function of stress?

MR. JAMES: Well, you know, that could probably be done. But in a project like this, you know, that's a research effort probably ten years --

DR. STACK: It's a difference between somebody works in industry and somebody works in the lab.

MR. JAMES: They want us to give them an answer.

CHAIR RICCARDELLA: You know, I guess what I heard that struck me is always Corps of Engineers over and over and over again. I wonder are we coordinating our research with what's going on, you know, all this seemingly experience with this kind of stuff with the Corps of Engineers?

MR. LINDBERG: Pete, John Lindberg from EPRI. Yes, at EPRI, we've been also working with Department of Transportation, Federal Highways, the Corps of Engineers, you know, looking -- our particular program is what we consider a cross-sector program. So it's not just nuclear, but it's fossil plants, it's looking at all applications of concrete in the electric power industry.

So in order to really look at all these things, we've also been benchmarking what Federal

Highways is doing, Department of Transportation, Corps of Engineers. Recently, in May, we had a concrete symposium and invited the industry in and had a good interaction. In fact, Randy was there. But, you know, a good interaction with the industry and our counterparts in other industries.

MR. PHILIP: This is Jake Philip. Yes, we are coordinating. We have been talking with the Corps of Engineers, Josh Moser and Brian Green at the Corps of Engineers, because they're interested in ASR for their dams. We also touch base with and, in fact, went and visited the labs out here with the Federal Highway Department because they have issues of ASR. We've also attended some seminars with them, workshops with the Federal Highway Administration out here in Virginia where the people from the Corps had come in. There were some other people who were working on ASR. In fact, there's a dedicated workshop just on ASR and what different people are doing. So we are in contact and in touch with them.

CHAIR RICCARDELLA: Thank you. Okay. Moving on, right on schedule. So next we will have Jeremy Busby of Oak Ridge. Thank you, Randy.

MR. BUSBY: Good afternoon. Thank you for the opportunity to spend a little time presenting what we're doing under the LWRS program in the area of concrete, concrete degradation, and NDE.

I'm Jeremy Busby. I'm the Senior Staff Research Member at Oak Ridge National Laboratory. One of my primary jobs is I manage the materials activities under the LWRS program.

As way of an outline, I'm going to spend just a couple of minutes going over the LWRS program, particularly the materials research and the motivation. I'm going to do that because our perspective is perhaps a little different than the other speakers on the agenda, so I want to talk about that just for a little minute to give a little context of our motivation and mission.

I'll spend a little bit of time talking about the EMDA findings and potential knowledge gaps for civil structures and concrete under subsequent license renewal. Mita mentioned that this morning with the end results of that study, but I will give you a little more meat into how we got to that point. And then I'll spend the bulk of the time talking about what we're doing in the LWRS program to support understanding in concrete degradation for the 60 to

80-year period.

I have a few slides on alkali silica reactions. I'll spend the bulk of my time talking about irradiation effects. I know that was a topic this morning. I'll also describe some of what we're doing in non-destructive evaluation.

Okay. You've probably seen this slide. I know Rich Reister and Tom Rosseel presented to the ACRS, I believe in April, an overview of the LWRS program. So you've seen this slide, and I won't spend much time on it. But the DOE program has been around for five years now, and our mission is to enable existing nuclear power plants to safely provide clean and affordable electricity beyond the current license periods and to inform re-licensing decisions.

There are four major areas of the program: materials, aging, and degradation, that's my job; advanced instrumentation and control; risk-informed safety margin characterization; and reactor safety technology.

The really important part I want to leave you with on this slide is the URL on the bottom right. Many of the reports, programs, plans in considerably more detail than I'll present are available at inl.gov/lwrs. Or if you Google LWRS, it's usually one or two.

We've talked about it, and I know you know this, but to set the stage, materials aging and degradation is a key need for subsequent license renewal. When we talk about another 20 years of service, you're looking at more time at temperature, time under stress, time exposed to cool inert, time exposed to neutrons. And most materials performance issues do not get better with increased exposure to any of those things.

So we're really looking at increased susceptibility and severity of known forms of degradation but also exploring the potential for new mechanisms of degradation that we've not spent a lot of time on in the past. I think the radiation effects in concrete falls into that category, and that's where I'm going to spend the bulk of my time today.

So that's sort of the motivation for why we're doing materials research: to inform re-licensing decisions, both by the regulatory and by industry. Our other mission is to develop the scientific basis for understanding, for predicting long-term degradation. It's not just to provide a bunch of data. It's to provide the tools that allow us to predict and extrapolate beyond the pile of data by itself.

We also have some activity to detect and characterize aging in situ, and I'll describe some of that. Some of our activities also touch on the mitigation techniques. We do not have any activities in concrete in that area.

I won't spend a lot of time on this. It is a very diverse materials research effort. LWRS supports foreign national laboratories and, roughly, a dozen universities directly, covering a wide range of tasks spanning all of the materials in the reactor, everything from concrete, cable insulation, the RPV, core internals, piping. So it's a broad portfolio of research.

The concrete effort is led at Oak Ridge National Laboratory. It had a number of co-authors: Yann Le Pape, Igor Remec, Kevin Field, Tom Rosseel. Dan Naus participated extensively until he retired several years ago or last year. We also have an activity on non-destructive evaluation techniques led by Dwight Clayton, and I'll show you some of that work, as well.

I showed you a lot of different tasks. There were a lot of different materials degradation and tasks on that map. I think we can boil them down into what I'm going to call the five Ms of our work. Many of the tasks are providing measurements of degradation. That's high quality data, a rigor level that would pass muster at NRC in licensee decisions. They provide key information for mechanistic studies. We do have many of our tasks looking at mechanisms of degradation. Beyond just the simple data curve, what's the underlying mechanism? What's causing that behavior?

Both of those feed into modeling and simulation, and I'll show you some examples of those activities in concrete research. And those are valuable because they help produce the experimental burden and help interpolate and extrapolate to other conditions beyond the experimental cases.

Beyond that, while understanding and predicting failures are valuable, non-destructive monitoring and the capability to determine performance in situ is also very valuable, and we do have NDE work going on. And, lastly, mitigation strategies, and I mentioned that already.

I won't go through this entire chart, but the major deliverables for the materials pathway are intended to inform decisions now and into the future. And we have a number of activities with major milestones due in the next two years: when the lead plant is selected and announced, in 2018 when the first subsequent license renewal application is expected to be submitted, the approval period, and, ultimately, by 2029. These are long-range activities. And, again, you can find all of these in the more detailed materials program plan at inl.gov/lwrs website.

So let me talk about the EMDA and more specific concrete research. Now, as I mentioned, the materials pathway has a lot of different activities going on or a lot of diverse materials in a nuclear reactor. And so when we started looking at extended service, we had to have some sort of tool to prioritize research. We have a finite budget, so we have to prioritize and do this wisely.

It's a difficult issue. There's a complex and varied material and environment system, and so we went back to the PMDA, NUREG-6923, and used that as a basis for a tool to develop that systematic and quantitative approach to prioritizing research. We called it the expanded materials degradation assessment, and it was expanded both in time to include the 60 to 80-year period explicitly. But also beyond the PMDA scope of core internals and primary piping, we also looked at pressure vessel, concrete, and cable.

We had four panels, so 32 members across four panels and over 1100 years of materials research experience in reactor applications. And we did a systematic PIRT analysis to come up with identifying potential knowledge gaps. And we used what's in the PMDA called the rainbow chart where susceptibility or likelihood of the failure is plotted as a function of knowledge of that mode of degradation for different materials and environments.

The place you want to be is in the lower right where you have lots of knowledge, the dark green field, lots of knowledge for a mode of degradation that's not very likely. Conversely, the areas in the upper left of that chart, the pink region, are where we know that a material and degradation mode is very likely to occur, but we have very limited knowledge to predict its performance or identify mitigation strategies.

So we performed this PIRT analysis over about 9,000 different material/environment/degradation mode combinations, scored it, summarized it, wrote analysis and white papers, into this EMDA document, which spans five volumes, roughly 2500 pages of enjoyment. Volume two covers the core internals and piping, volume three the aging of reactor pressure vessels, volume four is concrete and civil structures, and volume five is cable and cable insulation.

Given the amount of knowledge, we also wrote a volume one, which is an executive summary of the other four volumes and condenses those findings into a handy reference at the beginning.

The final versions, all the PIRT tables and all the data were submitted for approval and final publication as a NUREG last December. It spent most of the summer winding its way through all the levels of approval and review. We've now turned those documents back in, all of the copyright has been completed, all of the publications. So we hope that's a NUREG in the coming weeks and month.

Specifically, I want to talk about the concrete panel. It included a group of very diverse background, considerable depth of experience. Herman Graves from the NRC, Abdul Sheikh participated from the NRC. We had Yann Le Pape and Dan Naus. At the time, Yann was at EDF. He is now at Oak Ridge working and leading the LWRS program. Joe Rashid from ANATECH was a key participant. Victor Saouma from the University of Colorado Boulder and Joe Wall from EPRI were also key participants.

The group used established PIRT processes with one exception that I'm going to mention in a moment. They developed a list of relevant structures and components and developed a hierarchical identification of degradation modes, cross-referenced which components would see which degradation modes, including containment, internal structures, steel components, spent fuel pool, transfer canal, cooling towers, and a whole variety of cross-cutting issues.

The one exception was the panel identified that we could rank knowledge and susceptibility for all of these modes of degradation and components. But in civil structures, it does not capture the structural significance. For instance, some modes of degradation to an outlying service building may not be structurally significant to the impact and operation of the reactor building. So they added a fourth dimension, if you will, and voted on another criteria called structural significance, and I'll show you the results of that in a minute, which help them also prioritize which were most meaningful to service of the reactor building.

There's a very large spreadsheet that reflected the assessments of all of the panelists to determine the mean standard deviation and constructed rainbow charts. And here's an example from the concrete and structures, and it's just an example, where they include a structural significance. So you see here again on the Y axis susceptibility as a function of knowledge on the X, the traditional colored regimes. But you'll also notice that the dots for different modes of degradation are color-coded and size-referenced to indicate the structural significance. The larger the dot, the more important it is. And so that helped identify and reduce the key knowledge gaps into something that was useful for ranking.

This is a recap of the slide Mita showed this morning.

MEMBER SKILLMAN: Wait a minute. Would

you go back to that previous slide?

MR. BUSBY: Yes.

MEMBER SKILLMAN: You also add confidence value. What is confidence value?

MR. BUSBY: A confidence value is each panelist also had an opportunity to rank their personal confidence in that score. So you can almost think of that as an uncertainty bar. So that is the average confidence, personal confidence, of their judgment of the susceptibility ranked from zero to three. So a 2.6 is very high.

MEMBER SKILLMAN: Thank you.

MR. BUSBY: They're very certain about that. That's almost an analog to the knowledge.

MEMBER BLEY: So you didn't let them spread their evaluation across cell boundaries, but they can use that uncertainty to --

MR. BUSBY: Correct. It's almost the fuzziness of the number, if you will. How confident the panel, on average, felt about it.

CHAIR RICCARDELLA: So what are the individual dots then, the individual --

MR. BUSBY: It's not shown here. This is an example of the actual plots. This might be ranked to ASR in a containment building, so they're all cross-reference. This was just an example.

CHAIR RICCARDELLA: Okay. But each dot --

MR. BUSBY: Each dot is representative --

CHAIR RICCARDELLA: -- represents a mechanism?

MR. BUSBY: -- of a material/mechanism/environment combination.

MEMBER BLEY: And that's the average across all the --

MR. BUSBY: That's correct.

MEMBER SKILLMAN: Aren't the dots identified by the upper right small print?

MR. BUSBY: They are. So 4B is external sulfate attack, 5 is acid attack, shrinkage --

CHAIR RICCARDELLA: Those are just the specific ones that you included in this example.

MR. BUSBY: So these are all mapped together. It's a two or three hundred-page report with also white paper background assessments of specific knowledge gaps for each of these.

MEMBER SCHULTZ: So the numbers, how confident are you of the placement of the --

MR. BUSBY: Correct.

MEMBER SCHULTZ: -- mark?

MR. BUSBY: Right. If I were to rank something zero to three, and I said two, I also had the opportunity to say I'm confident of that or, I hate to use the phrase I'm guessing, but, you know, a zero was I'm not very confident at all but I have to put in something.

MEMBER BLEY: But if you have a two and a confidence value of three, you don't know where it sits. It's somewhere between --

MR. BUSBY: No, a high confidence means you're -- it's good.

MEMBER BLEY: So it's not an uncertainty --

MR. BUSBY: Correct.

MEMBER BLEY: So if you have a one -- could you do a zero?

MR. BUSBY: No, you could not do a zero. It's one, two, or three.

MEMBER BLEY: So one would be mean you're pretty, you don't know.

MR. BUSBY: Right.

MEMBER SKILLMAN: Well, that shows that radiation is one, whether it's not a whole lot of knowledge --

MR. BUSBY: Exactly.

MEMBER SKILLMAN: -- there's a medium amount of susceptibility, and the team is saying we're not really sure.

MR. BUSBY: And I have about 25 slides. That's exactly why we dove into that area.

MEMBER SKILLMAN: Bingo.

MR. BUSBY: You've hit it exactly.

MEMBER SKILLMAN: Thank you.

MR. BUSBY: Okay. The panel identified three high priority potential knowledge gaps for subsequent operating periods in the final EMDA relevant to containment shield, bio shield, RPV supports and buildings. And Mita presented this list. I won't go through it in any great detail but radiation, alkali aggregate or silica reactions, and creep fracture interactions.

They also identified issues with available remediation and mitigation technologies, such as liner corrosion, corrosion of the post-tensioned system. Lower priority but still were mentioned for consideration: boric acid attack in the spent fuel handling building and cooling towers corrosion and alkali aggregate silica reaction. I don't think there are any surprises there.

Now, we used that as the basis to prioritize what we're doing in the sustainability program with a primary focus on radiation and some activities on ASR.

MEMBER BLEY: Am I overstating what your reports say when I look at this and see the shield, the bio shield in the containment all show radiation as a big deal?

MR. BUSBY: I think that might, I think it's really only the bio shield --

MEMBER BLEY: I would have thought so.

MR. BUSBY: These are lumped together for convenience.

MEMBER BLEY: Okay.

CHAIR RICCARDELLA: I was going to say I didn't think you'd get much radiation on the . . .

MR. BUSBY: Before I dive into the technical bits, I do want to mention that the research is very collaborative to address this. It's been underway for several years. We have a very tight teaming with EPRI and the industry projects, frequent quarterly meetings to discuss projects, and I'll show the joint roadmaps in just a minute. NRC research, Mita, has been a growing partner and has participated very heavily the last year or so, and it's been a good addition.

I'll also mention some international efforts. I know Mita mentioned the ICIC collaborative group this morning. I'll talk about that a little bit, as well.

The collaborative efforts have been strong, and I think we've done a good job of leveraging the resources we have and not overlapping, or complimentary and not competitive.

To illustrate that a little bit, I'll show you a series of roadmaps, and I do not intend to get into the details. We put these together jointly with EPRI to sort of show who's doing what. And there are a lot of different boxes. They're color-coded to who's doing them, so green are the LWRS DOE actions. The time line runs from top to bottom prior to existing knowledge and then longer-term activities towards the bottom. Left to right is from fundamental to structural significance, so going from being basic mechanistic microstructural features all the way up to large structures.

In this case, the roadmap is showing you the ongoing research that's supporting irradiation effects. Just to give you some highlights, and I'll show you more technical slides, the DOE program is looking to define a unified irradiation parameter, the so-called DPA of concrete. And I'll show you the outcome of that in just a minute. Looking at swelling damage, modeling of radiation effects, as well as irradiation of prototypical concrete in our test reactor and post-irradiation examination.

We have similar roadmaps for alkali silica. And as you heard this morning, there's a lot of ongoing activity. We're updating this one frequently, and it's hard to keep up with all of the changes and new projects. But I think that's a good sign that there's opportunities for collaboration and coordination.

And, finally, creep fracture interaction. There is a very large database from the Department of Transportation that's housed at the University of Northwestern, which is the key basis for what we're hoping to do in this area is translate that database and understanding into nuclear structures.

So let me talk about the LWRS research in particular. Concrete structures are of interest for long-term operation. We've heard that this morning, and it's a key area of emphasis under LWRS. In fact, this is, roughly, 20 to 25 percent of my materials research budget.

We've looked at a number of potential environmental effects: aging, elevated temperatures, irradiation, and migration of hostile species. I do not have a dedicated slide, but we have developed a nuclear concrete materials database. NCMDB has been completed. It provides a literature survey of all the data that's out there, as well as operational experience. You can get to it via the LWRS website and go search and hunt through all of the data that's out there, the conditions on who's done what.

More recently, the formation of a concrete irradiation damage working group has been a highlight to help develop protocols related to removal and testing irradiated cores and potential sources of irradiated concrete cores, and we talked about that this morning in relation to Zorita, and I'll show you two other options that are --

CHAIR RICCARDELLA: So are you involved in the Zorita program?

MR. BUSBY: I'm aware of it. We have been engaged through EPRI and through the NRC in a number of different potential opportunities. As Mita mentioned this morning, the DOE program is managing the Zion harvesting, and we're sort of keeping in contact. The idea is is that too many parties, all at the same decommissioning site, gets a little intractable from a utility. So in both cases, one is the, I'll say the word front door in coordinating with the others.

CHAIR RICCARDELLA: Okay.

MR. BUSBY: So I'm certainly aware of the internal components and the cable that's been harvested from Zorita.

CHAIR RICCARDELLA: Zion is yours but not Zorita?

MR. BUSBY: Correct. We're all aware of each other's activities, and we do talk about that frequently. And, again, just to launch into the specific research, it has been guided and prioritized by the EMDA fundings.

So I'm going to talk about ASR for just a minute. It's been hit pretty heavy this morning. We have a number of activities, including investigating the residual shear capacity of massive structures using numerical simulation, and I want to show you some preliminary results that were less than a month old.

So we've looked at the design and fabrication of a large test ASR mockup similar to what you heard from NIST this morning which comes with a confinement system and allows for the development of monitoring and a study of damage evolution. We're also looking at investigating the possibility of a coupling or synergistic mechanism with irradiation-induced expansion. As you heard, ASR can lead to expansion and swelling of the aggregate. Irradiation can, too, and there's the potential, when in a specific regime within the structure, those may be synergistic effects. And I'll touch on that in just a little bit.

CHAIR RICCARDELLA: Don't you need the moisture for ASR? Are you likely to have moisture where you have irradiation?

MR. BUSBY: That's a good question. There's gamma radiation. You can get a radiolysis that breaks down. We are looking into that, but the potential is there.

I mentioned that there's a conceptual design for an alkali silica reactor test system. This has been completed. For scale, this a 3 meter by 3 meter by 3 meter cube. It's a little larger than the 4 foot by 5 foot by 14 foot beam that was described this morning. This is a cube which is constrained, I'm sorry, compressed in two directions, allowing ASR and swelling in the third dimension, so more representative of a massive bio shield type structure. It will be fitted with an extensometer, fiber optics, and allows in-plane restraining force in two different directions.

Now, I say conceptual. This is something that's on our plate for the future. We need a little more funding. This would go into the University of Tennessee in their brand new civil engineering building and large structure capability.

More recently, Victor Saouma from the University of Colorado Boulder has been working under the LWRS program to provide simulation of structure restraining effects on ASR swelling. And his models perform the same sort of restraint, so it's restrained in two directions. You see that in the diagram in the upper left.

He's now able to predict swelling and resulting strain in all directions. And so that's what you see on the plots on the right. Stress and strain on the two upper plots as a function of time, while strain resulting from alkali reactions in both the vertical direction and volumetric strain are shown in the bottom two plots. You can also put that in a 3D model and you can see a square cube which looks like a little bit of a marshmallow on the top. That's the ASR swelling in the non-restrained or confined direction.

I do want to stress this is preliminary. This data is less than a few weeks old. We've not fully analyzed it, and we'll continue to benchmark and refine this model.

DR. STACK: Is it data, or it's --

MR. BUSBY: This is a model prediction. I want to stress this is new.

DR. STACK: It says data but it . . .

MR. BUSBY: I apologize. No, this is a model, and we need to validate it with data.

CHAIR RICCARDELLA: But it will be compared to the tests that you described on the -- I mean, it's a model of --

MR. BUSBY: Well, as well as other programs. You heard from Vanderbilt University this morning and from NIST. We've talked at the RILEM OECD meeting in June that I'll describe in just a minute about coordinating and sharing data, knowledge, and experiences.

CHAIR RICCARDELLA: But this model looks like it's specifically of the test that you described in the previous --

MR. BUSBY: Yes, right. And that was the first starting point. What you could do -- and that's the next slide. Thank you for the segue. You could also do beams and put them under different loading conditions. And so in this case, it's a large rectangular cross-section beam sort of in a three-point bend type configuration. So the model is flexible enough to different test configurations.

CHAIR RICCARDELLA: But from what NIST was doing, they were doing ASR materials and then benchmarking non-ASR. Are you doing non-ASR susceptible materials in these tests?

MR. BUSBY: That is, that is the intent. These models, this is fairly new stuff, so this is only on an ASR type condition. But, yes, you could go back in and put in a different composition for a non-ASR susceptible composition and see the difference. I think the real trick here is the finite element tool, the nonlinear dynamics.

CHAIR RICCARDELLA: Dynamics? This is dynamic loading?

MR. BUSBY: Not in this case but some of the mechanics are nonlinear, especially where you get towards failure.

DR. STACK: Life is always a constitutive equation.

MEMBER SCHULTZ: For some.

MR. BUSBY: I mentioned it just a minute ago, and I know you heard this morning, the NRC is participating in the OECD groups and there's also RILEM, which is, again, a French acronym that I won't pretend to be able to pronounce. The two committees have formed a joint committee with a focus on ASR. The kickoff meeting was here in Washington D.C. at the EPRI offices at the end of June. Neb Orbovic, the Canadian regulator, the lead. Victor Saouma, Yann Le Pape, were organizers. We had 37 participants from a host of countries and institutions, a much larger interest group of about 60 people. So that was a good step towards coordinating and collaborating and sharing resources on this important mode of degradation.

Let me shift focus to the bulk of the presentation and radiation use effects. I know we talked about it extensively this morning. The current understanding, at least in recent years, has been largely based on the Hilsdorf curve, and I know you talked about it a lot, dated back to 1978, with an onset of reduction of strength of about one times ten to the 19th per centimeter squared. And, again, let's plot it here as compressive strength as a function of neutron fluence.

But I want to highlight there's about 27 data points on there. And if you really dig into what those data points are, there's a lot of different neutron fluences used, energy cutoffs greater than 0.1 MeV, greater than 1 MeV, thermal neutrons, gammas not reported. There are a variety of different aggregates and compositions. Some of these are using amorphous glass aggregate, metal slag aggregates, a variety of irradiation temperatures all the way up to 200 degrees C.

And so when we look at that data very

carefully, we have to question the applicability to nuclear power plant applications. And that's why when you saw on the EMDA you pointed out the low confidence factor. That is the exact reason. When you start looking at the data that's available, it's not clear that it's relevant to water reactor conditions and life extension.

MEMBER BLEY: Jeremy, on that top picture, the one we saw earlier, those two little marks outside beyond two. Are those actual data points out there?

MR. BUSBY: Yes, they are.

MEMBER BLEY: Okay. So that's what --

MR. BUSBY: But the aggregate and irradiation temperature are different.

MEMBER BLEY: Than the others.

MR. BUSBY: Yes. And so the question is is that need real or not, and is it fair to include those two when they're not relevant. So we spent a lot of time thinking about that, and I'll spend some time going through that.

CHAIR RICCARDELLA: Now, this morning the benchmark number I heard was 10 to the 20th, that at 60 years the plants aren't past 10 to the 20th. You seem to be zeroing on 10 to the 19th.

MR. BUSBY: I'm going to come back to that in just a minute.

MEMBER SKILLMAN: I think Mita corrected the comment about 10 to the 20. She said it's really 10 to the 19th. I believe she corrected that.

MEMBER SCHULTZ: That range was pulled back.

MR. BUSBY: We spent a fair bit of time over the last 18 months developing a strategy for investigating irradiation effects in concrete. The first step was to characterize the radiation fields, determine bounding values for fluence and gamma ray dose in the biological shield at 80 years of operation. And we've done that for a variety of different designs and configurations, and it turns out that's actually very important.

We also want to obtain more data on the effects of neutron and gamma radiation, as well as extended time at temperature. You want to be able to separate irradiation and thermal aging effects, and to do that we're going to irradiate mineral analogs of aggregates to evaluate swelling, prototypical concrete to levels equal to or greater to expected and extended service, go beyond the so-called mean, and harvest and test irradiated concrete from decommissioned plants, U.S. and international included. Also, in doing that, we'll develop a more robust fundamental understanding of the effects of radiation, and we'll do that via a collaborative research effort.

So the first step is examining what really are the limits to fluence in the radiation field? Well, it seems fairly logical. The biological field, that's what it's there for, will receive the highest neutron fluence. But it's also a safety-related structure and provides essential radiation protection. So if you lose integrity, you lose a lot of key features. The structure typically consists of Type II portland cement, fine aggregates like sand, water, admixtures, and normal-weight or heavy-weight course aggregates.

Typically, it's bounded by a design at 65 degrees C with peak values not existing 93 degrees C, which is why comparing irradiation effects on the Hilsdorf curve at 200 CC may not be relevant, and we really needed to dig into that.

We can also infer flux and fluences in energy spectrums in the biological shield from RPD dosimetry reports, and that's exactly what we've done.

This is some work from Igor Remec where he's taken actual dosimetry and models from vendors from the RPV and modeled it through the cavity and into the biological shield. And so what you see is neutron flux is a function of distance from the reactor pressure vessel inner diameter, some centimeters, for a variety of different energy groups, all the way from thermal up through 1 MeV neutrons.

Igor has also calculated gamma fluxes. I've not shown them here for simplicity. But that's an important area that we'll be evaluating in the coming year.

Now, you can take that for a variety of different geometries. We're really only focused on PWRs because of the higher fluence. And what's plotted here is neutron fluence at 80 years of service for two-loop and three-loop PWRs, two-loop is the cluster on the left and three-loop the cluster on the right, for 40, 60, 80 years using different assumptions about the energy that's really causing the damage, from thermal 0.1 MeV, 1 MeV.

I only show this to illustrate the difference you can get between small PWRs and big PWRs, two loop and three loop.

DR. STACK: It even gets more dramatic when you go to four loop.

MR. BUSBY: Exactly. And I think I have that in just a minute. So this is an important point. What energy do you use when calculating damage? I know the metals community has gone through this with internals and pressure vessels. This is the time for the concrete community to think about this, and we've done that.

CHAIR RICCARDELLA: And is this at the inside surface of the shield wall?

MR. BUSBY: Yes, that's correct.

CHAIR RICCARDELLA: So there will be some attenuation as you --

MR. BUSBY: Correct.

CHAIR RICCARDELLA: -- go into the concrete itself?

MR. BUSBY: Exactly, exactly. And we see that here.

CHAIR RICCARDELLA: And so what energy levels are we concerned with?

MR. BUSBY: If you bear with me, that's the very next slide.

CHAIR RICCARDELLA: All right.

MR. BUSBY: I do want to point out that there are some guidelines in the reg guides for different societies and different countries. ASME, Japan, ANS, and British all have their different guidelines for what's an acceptable upper bound. And it really depends on what energy you use, what assumptions, and what the plant design is.

So we really wanted to look at this in a little more detail and get a little more resolution on this question. So Igor spent the last nine months looking at a unified parameter for irradiation-induced degradation. And what's plotted here is DPA per second as a function of neutron energy. And, in effect, if you now integrate over energy, how much damage you get, you can get some valuable information out of this.

There are three different aggregates: calcium-based, silica dioxide, and silicon. And if you integrate using only 1 MeV or greater, it's only 20 to 25 percent of the damage. And in reality, the cutoff energy should be greater than 0.1 MeV, which accounts for 90 to 95 percent of the damage.

And so what you'll see, as we've now adopted this as our standard, with the rest of my presentation and I know EPRI's presentation, when we talk about radiation fluence, everything has been normalized to greater than 0.1 MeV. So this is a really important thing as it helps us put our hands around what's a reference value that we can all talk and we're all comparing apples to apples and oranges to oranges.

CHAIR RICCARDELLA: But you're saying a DPA is a direct measure of damage or --

MR. BUSBY: It's actually a calculated displacement parameter. DPA stands for, you know, each atom on the crystal lattice has been knocked off its site once at 1 DPA.

CHAIR RICCARDELLA: But to correlate it with damage, you'd really have to be doing some compression tests or something.

MR. BUSBY: Sure, sure. You can correlate DPA to fluence, and we do need to correlate fluence to DPA to damage. And that's sort of a next step. But we all have to be talking about the same fluence on the same terms, and this was an important step.

These results are preliminary, meaning only a couple of months old, but they should be published in the open literature by the end of the fall, certainly in the next international committee on irradiation effects.

DR. STACK: But, I mean, it's really not surprising. I mean --

MR. BUSBY: No, but we needed to go through it and do it so we're all talking about the same thing.

CHAIR RICCARDELLA: Why do you say it's not surprising?

DR. STACK: Well, because we've known for a long time that most of the DPAs in an LWR spectrum are greater than 0.1 MeV.

CHAIR RICCARDELLA: But in reactor, we still only worry about greater than 1 MeV, right?

DR. STACK: No, no, no, no, no, only in fast breeders.

MR. BUSBY: Now, this is all calculation. And if I go back to the Hilsdorf curve, there were a bunch of different energies listed. So there's apples and oranges and temperatures, fluxes, fluences, aggregates.

We also wanted to spend some time looking at is there more irradiation data out there beyond the open literature? And it turns out there is. If you know where to look in various government and national lab reports and internal documents, there's, roughly, 300 more data points that haven't been explored and were not included in the Hilsdorf curve. We had a young researcher, Kevin Field, who spent about nine months, and I'm going to use the phrase "dumpster diving," looking for those old reports, digging them out, collating the data, putting them in a spreadsheet with fluence, energy cutoff, temperature, type of aggregate, type of cement, specimen geometries and other properties. It's now in one database, and when you plot it up you now have, instead of the Hilsdorf curve with 27 data points, we're calling the field curve with 300 data points. The upper left --

DR. STACK: So it's still, like, one set that's really relevant.

MR. BUSBY: I'll show you that in just a minute. I'll show you that in just a minute. Our compressive stress is plotted in the upper left with normalized, so this is relative to the starting condition as a function of fluence, there's 300 data points, and we've now got enough data that we can plot confidence bans. And we still see a need, a drop-off in performance around 5 times 10 to the 19.

Don't worry about the A, B, C, and D lines. Those were only used for modeling and calculating average values in different regimes.

CHAIR RICCARDELLA: But the Hilsdorf curve had apples and oranges. Certainly, this is --

MR. BUSBY: It does, but we now have enough data -- I'm going to show you that in just a minute. We have enough data and resolution on what those apples and oranges are, and there's enough data that we have the ability to throw out the apples from the oranges and still have enough data to get relative terms.

The thing I also want to point out is in the lower right where dimensional change is plotted as a function of neutron fluence. It's swelling of the aggregate, some shrinkage of the cement past that could lead to microcracking and loss of strength, and so that will be the focus of our efforts going forward.

You raised a very good point. There's lots of apples and oranges. And when you show it in black and white, that's certainly true. But we have enough data from these reports that we can sort it by aggregate type, we can sort it by cut-off energy. And when you look at it this way, it actually goes back and supports the 0.1 MeV cutoff energy. And so it's not just 300 data points, there's enough resolution on what those data points are and enough of them that we can throw out and get to the apples and apples and still feel comfortable about a curve.

Now, I mentioned swelling. We call it radiation-induced volumetric expansion is what the civil engineers have termed it. It suggests that a significant loss of the concrete mechanical properties, the compressive strength, the tensile strength in the elastic properties is due to radiation-induced swelling in the aggregates. This is primarily due to amorphization of the crystal structure in the aggregate, which leads to internal strains between the cement paste and aggregate and can cause microcracking. This onset is expected to occur to about 1 times 10 to the 19th for e greater than 0.1 MeV based on the curve for alpha quartz, which is the most common mineral used in nuclear power plants.

And so based on calculations for peak neutron fluence in the biological shield, we're also doing a risk assessment where we're requiring detailed knowledge of the mix design, operating environment, and neutron environment. What's that saying is each plant may be unique with its own geometry, its own aggregate which is local to local geography, mix history. And so it becomes a more difficult thing. It's not a universal.

So where do you start with that, given all those different parameters? We've decided to start from a very systematic point of view and evaluate swelling on the five most common minerals, which encompass about 85 percent of the plants as a function of dose and temperature, starting with quartz, calcite, dolomite, muscovite, and a pure hcp for reference, using seven fluences up to 40 times 10 to the 19th which span from before swelling onset all the way through saturation, two temperatures, 50 degrees C and 200 degrees C representing both expected bio shield temperatures and helping us bridge to past literature studies and getting a range of effects.

Following irradiation, we'll determine dimensional weight, hardness, mechanical properties, and stress/strain, elastic modulus, as well as microstructural changes. If we find that swelling, even up past that threshold, is not significant, it gives us a good comfort that it may not be as significant in concrete mixes, as well. That would be the next phase where we evaluate swelling of aggregates and concrete as a function of dose and temperature using the same conditions.

I'm pleased to report this is no longer a paper study. The first six capsules when into the high flux isotope reactor or bridge this summer, so we had irradiation of hardened cement paste. And single crystals are the most common aggregate minerals. I already mentioned silica dioxide or quartz, calcite, dolomite. We tried to put muscovite in, but it's very difficult to cut, a specific thin specimen that went into the capsules and we ended up with shards and bits, so we're going to have to come back to the muscovite.

We have two different irradiation temperature capsules, two different irradiation temperatures in the capsules with a seal at 200 C, again, to relate to past date, and a perforator which gave us the lowest temperature possible in a test reactor.

Three neutron fluences, 0.5, 4, and 20 times 10 to the 19th, that came out of the reactor at the end of August were now in the pool. And PIE will start in October. The first set of PIE should be completed by this spring, allowing the second set of capsules to go in in the August of next year time frame --

CHAIR RICCARDELLA: PIE?

MR. BUSBY: Post-irradiation examination. Sorry. We've also done some additional studies. This was Dr. Field work where he was using ion beams. He had a fellowship at Oak Ridge with some internal funding to explore some of these problems and see how to apply advanced microscopy techniques to irradiated concrete or aggregates. And this is a tricky problem, especially if you're looking at cement or cement aggregate interfaces. If you remember this one this morning cement has a lot of water in it which does not do well in an electron microscope environment. So we had to develop a number of techniques to be able to perform these mechanistic studies.

Kevin also wanted to look at ion beam irradiation as a way to accelerate and understand amorphization in the aggregates. And so he used quartz and an argon beam to induce amorphization in a thin layer. So that's what's shown in the middle figure on the right where you can see in a TEM picture a nice piece of quartz amorphized over 500 nanometers, and now you can start calculating the strains that would be induced with cement based on that performance.

Most importantly for the LWRS in this room is that it helped establish and refine how we're going to do some of these techniques on the aggregates that just came out of the reactor. So this was doing our homework before the stuff came out. Start on something simple.

MEMBER SKILLMAN: Jeremy, I've been itching to ask this question since we started this morning, and I'm not sure if this is a good time or a bad time. So just let me ask the question and get it out of my system. We got into some situations where we had very high radiation levels, very high deposition rates, very high specific activities, and we were disassociating water and, certainly for the organic resins, we were taking styrene beams and turning them into 90 weight oil and making methane, ethane, propane, and butane. So the local radiation levels were so great, we were really decomposing material.

So much of the discussion today about ASR revolves around the paste, but it's clear, even in old concrete, there is water as part of that matrix. What examination or what consideration has been given to concrete in a high-flux environment where there is actually decompensation of the water, generation of hydrogen and oxygen, the effect that either of those will have on the pH and, hence, the rate of reaction of the ASR? That's my question.

MR. BUSBY: That's a very good question. I'm not sure I can answer it directly. I would, I don't personally know all the literature on that effect. We have considered and talked about it, I mentioned on the plot of the map neutron flux as a function of depth that we did not show on that plot to gamma, and we have looked at the gamma. The gamma is important because it is breaking down the water molecules, which dissociates the cement from the aggregate and that key binding agent.

We have explored looking at highly-irradiated concrete with very high fluxes, or at least the potential. We talked this morning about harvesting irradiated concrete from nuclear power plants.

We've also explored harvesting concrete

from other places that would see much higher fluxes and damage levels. For instance, beam ports installation neutron sources or any neutron scattering line is going to have cement or concrete shield plugs. We've looked at obtaining one or two of those, taking core specimens from both the irradiated side and the unirradiated side of that shield. We're still working on getting access to one of those. The high-end user facilities are a little nervous about letting us cut holes in their shield plugs.

We are hoping that the neutron source at Oak Ridge National Laboratory is planning to change out its shield plugs in the next six months to nine months. And once they change that out, we want to cut specimens from both sites to look at the exact effect you just mentioned. But I'm not personally knowledgeable of any data that's looked at exactly what you're suggesting, but we've thought about it.

MEMBER SKILLMAN: Thank you. Thanks.

MR. BUSBY: I hope I answered that. I do want to mention the irradiation effects we're talking about, you mentioned there is attenuation. This is a massive structure. It's designed to shield the vast majority of all irradiation, so there is attenuation.

How deep are the irradiation effects and what is the structural significance? If it's only a surface effect of an inch, a massive structure like the biological shield, it's probably not structurally significant and we've done our due diligence and can move on to other more pressing issues.

We have been looking at the structural impact from irradiation effects. As a first cut, we've been doing a first principles and evaluation of structural integrity as a result of degraded properties. If you remember back to the Field's curve, the A, B, C and D, are taking average values and best-fit curves to that data set, incorporating it, fluence and irradiation-induced swelling to obtain radial swelling profiles and then doing finite element and finite difference type evaluations to evaluate the depth and size of the potentially damaged zone and the internal stresses and strains.

This is an example. I'm going to call it very preliminary and early but an example of what we're trying to do. In this case, he used the Elleuch data from 1971. This is one of the more relevant points from the Hilsdorf curve which used a serpentine aggregate. And you can see what's plotted in the black line is the radial stress is a function of depth following irradiation, so not much change in the radial stress through the thickness of the structure.

However, if you look in the vertical or hoop stress direction, the red and the blue lines, depending on where you are, you can see a fairly significant compressive or tension stress applied or, I'm sorry, imposed due to swelling of the aggregate but only over a depth of 0.1 meters, 10 centimeters deep, which leads us to believe that even if the material and aggregate experiences radical swelling, it may not be structurally significant to the broader and larger structure.

DR. STACK: Well, that's a fast neutron to radiation. I mean, that's 1 MeV, so this should be a conservative --

MR. BUSBY: We think so. We think so. But, again, we don't want to infer on an inference. We need to do some of the background work to back this up.

Now, it's also a little more complicated than that because deconvoluting temperature shrinkage and irradiation effects is not simple. Many of these effects are interrelated and synergistic with each other.

Just an example, to go back to that same Elleuch experiment, you also have to consider, going back to the point earlier, the hydration level where neutron fluence is a function of time on the left, temperature in the center, and relative humidity is on the right. And so you have to be able to have the tools to decouple these effects and understand what's due to irradiation and what's due to dehydration. We don't have those today, but we are looking to couple some of these irradiation ASR type mechanisms together, include creep, shrinkage, and cracking, so we can understand tensile or compressive stress and resulting dimensional change for both irradiation and ASR.

So this is very preliminary. We have a new post-doc that's starting to work and develop some of these models and ideas. Ultimately, we'd like to couple these together into a larger-scale finite element tool, such as the Moose-Bison framework at Idaho which can incorporate some of these different degradation modes and also help us understand structural impacts under the different scenarios in degraded concrete. But that will be a topic for a year or two down the road.

In terms of preliminary conclusions, and I just showed you on that plot the loss of tensile and compressive strength under irradiation, may have limited impact on structural integrity of the larger, more massive structure. There are internal stresses which are important and a result of irradiation-induced volumetric expansion or spalling of the aggregate, and those internal stresses may lead to internal cracking and microcracking, and that needs to be investigated in more detail.

We do have ongoing tests at HFIR and resulting post-irradiation examination will follow this next few months. We'll also continue to work on refined structural simulation, including creep and irradiation damage.

I'm going to close on this topic with just a couple of slides. This isn't just our work. We're working very closely with EPRI, particularly on the structural significance and joint harvesting. We are evaluating irradiated concrete from retired plants, the Zion, and I'll throw a new one on the table: the Barseback reactor. We have talked about Zion. NRC and EPRI have the lead there.

One challenge, and I know the discussion came up this morning about aggregate, it is a higher-density concrete in Zion than most of the U.S. fleet. And so that, we need to weigh that factor, considering how relevant it is to U.S. operating experience.

We are in ongoing discussions with both Barseback and Energy Solutions to obtain concrete cores. At Zion, Tom Rosseel, Yann Le Pape, Kevin Fields spent two days last December and marked some 90 different locations for a core sampling. Those included not only areas in the biological shield but also in other structures which higher thermal experience but no irradiation. Freeze-thaw, inside-outside, so that we can piece together not just the irradiation effects but separate out thermal effects and what might be due to curing or dehydration or other processes.

MEMBER BLEY: And it was essentially the same concrete?

MR. BUSBY: It was essentially the same. We also were able to keep most of the records. We found those before they were thrown out, so we have some of that data, as well. Now, Zion and Zion

Solutions is a little complicated. They've changed management four or five times, so we keep having to go back in and say, you know, we're here to help, we're not going to mess up your schedule or your funding, and so the timing is very sensitive. We have to be ready to go to drill holes. There are liability rules. We can't go in, and they have to drill them for us. So it's a real dance to get what we need out of that. But we are talking about it.

The other opportunity is by using one of those plants and field-harvested material, it's also an opportunity to establish and benchmark NDE techniques. We've got real service material --

CHAIR RICCARDELLA: NDE?

MR. BUSBY: Yes, non-destructive evaluation. If we develop a new sensor or technique that may be able to identify or measure swelling in irradiated concrete, it would sure be nice to do that in a real relevant structure, rather than, you know, small specimens on a lab bench. So we're trying to coordinate some of that, as well.

We intend to make a decision to proceed with harvesting cores, with Zion in particular, by the end of this calendar year. There's been a lot of traffic on that just this morning.

CHAIR RICCARDELLA: Well, if it's trying to swell and it's restrained, then it won't swell. It just develops stress, right?

MR. BUSBY: You want to take the measurements before you cut the cores.

CHAIR RICCARDELLA: But it's stress. You can't really measure stress.

MR. BUSBY: I'm sorry?

CHAIR RICCARDELLA: If it's completely constrained and it tried to swell, there will be no strain, right? All there will be is stress. You have to almost do something like a hole drilling and look at how it relaxes or --

MR. BUSBY: And there are techniques for that. We do it in -- sorry -- metal welds, the deep bore hole drilling technique.

DR. STACK: But, again, compared to a two-loop PWR, this is going to be pretty low fluence.

MR. BUSBY: Absolutely, yes. But it's really not that expensive to have them drill --

DR. STACK: No. I mean, it becomes a useful benchmark for your prototype.

CHAIR RICCARDELLA: Zion is low fluence?

MR. BUSBY: Relative to 80 years, yes.

DR. STACK: Relative to 80 years, a two-loop PWR.

MEMBER BALLINGER: There's a certain diameter that you can't go below because of the aggregate size.

MR. BUSBY: The last slide I'll mention on irradiation effects, and I know Mita mentioned it this morning, the International Committee on Irradiated Concrete. I missed a "C" in there. My apologies. There's an exchange framework meeting that's coming up in Helsinki in just a couple of weeks. This will be the second meeting. The first meeting was held in March in Madrid.

At this point, the key -- they'll continue to talk about joint research, share results, progress, plans. It was well intended and lots of interest the first time around. Tom told me this morning that there are eight different countries, 28 participants, and 15 institutions that are already signed up for the meeting in a few weeks, including the DOE program, the EPRI program, and the NRC program. So it's been a very positive interaction.

I know, Ron, you asked this morning about the Japanese. The Japanese do have a dedicated experiment that they paid for, so it's proprietary. But that same group of Japanese is participating and have been fairly open to share some of that data. Halden is participating, and the Spanish are, as well. It's a good group.

The last topic I'll mention, and I think I'm doing okay on time, is non-destructive evaluation. Mita talked about this a little bit this morning, as well. Within the LWRS program, NDE sensor technology is coupled under the same management as materials. And, in fact, we've been trying to do that in the same ZIP code, the idea being that the sensor and electronics folks are co-located with the materials. They go have lunch together, meet frequently, share materials degradation needs and sensor capabilities. And I think that's worked so far.

The LWRS program developed NDE roadmaps in fiscal year 2012, August 2012, on concrete cables, fatigue damage, and reactor pressure vessel steel technologies. Now, the roadmaps were based on workshops that were held incorporating both industry, academia, and materials research experts talked about key needs, key opportunities. Those are available on the LWRS web site.

Under the DOE program, several concrete NDE techniques are being explored. Oak Ridge, the University of Minnesota, and Engineering and Software Consultants have tested ultrasonic non-destructive techniques for volumetric imaging on thick reenforced concrete sections. There were seven different subtopics or, excuse me, ultrasonic techniques that were tested by the University of Florida at the Florida DOT. So we talked about getting the Department of Transportation Corps of Engineers. They've got a lot of experience in validated specimens for testing.

This was done in Gainesville. They looked at a rebar detection block and void and flaw detection block. And all techniques performed well on two, but each method had some limitations and shortcomings. This report came out last year when the focus of the FY 14 research has been taking some of those techniques, the most promising techniques, to the next step forward.

In particular, our NDE efforts have been focused on signal processing, rather than new sensor development, taking a validated sensor and interpreting the signals in different ways. In particular, we've got two advanced signal processing techniques, and I'll mention the modified total focusing method which has been applied to the simple 12-inch cube with a single valve for rebar, as well as the rebar void flaw techniques. We're also looking at synthetic aperture focusing technique.

DR. STACK: What are you actually looking for?

MR. BUSBY: I'll show you a picture in just a minute. I'll show you a picture in just a minute.

This technique is actually based on medical ultrasonic techniques where you really don't want ghost images and noise. You want to understand what's where with a fair amount of resolution and confidence.

So by taking some of the techniques that they use in that field and applying them to concrete imaging, we're able to take those same techniques and use them just a little different to get a larger amplitude and more reflected energy, which really is better signal than noise ratio. You can also narrow the frequency down that you're looking at, again improving the signal-to-noise ratio.

So the delay in your answer to your question, Bill, what's shown in this slide are two pictures of the same test block. This is a calibrated NDE concrete block with rebar running down the middle perpendicularly with the screen. The top is a typical ultrasonic technique. If you'll focus on the upper left white box, you see what looks like eyes coming out at you. That's not where the rebar is. There's one piece of rebar in that box, not two bright signals, and that's offset from where those signals are. That's one of the artifacts of ultrasonic where you get ghost images and shifts in spatial position.

By using these two signal processing techniques on the exact same specimen with the exact same sensor, you get what's in the bottom right. Instead of, again on the left box, two high-contrasted ridges which would indicate two pieces of rebar, you're hitting the more accurate location and no ghost images using the signal processing technique.

CHAIR RICCARDELLA: And what's the big red band underneath those boxes?

MR. BUSBY: That big red band is actually a surface reflection artifact, and there's really nothing there, although you have to know that that's really not there. It's better using the modified and improved analysis techniques. It's not gone yet, but it's certainly been reduced. That is an artifact.

MEMBER BLEY: In the bottom one, the two right-hand boxes that are sketched on there, are those also rebar pieces --

MR. BUSBY: Yes.

MEMBER BLEY: Yes, I guess you could see them up above a little bit.

MR. BUSBY: So this would be --

DR. STACK: I was going to say how deep are the --

MR. BUSBY: I'm afraid I don't know that. The report on this will be out next Monday so . . .

CHAIR RICCARDELLA: This is inspected from the top --

MR. BUSBY: That's correct.

CHAIR RICCARDELLA: Okay, okay. So they're like six inches deep or so.

MR. BUSBY: Implementation of this technique. We think we've worked all the bugs out of it. The signal-to-noise ratio, we've got considerable improvement. Our location and resolution on the object space has improved. No more ghost images. And we can also do some post-processing to continue to improve the signal-to-noise ratio, and that will be the focus of next fiscal year's work.

In summary, I know I've covered a lot of ground over the last seven minutes. The LWRS program has used an EMDA process in the prioritization to focus our research into several potential knowledge gaps for concrete structures and subsequent operating period. The majority of that work is focused on irradiation effects. We have activities and alkali silica aggregate reactions, and we have plans to do creep fracture work in the coming months and year.

Research is joint in these key areas, strong interactions with EPRI, the NRC, and international partners. And we hope that that collaboration and coordination will continue to be strong and grow from there.

I will leave time for any questions. Thank you all.

CHAIR RICCARDELLA: We're actually head of schedule. Are there any questions from around the table? I have one. I'd like to go to slide 42, if I could, just a profile plot. So you show that the damage in about five inches or so. Then if I go back two more slides to slide 40, there is the reactor vessel support.

MR. BUSBY: Slide 40. I'm sorry. I went the wrong direction.

CHAIR RICCARDELLA: Yes. You know, so how is that, the dimension of that reactor vessel support pad to that five inches? I mean, we say, oh, the five inches isn't very significant. But if it happens to be, you know, 80 percent of that support pad, it could be significant.

MR. BUSBY: You're absolutely correct, and that's why I don't think we want to just take that, you know, mathematical first principle calculation and say good enough. We need to have more resolution on what is the potential swelling-induced stresses and strains due to swelling for the different aggregate types and the different geometries and locations. That's where some of this coupled modeling might come together and give us a little more resolution.

MEMBER BALLINGER: That location is above the core. What's the dose up there? You're talking about belt line dose. Your orders of magnitude lower up above --

MR. BUSBY: That's absolutely true, as well.

CHAIR RICCARDELLA: But if you're getting swelling, you know, and you're getting, you know, you could be degrading the concrete down there that could have an effect, I think.

DR. STACK: But, again, I mean, his basic model is for a high-temperature, very high energy irradiation, so you sort of think that's conservative. I mean, I kind of agree. Yes, I mean, he needs a swelling model, and so the data he's used I think appear to be conservative if you consider that it's quite high temperature and it's a very high fluence, a high energy fluence. It's more for a GCFR than it is for an LWR.

MR. BUSBY: And that's another good point. The higher temperature means greater dehydration, and it's more difficult to separate out what's due to irradiation-induced swelling and what's dehydration due to the elevated temperatures.

MR. LINDBERG: John Lindberg, EPRI. In fact, that is one of the things, and I was just going to mention in my presentation that we are going to be modeling that from the standpoint of a structural analysis model. So, you know, looking at the swelling effects versus the attenuation effects on, you know, actual configuration.

CHAIR RICCARDELLA: And taking into account the reactor vessel support?

MR. LINDBERG: Right, right.

MEMBER BALLINGER: Now, due to the constraint and everything that's in here, if you get non-uniform swelling, has anybody ever seen any spalling?

MEMBER BROWN: From the biological shield?

MEMBER BALLINGER: From the biological shield.

CHAIR RICCARDELLA: I'm sorry. I missed that one.

MEMBER BALLINGER: Spalling. In other words, if you get swelling and there's this gradient through the system, everything is gradient, the constraint should result in spalling, concrete flaking.

MR. BUSBY: It could, but we're only, roughly, a little over half of what end-of-life fluence may be, even with the oldest plant right now. So you might not have seen it yet, but that doesn't mean it wouldn't occur by 80 years.

MR. FUHRMAN: I'm Mark Fuhrman from the Office of Research. So you're going to do experiments on different minerals, accelerated tests --

MR. BUSBY: Yes.

MR. FUHRMAN: Okay. So do you need to account then for the irradiation rate?

MR. BUSBY: Yes, and that's an important point. You have to consider flux effects. I also showed some ion irradiations which are even higher flux than the reactor, and by comparing the two using the same materials, we may be able to tease out some information on rate effects, at least at a first order.

It's an important question. How important flux effects are in irradiation damage is to be determined. They're not terribly important in stainless steels and core internals. They're very important in pressure vessel steels. So this will give us a first look at neutron versus ion, but I don't want to say that's the final. You've raised a very valid point.

MR. FUHRMAN: Thank you.

CHAIR RICCARDELLA: Okay. If there are no other questions, we're way ahead of schedule. We might actually get out of here before 7:00 tonight. It's 3:15. I'm going to call a 15-minute break, and we'll reconvene at 3:30.

(Whereupon, the above-referred to matter went off the record at 3:15 p.m. and went back on the record at 3:30 p.m.)

CHAIR RICCARDELLA: Next we have EPRI talking about some of the search they're doing, and then we'll open the floor for discussion.

MR. TILLEY: Okay. I'm going to go first. I'm going to go first and introduce you. I'm Rich Tilley. I'm a technical manager in the Long-Term Operation Program, which kind of performs a parallel function to the LWRS within EPRI. And this was established about five years ago to look more broadly at all the issues that might roll up to long-term operation, 40 to 60, 60 beyond. And so one of the issues that we've identified in that is going beyond the metal issues that we had long pursued and looking at some of these other issues, such as concrete and cables.

Of course, introducing concrete does give me the opportunity to relate my favorite anecdote about concrete, and that was one of my friends was doing a tour of Hoover Dam and was going through the formal guide and everything and asked the guide, "Well, how long is this dam going to last?" and, with a great deal of conviction and no hesitation, the guide replied, "A thousand years." So that's one reason why concrete doesn't come up to the top when you think about, well, we've got to do something about it now. It does have this long-life sense.

And just to kind of complete that Hoover Dam story, Hoover Dam will, in fact, hit 80 years next year. It was formally dedicated in 1935, and my grandfather was a rigging contractor for the construction. So that allows me to get in my best dam story.

But with that, I will introduce John Lindberg who will talk about our specific efforts in the area of concrete research. John is a program manager in NDE Innovation, and you'll see where the NDE part of that comes in towards the end. But it has been where we've kind of consolidated activities as we look, in concert with DOE and others, at the issues associated with concrete structures within the nuclear power industry.

So with that, I will now turn it over to John.

MR. LINDBERG: Okay. Thank you. All right, Rich. Next slide. So I guess I have the dubious task of getting us through the afternoon, and I think my slide deck isn't that large and I think I can get through most of the topics since a lot of them were already covered fairly well by some of the other speakers.

So what I want to talk about is give you a little bit of background of the EPRI program, talk about structures of interest, talk about irradiation damage, research we're doing in boric acid attack, concrete creep, alkali silica reaction, and then talk about research we've been doing in the area of inspections and NDE for concrete.

Next slide. So I may have mentioned earlier when I was responding to one of the questions, the program in EPRI for concrete is what we consider a cross-sector program. So when we first started this program back around 2009 - 2010, we did what was called a state of knowledge document, basically looking at the use of concrete for all of electric power generation assets, the types of degradation they may be subjected to.

So we looked at degradation in all the concrete structures, for not just nuclear power plants but fossil-fired plants, hydrodams, use in renewable energy, wind energy, use in power distribution, power transmission structures. But the main focus of the program primarily has been nuclear power plants because of the safety-related structures and the regulatory aspects. So the structures we're looking at are the containment structures, the RPV pedestals, spent fuel pools, concrete pipes, Torus-suppression pool, and also dry cask storage.

So when we started out the program, we developed a roadmap. And, basically, we treat this program much like we treat other materials degradation programs within a nuclear industry and other industries. But we took the approach of you need to understand the degradation mechanisms first. So we developed our degradation matrix and then look at how that degradation, you know, applies itself or cures in various structures, such as cooling towers, spent fuel pools, containments, and the RPV support structure.

So we looked at the aging analysis of individual structures. And then we looked at how do you assess for that damage, so specifically looking at determining, you know, the reliability and capabilities of the existing commercially-available inspection techniques and then also assessing and developing NDE inspection tools, so looking at non-traditional and new types of NDE methods that may be available, looking at the deployment of those techniques, and then also looking at new infrastructure, new plants, how you apply new plants with inspections.

And then we're working also on development of an asset management platform or what we call our concrete toolbox. So this is basically going to be something where, you know, you look at a particular degradation mechanism or issue and we provide guidance as to what are the inspection techniques that you can use to assess for that damage and then also look at what are the engineering tools that are available, once you've got inspection data, that will allow you to perform engineering evaluation and determine, you know, the remaining life of that structural integrity of that component.

So that is kind of what we call our toolbox and then also looking at repair and mitigation, looking at the durability of existing types of repair techniques that are used, quality control, and also inspection, how you monitor those repairs after they've been made.

Next. So one of the things that, since this is an EPRI research and most of our research is funded by members, utility members, we established a technical advisory committee back in January of 2013. Since then, we've had five face-to-face meetings with the advisory committee and four webcasts.

And so the vision of this concrete technical advisory committee is to provide tools for long-term safe and reliable operation of concrete infrastructure. And the mission is to identify industry needs and emerging issues pertaining to concrete, provide guidance for construction, inspection, evaluation, and repair of concrete structures, and then coordinate work with other industry groups to provide comprehensive solutions.

So as you can see from some of the other discussions that have occurred today that we are coordinating our research work and collaborating with other industry groups to ensure that we have comprehensive solutions and that we're also utilizing our research dollars in a cost-effective manner.

But one of the main things that's coming out of this concrete technical advisory committee is the exchange of operating experience. So this concrete technical advisory committee meeting offers a time during the meeting where each of the utility members, and this is an international organization so we have international participation and not only U.S. participation, but they can exchange where they've had issues with concrete and talk about the types of issues they've had, how they've dealt with it, what sort of inspection they're doing, what sort of repairs they may have done, what sort of monitoring and trending they're doing.

So it has allowed a means for the civil and structural engineers that are responsible for concrete issues at the plants to talk to one another, whereas I think in the past, for the most part, most of these guys have been sort of on their own, doing their own thing, and, you know, haven't been able to exchange their information and, basically, work off of lessons learned from other people.

So to the structures of interest. And we've all mentioned this before, but one of the common areas, cross-sector area is cooling towers.

MEMBER SKILLMAN: Before you go on, my experience is normally a plant or a group of plants will have a subject matter expert, they'll have a program engineer somewhere in the system or one program engineer covers three or four plants. The question I have is how energetic have the owners been or the licensees been in ponying up individuals to participate?

MR. LINDBERG: We've actually got really, really good participation. Like I said, we just started this within the last couple of years. We have, I would say at this point, the last two meetings we've held we have about 25 participants, 20 members, good, you know, international content. At least a third of those participants have been, you know, from international members. And most of the utilities have ponied up either a site guy or the corporate guy or both. And they've been really willing; and, like I said, we provide a time in the agenda for operating experience, so they've been willing to talk about, you know, the issues they've had at the plant during the operating experience part. But then we also have a time where we may have a specific discussion on, say, like ASR or issues at Davis-Besse or whatever.

So it's been a really good experience from the standpoint of the exchange of that information, you know, whereas the other plant may read about it, you know, in an IE bulletin or operating experience report or whatever. But now they get to interact directly and, you know, a lot of discussions after the meetings. You know, so there's been, you know, really good interaction.

MEMBER SKILLMAN: Thank you, John. Thank you.

MR. LINDBERG: So, once again, the structures of interest talked about the cooling towers. That's an area that really, you know, applies to both fossil generation and nuclear power plants. Containments. And within the containment we're talking about the containment structure but also focused on the RPV pedestal, the support, the biological shield, looking at spent fuel pools, dry cask storage, any of the buried pre-tensioned concrete pipe, and then intake structure.

CHAIR RICCARDELLA: I guess, all day, this is the first I've seen with cooling towers on the list.

MR. LINDBERG: Yes. And we have dealt with specific issues with cooling towers, degradation of cooling towers at a nuclear power plant.

CHAIR RICCARDELLA: There has been some?

MR. LINDBERG: Yes. And, basically, they were using, basically use municipal city water that is treated with chlorine. So it's subject to corrosion of the rebar due to the chloride environment of the water.

CHAIR RICCARDELLA: Are they generally pre-stressed or not?

MR. LINDBERG: I don't think they're pre-stressed, no.

CHAIR RICCARDELLA: Just reenforced?

MR. LINDBERG: Yes, just reenforced.

MEMBER BLEY: Following up, we're only see reactor-related things here. Is there a program at EPRI looking at concrete for, say, waste disposal facilities that have concrete structures in ground?

MR. LINDBERG: Well, one of the things we are looking at, you know, in particular, dry cask storage. But, you know, we're pretty open to looking at concrete in, you know, wherever it may be used within the nuclear power plant, whether it's a safety-related use or a non-safety-related use.

So when we started the program, one of the first things we did, and, of course, Jeremy talked about the matrix, but in 2011 we worked, prior to 2011 we worked on a matrix looking at degradation, the possible degradation mechanisms for the concrete structures, looking at operational experience associated with those degradation mechanisms. We developed a degradation structures index of which has been published in what we call our concrete structures aging reference manual, and that number there is the number of the technical report that this is in.

But if you look at this, I know it's hard to see that matrix, but you can see there's a number of things like chloride diffusion with concrete, boric acid effects, radiation damage, reactor cavity concrete. You know, all of those had a high-ranking. But what we used this prioritization for is really to look at how we were going to prioritize our research needs and gaps. So that's what we used as a basis, along with our roadmap, in terms of determining the prioritization of the research that we're going to do.

Next slide. Okay. So one of the first areas, we've seen these two sketches already, but those are the areas of interest: basically, the RPV support, the concrete biological shield. I won't go into that.

But one of the things that we're looking at, and, you know, Jeremy talked a lot about the fluence values, and we've had a lot of discussion on this over the last couple of years. And so what we looked at is data. We extrapolated data that's reported for RPV, 1T data from the ADAMS database, converted to the energy of the 0.1 MeV. This is all the data that's basically plotted out for PWRs. And what you can see is, basically, it is the two-loop and three-loop PWRs that are of concern in terms of reaching what we call this projected 80-year fluence line, and that corresponds to 6.8 times 10 to the 19th neutrons per centimeter squared.

So next slide. So when we look --

CHAIR RICCARDELLA: I'm sorry. What are the bars? Explain that to me.

MR. TILLEY: They're individual plats. So it's the fluence values projected to an 80-year operation.

CHAIR RICCARDELLA: For each plant?

MR. TILLEY: Right, right.

MR. LINDBERG: This is utility data that's reported to the NRC and is published in the ADAMS system.

So from the next plot are the BWRs. You know, what you can see there is the fluence levels are a order or two magnitude lower; and, therefore, you know, basically, the BWRs are not bounding. So of concern really are the PWR two-loop and three-loop Westinghouse PWRs.

Next slide.

CHAIR RICCARDELLA: Why is there such a difference in some plants?

MEMBER BROWN: What's the answer?

MEMBER SKILLMAN: Shielding. The shielding --

CHAIR RICCARDELLA: There's a huge difference --

MEMBER SKILLMAN: The location of the reactor vessel in the shield, the thermal shield --

MR. LINDBERG: Yes. The other thing is most of the ones that are on the higher end there are smaller two and three-loop Westinghouse units. So there's a small reactor vessel, so it's probably less distance between the fuel and the vessel wall.

CHAIR RICCARDELLA: But even among a given plant type, there's a pretty big --

MR. LINDBERG: Yes, yes. But I think this is a very important data to look at, very representative.

CHAIR RICCARDELLA: And is this linear with time, so 60 years would be three-quarters of the way?

MR. TILLEY: Yes, roughly. There were some assumptions made as far as capacity factor and kind of the extrapolation.

CHAIR RICCARDELLA: Yes.

MEMBER SKILLMAN: Yes, let's go back to that BWR slide. Tell us what is that beast on the far right? What is that --

MR. TILLEY: On the far right. Which one? It's probably going to be one of the non-jet pump plants, okay, because, again, when you start putting in the jet pumps, you're actually putting distance between the core and the wall. So, most likely, that's going to be one of the old smaller --

MEMBER SKILLMAN: Yes. Thank you, thank you.

MR. LINDBERG: Okay. So Jeremy talked

about this before, but the data previously summarized by Hilsdorf and others have neutrons of different energy, many different data points with temperature greater than 100 degrees. And, you know, what we are doing in collaboration with the DOE LWRS program is, basically, evaluating and trying to classify the data. This is a plot of the 307 points that Jeremy showed before.

But one of the significant things is looking at, and Jeremy talked about this, was the attenuation in concrete of radiation. So the simplified models for two-loop and three-loop PWRs were developed using a Monte Carlo N-Particle Code with a cavity concrete constructed with portland cement. And from this data, from the graph that you can see here, the neutron fluence drops by an order of magnitude in the first several inches of concrete. So that's data that Jeremy talked about. That's data that we're looking in collaboration with them to determine, you know, what are really the effects of that attenuation in concrete.

So I mentioned we established that this 6.8 times E to the 19th neutrons per centimeter squared, you know, is bounding the U.S. fleet for a neutron damage in concrete to 80 years operation for energy of greater than 0.1 MeV. That's something that we've agreed upon. That's something that we're working with to establish as a value that we work with. At a concrete depth of three inches, the bounding neutron fluence drops to 1.4 times 10 to the 19th.

So the existing data that we see for energies of 0.1 MeV shows no loss of compressive strength up to 2.3 times 10 to the 19th. It appears that margin is adequate for 80 years of operation, that loss of compressive strength is more of a near surface effect. But additional work is planned to further quantify this margin.

MEMBER BLEY: Is there any reason to expect any difference here if you have other forms of degradation happening in the concrete?

CHAIR RICCARDELLA: At the same time.

MEMBER BLEY: At the same time. So is it linear, or is it that you might get some --

MR. LINDBERG: Well, we've had a lot of, we've had a lot of discussion on that, and I think Jeremy touched on that. And those are the things that we've got to try to look at and see if we can quantify what the synergistic effects may be on multiple or more than one degradation mechanism.

CHAIR RICCARDELLA: Has anybody irradiated concrete with ASR?

MR. BUSBY: Jeremy Busby, Oak Ridge National Laboratory. So that's a fair question. We've thought about it, but we decided to start simple and work our way up to that first. But we have talked about it. Yann has that in his FY 17 - FY 18 plan to explore synergistic ASR irradiation. He even has a term for it, irradiation assisted to ASR. So there is the potential that the swelling could be synergistic, but it's probably a very narrow region where you would have both.

So we have talked about it, but we've not put any experiments in play yet.

CHAIR RICCARDELLA: You need moisture for the ASR. In that region where you get the radiation, there probably isn't a lot of source of moisture.

DR. STACK: Let's hope not.

CHAIR RICCARDELLA: Over a long term.

MR. TILLEY: The other part that Jeremy presented is looking at, like, gamma heating and the like and where's the gamma max. So all these things come into play, but we are looking at that as, let's say, follow-on activities, as we start bounding with more engineering analysis, where does this really impact the structure.

MR. LINDBERG: So the data indicates that available, you know, in any case, that there is adequate margin. But additional work is being performed. Jeremy talked a lot about this. But, you know, what we've done is we've tried to, you know, in collaboration, we've tried to split up the task, and so the LWRS tasks are really looking at the fundamentals of the radiation damage, looking at the neutron and ion irradiation of mineral analogs to characterize swelling. Jeremy talked about that.

And then this other area is this structural significance of the radiation damage due to the near-surface swelling. So kind of the way that's being split up is Oak Ridge is going to be doing the fundamental studies, and then we're going to be looking at the engineering analysis, structural analysis, and the modeling, looking at the swelling effects, the attenuation effects, trying to build models that will, you know, hopefully help us understand, you know, what is actually occurring with irradiation damage.

So the next area we want to talk about is boric acid attack. And within the PWR spent fuel pools, they contain boric acid in the water to absorb neutrons emitted from the spent fuel. The spent fuel are susceptible to leakage due to cracking in the seam and plug wells in the liner. There's been instances, operating experience in the industry, where there has been spent fuel pool leakage.

So boric acid is known to react with the cement paste and some aggregates causing degradation of mechanical properties. And from the picture on the right there, what you can see is it's basically a cut-away of the concrete behind the liner wall. You can see an area where there is corrosion and potential for corrosion effects on the concrete.

Next slide. So, typically, leakage is collected in channels beneath the seam welds. These collection channels can be obstructed by the re-precipitated materials leached from the cement paste and the concrete. What happens then is you get pooling of the water beneath the liner and, of course, this water then finds other leakage paths through seams in the concrete, whatever, and can actually eventually leak out through the reactor building structure, and that is what has actually occurred.

Next slide. So EPRI has a project to study the effects of boric acid on concrete degradation and spent fuel pools. It basically builds on previous work that has been done, looking at the reactivity of different types of aggregate, performing computational modeling of the reaction process, characterizing the reaction products, and then trying to make a more accurate determination of the reaction front.

MEMBER BLEY: I've got a question for you about this because I'm thinking back to when we used to see a few more leaks around highly-borated systems in PWRs and whether you had that large crystal pile up quickly of mushy, kind of boric acid. I would expect, if you get any leakage into these channels, that what you start getting. Even if it's high and it's running down, you start building up like a paste-like substance that will be right up against the surface. That's the kind of thing you've been looking at?

MR. LINDBERG: Yes, that's basically what occurs. Now, one of the problems is the fact, basically, you know, you've got the spent fuel pool liner and then you've got the concrete there and the channels are behind it. But there's very limited space, so it's very difficult to go in and really determine that you've got this build-up.

CHAIR RICCARDELLA: Yes, there's no visibility.

MR. LINDBERG: Yes.

MEMBER BLEY: So have there been tests or something? How are you getting out this business of the boric acid attack on the concrete?

MR. LINDBERG: Well, basically, and I'll explain a little bit, what we're trying to do is determine how much of a problem or what is the potential for this problem. Related to that, we also have activities in the inspection side where we're specifically looking at the spent fuel pool liners, degradation of the spent fuel liners, equipment liners, whatever, trying to inspect for that. And then, you know, we may be able to, but, since there is an interface between the liner and the concrete and the channels, it is difficult to inspect, would be difficult to inspect from the liner side. But we do have activities on looking at, you know, the spent fuel pool liner degradation.

So this specific project, looking at the effects of boric acid, is a collaborative project with the Materials Aging Institute and CEA in France.

So this is showing the time line right now for the project. We kicked this project off last year in 2013, and we started out looking at, basically, updating a database of chemical transport calculation, looking at the aggregate's reactivity. That research has been completed. Now we're performing cement paste leaching experiments, concrete leaching experiments, and then we just started chemical transport simulations.

The project will conclude at the end of 2015. We'll be producing a report at that time. But the results are going to be used to determine the rate of degradation and, if appropriate, be used to develop a toolbox to perform generic structural assessment of the boric acid leakage leading to degradation for a typical spent fuel geometry.

MEMBER BLEY: I guess what I was getting at is, when you do experiments like these, on the surface I might think you'd use the boric acid concentration that's in the water. But you might see a much higher concentration because of the buildup of these crystals there, so I hope the experiments are looking at much higher concentrations --

MR. LINDBERG: Right, right. They do, basically, have a range of concentration of the boric acid because, you are correct, you know, once it begins leakage, you get the boric acid in direct contact, it is much higher concentrated.

MEMBER BLEY: Okay, thanks.

MEMBER SKILLMAN: The yellow box, the last several words, for a typical spent fuel pool geometry, are you pointing to the potential for structural degradation at the bottom of the pool? Is that what you're pointing to there?

MR. LINDBERG: We are looking at that, but that's not what -- specifically, we're looking at it in terms of vertical structures, but we can also relate it to the bottom of the fuel pool.

MEMBER SKILLMAN: I'm struggling to understand a change in spent fuel pool geometry. Those are mighty robust concrete boxes, and they're lined with stainless steel. So tell me --

CHAIR RICCARDELLA: It's the liner geometry. Specifically referring to the liner here?

MR. LINDBERG: Yes, to the liner. Yes, yes, to the liner.

MEMBER BLEY: Let me ask you a question about that because in last year's NRC study of the, you know, the seismic study on spent fuel pool, the particular spent fuel pool they looked at had a liner that was built with essentially no seams in high-stress areas which would make it very strong, but I don't know if that's typical. I don't know if that's a unique design, or if most of them are built that way. If they're not, they'd be a lot more susceptible, and I wonder if you're looking at --

MR. LINDBERG: Well, most of them --

MEMBER BLEY: I don't know what a typical one is.

MR. LINDBERG: Yes, most have channels, but most have been built from plate and so there are a number of seam walls.

MEMBER BLEY: Yes, but the plate --

CHAIR RICCARDELLA: Are they partial penetration walls or full --

MR. LINDBERG: I believe they were supposed to be full-pen welds, but I believe the thickness of most of the plate is around 3/16ths of an inch.

DR. STACK: But in the particular spent fuel he's talking about, there was a rolled edge that came up so that you didn't try to do a --

MEMBER BLEY: It didn't have welds at the high-stress places.

CHAIR RICCARDELLA: The point is there's differences in spent pool liner geometries. And maybe in that yellow box, you should be considering whether to look at a worst-case spent fuel pool geometry rather than typical.

MEMBER BLEY: Or make sure you know what the range of them is.

MR. LINDBERG: Right, right. Well, and that's, we still have --

MEMBER BLEY: Everybody we've talked to knows about the range so far.

MR. LINDBERG: Yes, yes. That's really, you know, from that perspective, that's work that's out in the future. So we're waiting to get the results of, you know, these other chemical transport studies before we determine, you know, exactly how we apply them to the actual field geometries.

MR. TILLEY: As John indicated, you know, this is part of a kind of parallel effort. We're also looking at how do we do a better job of inspecting the liner and addressing any leakage before it goes very long. But part of this is also looking if you had, which was also said it's tough to detect our priority, how quickly does it potentially turn into an issue because it's attacking the concrete.

CHAIR RICCARDELLA: Okay. Are there other areas where you might get boric acid, like, you know, if you have the leaking valve in the primary coolant system or something and it's dripping? I mean, we've seen boric acid around the reactor coolant systems.

MR. TILLEY: But you're probably not worried as much about the concrete around there as you are about the metal around it.

CHAIR RICCARDELLA: Yes.

MEMBER SKILLMAN: After Davis-Besse, almost all utilities implemented very rigorous boric acid leakage programs and controls. They were identifying every dot and following up. So that's pretty much under control.

CHAIR RICCARDELLA: There's no form of leakage monitoring that you could do on the spent fuel pools? I mean, is there a way you could determine how much, if there's any leakage in these channels?

MR. LINDBERG: I believe that some may have -- and they call it telltales that they look at, what sort of leakage they're getting across the telltales. And in cases where it is changed from where they've had leakage, you know, had a regular type of flow to where it has decreased, that kind of may be of concern. I mean, increase, of course, is a concern, actually any change. But a decrease in that leakage would, you know, lead you to the path that something, for some reason, it's no longer going down through the telltales.

MEMBER BALLINGER: But leakage out there is a really bad hair day.

CHAIR RICCARDELLA: Well, evidently, they get some if they have these channels. I'm surprised.

MR. LINDBERG: Okay. So the next area is concrete creep. There was some discussion of that. Concrete deforms slowly, nonlinearly with time, subjected to loading, post-tensioned containment, static loading, causing dimension change, loss of post-stressing, cracking liner deformation.

So EPRI is evaluating creep deformation of concrete structures to determine if and where it may be an issue. So, primarily, what we're doing here is a literature survey, looking at what existing information exists on concrete creep and whether or not those conditions would exist within a nuclear power plant, where they may exist, and whether or not that may be an issue. So we are also collaborating with the LWRS program on this particular area of research.

But also what we're doing here is we're assessing the feasibility of new NDE techniques for characterizing concrete creep. One of the things, and I'll talk about this a little bit later, is the use of nonlinear ultrasonics to detect creep. And we currently have some research that we're doing with Georgia Tech on applying nonlinear ultrasonic techniques to detect this sort of degradation.

Next slide. Okay. Alkali silica reaction. I don't think I need to go through this slide. I think it's been covered pretty well today.

So what the plots on the right are kind of showing you and the red dots there, and this is information, in the U.S. it's information that was taken from Federal Highways where they looked at incidents where they've had ASR in highways and looked at the reactivity of the aggregates.

So what you can see in this plot, and also in those plots are the blue triangles, are areas where there's nuclear power plants. So what you can really see in this plan is you're apt to find reactive aggregates, you know, in a pretty broad distribution across the U.S. and Canada. So, you know --

MEMBER BLEY: It looks like you get them in the desert, as well as in the --

MR. LINDBERG: Yes, yes, yes. So, you know, it has a pretty even distribution.

DR. STACK: But you were supposed to test for that.

MR. LINDBERG: Yes.

DR. STACK: I mean, it wasn't though you just dug up --

MR. LINDBERG: Right.

DR. STACK: -- to the nearest gravel pit.

MR. LINDBERG: Right. So --

CHAIR RICCARDELLA: They're ACI tests, but I think, subsequently, they found out that some of those tests weren't --

DR. STACK: How many plants were built after the new, before the new screening criteria and then after?

MR. LINDBERG: So that's a good segue. The concrete that was used during construction of the existing fleet was tested and considered non-reactive at that time. But those aggregates today may be classified differently due to our improved testing methods. So what we're trying to do is take a look at the difference in the testing methods and then provide utilities with tools to evaluate the risk of having alkali silica reaction at their plants.

DR. STACK: Is it something where they could take core and then retest their aggregates? I mean . . .

MR. LINDBERG: I can't say that right now. I think that may be a possibility. I think some of the tests may allow you to do that. But we're actually just beginning to start this research.

So, you know, our intent is really to look at developing a map of geographic distribution of reactive aggregates. So, you know, I can't say for sure where the research will lead us, but, you know, the intent is really looking at a difference of the testing methods and, you know, looking at those testing methods, how we may compare what the aggregates are today versus what they were back at the time of construction.

So we're going to, you know, evaluate and compare the reactivity of the aggregates based off the current testing methods. Also, what we're looking at is testing various NDE methods on large ASR mockups. So we're currently going through looking at some of the commercially-available NDE techniques. We just recently fabricated a number of ASR mockups, so we're testing and trying to determine what are the better NDE techniques for looking for ASR.

Also, once again, we're looking at non-linear ultrasonic testing. So we're doing R&D in that area for ASR damage. So what we're trying to do is provide comprehensive tools to assess the risk and manage, as appropriate, ASR.

CHAIR RICCARDELLA: It seems like what would really be a breakthrough, as I look at this picture you have in the upper right-hand corner there, I mean, you see all that on the surface, but that might just be where it's unrestrained. And the question is what if you go five inches or ten inches or twelve inches below the surface and, you know, if you had NDE technique that would allow you to do that and maybe --

MR. LINDBERG: Right. And that's the sort of thing we're working towards, you know, with our research. But, you know, I would say it's a giant leap to say that we're going to get there.

CHAIR RICCARDELLA: I mean, that cracking on the surface is liable to mask what goes on.

MR. LINDBERG: Right. And, you know, the current method that they're using right now to monitor ASR is what they call the combined cracking index. So, basically, all you do is take like a one-foot by one-foot square, or I believe it's a one-meter by one-meter square, and you look at it visually and you basically, you know, you create a plot, you try to measure all these cracks, and then you go back in time, you know, later inspection, and try to compare that data.

Right now, the way they're doing this is basically by direct visual methods using a camera and a guy evaluating that data. What we're trying to do right now is develop image analysis techniques that would allow you to take, you know, a high resolution video image of that area and then go back, using a reference point, take another visual image, use image analysis software, and be able to compare, you know, the plot, the original plot with the subsequent plot and to make that more quantitative. Right now, it's kind of qualitative. You know, it's done in a manual fashion. It's not very efficient.

CHAIR RICCARDELLA: What about completely different techniques, like ground-penetrating radar --

MR. LINDBERG: Right. And so one of the other, one of the other things we're testing right now is the use of shear wave tomography. So think of it in the piping or vessel world as like phased array ultrasonics. So, basically, we're trying to use that as a means to can we determine the depth of the cracking. You know, this cracking is very, very fine cracking. It's on the orders of microns, you know, 20 microns to maybe 100 microns wide, so it's not real wide, much like stress corrosion cracking in stainless steel.

So what we're trying to do is look at what type of techniques, like the shear wave tomography, that might allow us to quantify it better in terms of depth.

MEMBER SKILLMAN: John, let me ask you to go back to slide 26 for a minute, please, the second bullet. At first read, that would say, golly, we've got some improved testing methods where we can take another look at these aggregates. Would it be more accurate to characterize that bullet as we are now sensitive to the chemistry of the aggregate and, hence, we are focusing on methods to understand that chemistry?

MR. LINDBERG: Yes, I think that would be a better way to characterize it.

MEMBER SKILLMAN: Because I'm wondering if it really is improved testing or if we'd had an a-ha moment and said, golly, we haven't been looking at the right thing for a long time, we better look at that.

MR. LINDBERG: Yes, I think it's better characterized that way because I think really now the newer methods, there's multiple tests that you do versus back at the time, I believe, it was a singular test.

MEMBER SKILLMAN: Thank you. All right, thanks.

MR. LINDBERG: So the last area I'm going to talk about and it's probably the area I'm the most comfortable with because I've spent most of my career in inspection of nuclear power plant components, but it's in the area of concrete inspection. So one of the things, when we went through our first state of the knowledge, you know, looking at concrete inspection, concrete degradation, concrete degradation and concrete inspection, and one of the first things we identified as a technology gap was the fact that most of the inspections that are performed on concrete are performed manually. It's a manually-applied technique. Usually, it's a guy with a hammer, you know, impact echo, impulse response, resistivity measurements. But most of the time, it's a guy working off a scaffold taking manual measurements, taking the manual measurement, recording the data. Some of the equipment now does allow for data logging. But, you know, most of these guys are working off of scaffolds. So, you know, what you can see in the pictures on the left there is, you know, are some cooling tower inspections being performed, and here these guys are working off of a scaffold.

And so, you know, one of the things we looked at is that there's got to be a way of doing this, performing inspections in a faster, less costly, a safer way, certainly a safer way. You know, it's not easy. Most of your cost of the inspection of a large concrete structure is in, you know, getting that scaffolding there, getting the people up to the scaffolding, moving scaffolding around. It's really not efficient. So most of it is --

CHAIR RICCARDELLA: Training those people to be on a skywalker or suspended in the air.

MR. LINDBERG: You know, and it's not a place where people want to be. So, you know, it's not just cooling towards. You know, they do the same thing off of hydrodams. And in hydrodams, a lot of times guys are working off scaffolding or repelling down the side of the hydrodam, you know, gathering data, logging it, stuff like that. So it's not very efficient. So we looked at are there ways to make that more efficient?

So what we got looking at is how do we automate this. And we got looking into robotic devices, and we actually went out on a request for proposal. We used a company, a technology innovation company. We got, basically, a response from 43 different companies with, basically, 43 different types of solutions, from crawlers, from unmanned aerial vehicles, devices that would climb, like spiders, things like that.

So we went through a process -- what's that?

CHAIR RICCARDELLA: Most of those are magnetic.

MR. LINDBERG: Yes, a lot of crawlers are magnetic. So what we ended up with was a crawler, this concrete crawler that you see on the left. This is a commercially-available device, and, basically, what it does is it has like a vacuum motor in the center. You can see sort of in the area there. There is a vacuum motor. It creates a vacuum in a vacuum chamber type area. It has treads on it that allow it to, you know, maneuver in a direction. And so, basically, it sucks itself up against a vertical structure. This is a regular, pretty large device, but it has the capability of carrying about a 20 kilogram, or 45 pound, payload. So what that allows you to do is mount various types of NDE inspection tools or devices on it so that you can look for corrosion, you can look for moisture, you can do crack mapping. You can look for areas where you may have voids, de-laminations in the concrete. It allows you a lot of options. And the key advantage of this technology is in its flexibility to culminate different inspection devices.

Next slide. So one of the things that I mentioned before, that this is a cross-sector program. And one of the advantages of having the program cross-sector is, you know, the hydrodams, hydrodam infrastructure is getting also aging. A lot of our hydrodams -- it was mentioned Hoover Dam is 80 years old. Typically, a lot of the dams, hydrodams are 60 to 80 years old, maybe even older, and so they have issues. They have similar types of issues.

So we had what we called a supplemental project where we were working with the renewables group on hydrodams, and one of the first demonstrations that we did of this, field demonstrations we did of this crawler device was at the hydrodam in Niagra Falls, and we did that in July of 2013. At that time, we outfitted it, I believe, just with what's called impact echo and then also had a mapping location, mapping device that would allow you to collect data and basically keep track of location where you were collecting data.

Since that time, we've developed some good lessons learned from that data, from that demonstration. We performed -- in July of this year we went to another dam, Claytor Dam, in Virginia and performed additional inspections there where we looked at use of ground-penetrating radar and also added a different technique, air-coupled impact echo, and then changed our location and mapping device to improve its capability. And then, most recently, in fact last week, we just did a demonstration down at Crystal River in a small section area of that containment structure before they remove that structure, disassemble and remove that structure.

MEMBER BLEY: Was this thing designed for your program, or it was commercial already?

MR. LINDBERG: So what we did here -- and that's a good question. What we did here is we, basically, took commercially-available technologies, so it was a commercially-available crawler. Then we took commercially-available ND techniques, integrated it with that, and then commercially-available, you know, mapping, location and mapping type technology. So what we really did was integrate all of those three technologies.

MEMBER BLEY: This thing works pretty good, or does it fall off once in a while?

MR. LINDBERG: It works pretty good.

During the first demonstration at Niagra Falls, it was kind of interesting because we went to Niagra Falls and we figured, well, that would be sort of a nice cool setting during the summer. Well, it turned out the week we were there they were having temperatures in the upper 90s, low 100s. The temperatures on the face of the dam, which was actually getting hit with the sun directly in the afternoon, was about 130 degrees. So we had a problem with the adhesive on the treads, and it actually deteriorated. So they had to make, you know, improvements.

So we've been making improvements, you know, with the crawler device. And, actually, what we're in the process of doing now is trying to transfer this technology to the industry. So the way we're going about that is trying to commercially license that to vendors that may be interested in, you know, taking this technology and actually providing a service. And we have discussions currently ongoing to do that.

So we believe there is interest in this. We believe that, you know, it can be used to perform inspections of large concrete structures.

MEMBER BLEY: Can it cover full areas or

just sample here and there?

MR. LINDBERG: I believe that, you know, what you want to do is try to, you know, look at sample areas. So the last demonstration, last two demonstrations we did, the ground-penetrating radar, you can pretty much run that continuously. But some of your other inspection techniques, you're basically, you know, pinging, you know, pinging, getting a set of data in an area. So you'd set up a grid, a one-foot by one-foot grid or a two-foot by two-foot grid, depending on the area, how large of an area you want to sample. So I believe that what you'd want to do is set up some sort of sampling program.

So going back to looking at NDE capabilities for concrete. So what we've been doing all along with this program is looking at what the existing NDE capabilities, what sort of techniques, technology is already being used out there. And a lot of it has already been used in the transportation, you know, highways. But as we go along and look at the degradation mechanisms, look at the structures that are affected by these degradation mechanisms, we've been looking at the NDE techniques. So we're looking at techniques for corrosion of embedded steel, looking at single defect type, techniques for single defect, such as de-laminations, voids, vertical cracks, and then also looking at, you know, pattern cracking, your ASR, your freeze-thaw, you know, temperature damage.

And what we're trying to do here is really take a look at these techniques, the capability of these techniques, you know, the limitations, the reliability of these techniques, and help develop some guidance so when you have a particular degradation mechanism these are the better techniques to use to, you know, assess that degradation mechanism.

We have this vision. It's a vision that maybe someday that we can feel confident enough in the capability and the reliability of these techniques that you may be able to use these techniques in lieu of core samples, taking core samples and doing destructive analysis, that you'll be able to use these techniques to perform your assessments, your engineering evaluations, when you have degradation. But I think that's a vision that all of us have, but I think it's going to take a while to get there.

The other thing that, you know, in looking at all the NDE capabilities, what it's allowing us to do is basically develop an independent resource for concrete NDE technical capability assessment and development. So, you know, over in the reactor pressure vessel side, the piping side of the plant, you know, the primary pressure boundary side of the plant, EPRI has kind of become the independent assessor for any of the, you know, non-destructive examination technologies that are out there being used. You know, we perform procedure qualifications, personnel qualifications. When plants have issues with piping exams, any kind of reactor vessel exams, component exams, we typically go out, assess that data, assess compliance with procedure, you know, the procedure, qualified procedure. And so we're developing that same capability in the concrete area so that if a utility has a particular emergent degradation issue that may come up, you know, when they're in an outage situation, they can call us and get advice in terms of what sort of NDE techniques they should be using to assess that and also look at, you know, what sort of, you know, their long-term plans they may have in terms of assessing and monitoring for various degradation mechanisms, such as ASR.

So along with that, we're looking at new inspection techniques. And I've mentioned nonlinear ultrasonics. So what nonlinearity can do and, you know, a number of people have mentioned about the nonlinear behavior of various degradation mechanisms, so what we're looking at is using nonlinear ultrasonics to give us information on the degree of damage that may be occurring in concrete subjected to radiation, carbonation, alkali silica reaction, temperature damage.

Some of the initial work that we did a few years ago and some of the plots you see to the right here starting out at the top relate what is called the acoustic nonlinear parameter beta with temperature damage that has occurred in a concrete test specimen. And what you can see in these various plots here, at the top you have a plot at 20 degrees C. That parameter shows the beta parameters around 22. The 120 degree plot showing it somewhere below between 21 and 22, and then the 250 degree plot shows it between 19 and 20.

So what we have shown so far, and this is still fundamental research that's going on, but we have shown that you can detect, using nonlinear UT you can detect damage that's occurring, you know, damage that's occurring to temperature effects in concrete.

Next slide. So what we're looking at is a variation -- a lot of this research that's being done right now is being done at Georgia Tech and Northwestern University. Also, the University of Texas is doing some of this. But some of the research that Georgia Tech has been doing right now is they're looking at co-linear wave mixing, and this is currently a technique they're using to evaluate bar samples for measuring the acoustic nonlinear parameter beta. And they're getting good correlations with observed between the acoustic nonlinear parameter measurements and the expansion of bar samples due to ASR damage.

And the plots below show you the samples, the elongation of three different samples, plot in blue, black, and red. And then correlating that to the normalized amplitude from the nonlinear UT that's being performed. And so we're getting correlation of the data between the ASR damage and the acoustic nonlinear UT data.

And so really what we're looking at with this, and we're not just looking at this nonlinear UT for concrete but we're also looking at it for vessel steels, stress corrosion cracking, and stainless steels. So it's being used for a number of different studies.

But really what you're looking at is trying to find degradation in a microscopic scale when it's first occurring versus the current techniques basically look at it in a macroscopic scale, when it's already occurred, when it's already propagating and growing. So what we're hopeful, and this is still fundamental research, but we're hopeful that we'll be able to use nonlinear UT, be able to apply it in the field and detect, you know, degradation at its initiation and when it's first propagating.

So the last thing, and you can't do inspection testing without mockups. So most of the time, new inspection techniques are normally developed using small laboratory-sized specimens. And we've done a lot of work using small lab specimens. But the real structures are larger, behave differently. In our discussions with Federal Highways, DOT, a lot of the mockups they have are representative, typically representative of the sections that you find in highways, which are typically inches thick. Our concrete structures are basically, you know, feet thick or a meter thick. So we have been developing much larger mockups with various degradation and damage mechanisms for testing and validating existing and new NDE techniques.

And we are sharing these samples. They're being used by three different universities. I mentioned Georgia Tech, Northwestern, and University of Texas, and also we're sharing them with Los Alamos National Lab, some of the work they're doing for us, also.

So one of the things in developing these mockups, it's, you know, concrete always cracks, but you can't always get concrete to crack where you want it to crack. And so it is very difficult, you know, creating mockups that have or are representative of what you're going to see, the types of flaws you're going to see in the field. So it's raised some interesting challenges, and the unfortunate thing is is you pour a large mockup and you don't get the flaws you want to get. You basically are tossing away a large concrete mockup.

MEMBER BALLINGER: Thought about using it for sidewalks?

MR. LINDBERG: Okay. So to summarize, the concrete research at EPRI is in progress with a strong nuclear and a long-term operation focus to support the utility decision-making process. So as I mentioned before, the roadmap we're following is a similar roadmap that we've used for, you know, degradation, looking at degradation mechanisms in other parts of the plant, the reactor pressure vessel, piping, where you develop a degradation matrix, you look at the degradation mechanism, you develop a matrix, you look at those mechanisms and how they would basically occur, what structures they occur in. And then you look at how you're going to assess for that degradation, the NDE, look at the reliability of NDE, the capabilities of NDE techniques, look at developing new NDE technologies, and then developing an asset management platform and looking at repair mitigation solutions.

So that's basically all that we had to present for an overview of our concrete program at EPRI.

MEMBER BLEY: John, most of what you talked about, I think, are in -- I won't ask you about the proprietary reports, but most of it seemed to be in the reports we've seen. Do you have any more reports coming out soon? Are there some of these areas that are ripe to have new information out?

MR. LINDBERG: Yes. We do have, I believe we've got two or three more reports coming out. There's one coming out on the crawler. I think there's a couple others on some of the NDE work that we've been doing. But you are correct. Many of these are proprietary for members, but, where we do see that they would have use to the industry, we have been trying to free release some of these reports.

MEMBER SCHULTZ: John, we've talked a lot today about fundamental research, as well as the application of research, to the OWR sustainability project. And I presume that, I'm hoping that EPRI is also making sure that the lessons learned from quite a dramatic investigation over time here and going forward that the lessons learned are also being forwarded to the construction program, new construction program.

MR. LINDBERG: That's a good point, and we really didn't talk to that. But we do have an interface with what we call our advanced nuclear technology program where we are looking at new plant construction. So, in fact, that is one particular area where we did, within the last year, issue a guide book, and it's much like a handbook, where we summarized lessons learned, good practices for construction, you know, looking at quality control of concrete as it would apply to new construction.

So that is, you can go online and get that particular handbook. But we are directly relating to, you know, we are directly tied in and do research for, you know, the new plant portion.

MEMBER BALLINGER: For example, Summer and Vogtle, where's the best place to get aggregate? Is it near Summer and Vogtle or is it --

MEMBER SCHULTZ: I was looking at the map.

MEMBER BALLINGER: -- somewhere else?

MEMBER SCHULTZ: It's not clear at that scale.

MR. THOMAS: Somewhere else.

MEMBER BALLINGER: Somewhere else?

MR. THOMAS: They had a supply problem.

MEMBER BALLINGER: But they did do it there? Oh, okay, that's great. They did do that.

MR. LINDBERG: So when they are using all the current ASTM testing, I hope it's for ASR. So, in fact, we took a field trip there back, I believe it was December of last year, and we kind of tried to really baseline, you know, where our thinking was to produce this guidebook, get a better understanding of some of the issues that they are, you know, really dealing with on the construction side. And, typically, you know, they're not much different than they were 30 or 40 years ago. It's just the design of the plant is a little bit different. They've got some different challenges there.

DR. STACK: Aren't there some things they do with concrete these days, though, to make, like, higher fluidity, you know, especially if you want to fill something like that shield wall for an AP1000 where it's a pretty complicated structure that you're trying to pour the concrete into?

MR. LINDBERG: Yes, yes, there are some things, different things that they can do.

DR. STACK: And do we know whether those changes made differences in things like aggregate reactivity?

MR. LINDBERG: I believe that, you know, they're doing the testing, you know, they do the ASR testing in accordance with whatever ASTM standards. But if they change anything different in their mix, they have to run it through all the various ASTM tests and, you know, basically be able to meet all their 28-day test specimen requirements and things of that nature. So even though they may be looking at changes in the mix, if they do do a change in the mix, they have to reconcile that with design.

MEMBER SKILLMAN: Building on Bill's question, I would be curious whether or not for these complex geometries they're using some form of epoxy or retardant or something to make the concrete flow more easily and, if by doing that, they've really made a change that will haunt them 20 years from now.

MR. LINDBERG: Yes, I can't speak to that directly, what they may be doing.

MEMBER SKILLMAN: Interesting question.

MR. TILLEY: I'll take a note of that and see if we can't get you some further information on how -- we'll talk to our ANT group and see whether they are making any fundamental changes in the materials being used.

MEMBER SKILLMAN: It's the additives. Additives, custom additives for custom characteristics.

MR. LINDBERG: I know, you know, when we

were there, you know, they talked about things that could be done. They tend to stick with the standard mixes because, otherwise, you're having to reconcile design against what was designed and what the design mix is.

CHAIR RICCARDELLA: Currently operating plants where they have that issue, do they do periodic core sampling? I mean, is that something that's done?

MR. LINDBERG: If they have a particular issue, yes, they are doing core sampling in order to do analysis of that issue.

CHAIR RICCARDELLA: And that's what you would try to replace with your NDE?

MR. LINDBERG: Right, right.

CHAIR RICCARDELLA: Are these calibrated with --

MR. LINDBERG: Yes. I think the other thing, too, and I should have said something sooner, one of the things when they go out and do these NDE techniques when they have an issue at a plant, a lot of times what they're looking for is where is the location of the rebar so they can do core drills and then what is, in the case of Crystal River or Davis-Besse where they've had issues, you know, basically use the NDE technique to try to scope out where the damaged area is so they know how to target, where to target, you know, their core drillings, so they minimize the number of core drills that they're doing.

CHAIR RICCARDELLA: And then, you know, as part of this SLR program, is the industry going to be developing AMPs, aging management programs, for these various concrete structures?

MR. TILLEY: This is, as Mita presented, there are eight AMPs that are in the structural category in GALL. And the one that --

CHAIR RICCARDELLA: Structural category but what does that mean?

MR. TILLEY: Well, it's like the IWE/IWL are and the like. Those are AMPs, aging management programs, in the structural category, so doing your visuals on your containment and the like. Their structural monitoring that these have been very broadly written, and one of the issues that Mita mentioned is they are looking at do they need to be modified for SLR. There are some things, like irradiation effects, is not currently in any of those in a specific fashion.

CHAIR RICCARDELLA: When you say IWE/IWL, you're referring to Section 11?

MR. TILLEY: Yes, exactly, ASME type requirements are carried over --

CHAIR RICCARDELLA: Probably mostly visual, though.

MR. TILLEY: Yes, exactly.

CHAIR RICCARDELLA: It would seem, if you have some degradation, if you have ASL, ASR, for example, there would be something that triggers you to do core samples, as opposed to an individual licensing action.

MR. TILLEY: That's part of what is being looked at currently is looking at how extensive is something like Seabrook, can it happen other places, or is it a plant-specific issue. Same thing with these irradiation effects. As you saw, it's not a one-size-fits-all type situation. We're going to have to do probably plant-specific evaluations to look at is this an issue for that plant or not. So we'll be going through exactly that kind of evaluation and providing input into that process. One of the areas we don't currently have a lot of guidance is in the structural area.

CHAIR RICCARDELLA: Is that something NEI has --

MR. TILLEY: We're working in cooperation with NEI through -- NEI, as you know, has their various license renewal implementation working group, their mechanical, electrical, and structural working groups. So that's a good source for getting operating experience feedback and the like, so we are tied in with their activities to make sure that we're addressing it from a research need standpoint.

MR. LINDBERG: So, you know, that's also an area where we have this concrete technical advisory committee. And so, you know, our utility members will advise us. If they feel that the issue is significant enough, they will advise us as to, you know, whether or not we need to be producing guidance, you know, inspection and evaluation guidance, how detailed that guidance needs to be. You know, you're familiar with the materials reliability program and the boiling water reactor vessel and inspection program. And so, you know, do we need that type of guidance, or is it guidance just on the inspection methods? What's the best inspection method for ASR? So --

CHAIR RICCARDELLA: Structural stuff like this fall under, would that fall under MRP or not?

It's the material.

MR. LINDBERG: It is material degradation, so, you know, you bring up a good point. Depending on the significance of these degradation issues at the plants, it could very much fall under, you know, the materials program. Currently, the program is within the NDE program because a lot of the work is within NDE.

CHAIR RICCARDELLA: Well, thank you. Do we have any other comments from around the table?

MEMBER SKILLMAN: Well, I would like to thank all of the presenters for a very excellent use of the day to inform the members of the number of issues that are emergent. You pointed to scenarios perhaps that we weren't as sensitive to that we now need to be sensitive to, and it's very timely because we've entered the realm of subsequent life renewal, that is 20 years plus 60, and it's clear there are some areas where our knowledge is not as keen or as thorough as it needs to be. But I want to thank all the presenters for a very comprehensive set of presentations, for their preparation, for their travel. Thank you very much.

CHAIR RICCARDELLA: We're going to do one more check. If there's anybody on the line, hang on. We're opening the bridge.

MR. KEEGAN: Hello. This is Michael Keegan with Don't Waste Michigan.

CHAIR RICCARDELLA: Yes.

MR. KEEGAN: Hello?

CHAIR RICCARDELLA: Hello, we hear you.

MR. KEEGAN: I'm Michael Keegan with Don't Waste Michigan. I'm an intervenor at Davis-Besse, the shield building has been cut into four times, and we have a contention current before the ASLB, and I just wanted to alert the ACRS off the top that Davis-Besse --

MEMBER STETKAR: Mr. Keegan, you're breaking up just a little bit. I don't know if you're on a cell phone or if you can adjust it a little bit.

MR. KEEGAN: Hello? Is that any better?

MEMBER STETKAR: That is wonderful. We just want to make sure we have everything on the record correctly.

MR. KEEGAN: Very good. Thank you, thank you. Michael Keegan with Don't Waste Michigan, intervenor at the Davis-Besse Nuclear Plant. Currently, we have a contention before ASLB regarding the shield building. It's been cut into four times to replace equipment, and the shield building currently does not meet design basis. It's also out of plumb. And back in 2011, a couple of engineers were concerned that if there were a mild to moderate earthquake that 90 percent of the shield building could come sloughing off.

And so the realtime question I have is who's looking at what, what would occur if 25,000 tons of shield building came tumbling down into the metal secondary containment and tipping it into the reactor in realtime? I mean, these are not theoretical aspects. You know, it was a wonderful academic discussion today, but there are realtime issues that are not being addressed by the ASLB --

MEMBER STETKAR: You're breaking -- can you say the last sentence again because you broke up there.

MR. KEEGAN: Okay. I'm sorry. It was a wonderful academic discussion, but there are realtime issues that we have before the Atomic Safety Licensing Board that they have ducked thus far, a realtime issue. What happens if that concrete comes sloughing off and tips into the secondary metal containment and tips into the reactor in realtime? Not 20 years from now, in realtime. What happens if that concrete turns to mud?

They put the root cause on the blizzard of '78, but there are falling and cracking which occurred in 1978, and they blamed that they did not seal the building properly. Well, now they've sealed the build and water is locked inside. Now we're into a freeze-thaw. And the linear equations, really we're talking curvilinear equations, accelerated freeze-thaw and cracking. And when is there going to be a series of investigations at the Davis-Besse shield building to meet design basis, and it's not there. And I just wanted to alert you to that in realtime and the urgency of these in realtime. So that's my comment.

CHAIR RICCARDELLA: Okay. Thank you.

MR. LEWIS: Marvin Lewis, member of the public. Can you hear me?

MEMBER SKILLMAN: Hello, Marvin.

MR. LEWIS: Hi. Look, you know, I worked, was in charge of a concrete lot for a year or two, and one of the problems we were coming across and I didn't hear it discussed, though I'm very, very pleased to hear what I did hear discussed, namely that we're running out of good quality concrete because we don't have cement, we don't have that fine stuff that they used back in Roman times called the volcanus, and portland cement is running out or has run out. And I'm not saying that you didn't do a good job looking at the aggregate. I'm glad that you're looking at the aggregate the way you are, but the cement itself has raised a lot, a lot of questions.

And all you do is have is pours that were being done a year ago versus pours that were done about 40 years ago, and the pours 40 years ago look better than the pours right now. And I really think the kind of information you're looking at for the aggregate you should also look at for the cement itself. And just a suggestion, and thank you for allowing me to make it. Bye.

MEMBER STETKAR: Thank you, Mr. Lewis. Anyone else out there?

CHAIR RICCARDELLA: Okay. So with that, we'll close the meeting. Thank you very much.

(Whereupon, the above-referred to matter went off the record at 4:51 p.m.)

UNITED STATES NUCLEAR REGULATORY COMMISSION
*Protecting People and the Environment*

# Concrete Degradation Research

**Advisory Committee on Reactor Safeguards**

**Structural Analysis/Plant License Renewal Subcommittee Meeting**

**September 19, 2014**

**Rockville, MD**

**John Burke**
**Madhumita Sircar**
**Office of Nuclear Regulatory Research, USNRC**

# Topics

- Operating Experience & Research
- Expanded Materials Degradation Assessment Results (NUREG/CR-7153, vol. 4)
  - Effects of Irradiation on Concrete
  - Alkali-Silica Reaction
  - Creep-fracture of Posttensioned Containment
- Other area of research – LWRS Workshop and Roadmap
  - NDE
- Dry Cask Storage System
- Discussion & Q/A

# Concrete Degradations

Operating Experiences

&

Research by NRC

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Concrete structures are reliable and durable, but degradations do occur.

Some form of interventions are needed to continue with the desired durability.

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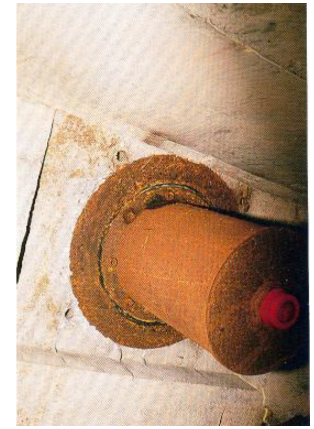
# Operating Experience (OpE): concrete structures are reliable and durable, but degradations occur

Spent Fuel Pool Leakage

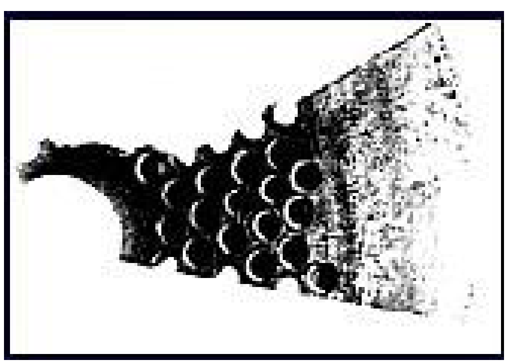
Water Intake Structure Rebar Corrosion

Concrete Cracking Outside Containment Wall



Corrosion of Grease Cap

Grease Leakage Outside Containment Wall



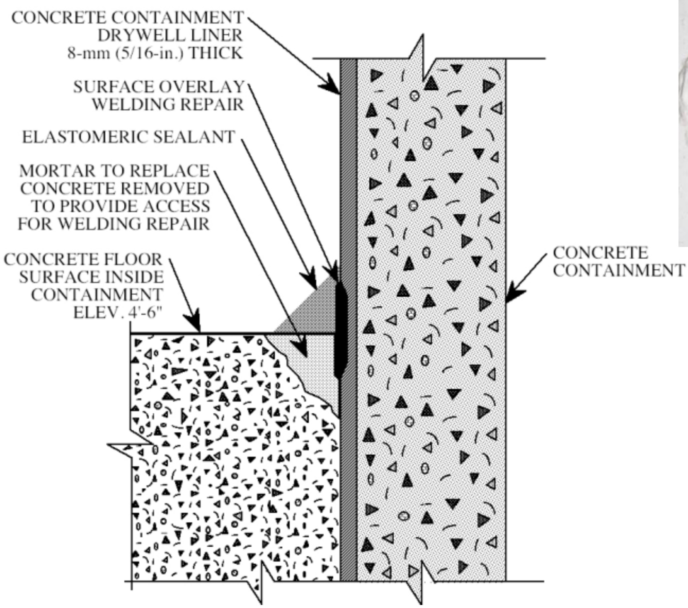
Anchor Head Failure

Containment Dome Delamination Repair

Concrete Wall Water Infiltration

# Operating Experience (OpE): – backside liner corrosion

## Moisture Barrier Degradation




**Conceptual Drawing Illustrating Liner Repair**

## Several plants have identified liner corrosion perforation between 1999 and 2009

**Paint Blister**


**After Corrosion Product Removal**

**Embedded Wood**



**After Removal of Containment Concrete for SGR Replacement**

**D.S. Dunn, A.L. Pulvirenti, and M.A. Hiser, "Containment Liner Corrosion Experience Summary Technical Letter Report," USNRC, August 2, 2011 (ADAMS ML112070867).**

**J.P. Petti, D.J. Naus, A. Sagüés, R.E. Weyers, B.A. Erler, and N.S. Berke, "Nuclear Containment Steel Liner Corrosion Workshop: Final Summary and Recommendations Report," SAND2010-8718, July 2011 (ADAMS ML112150012).**

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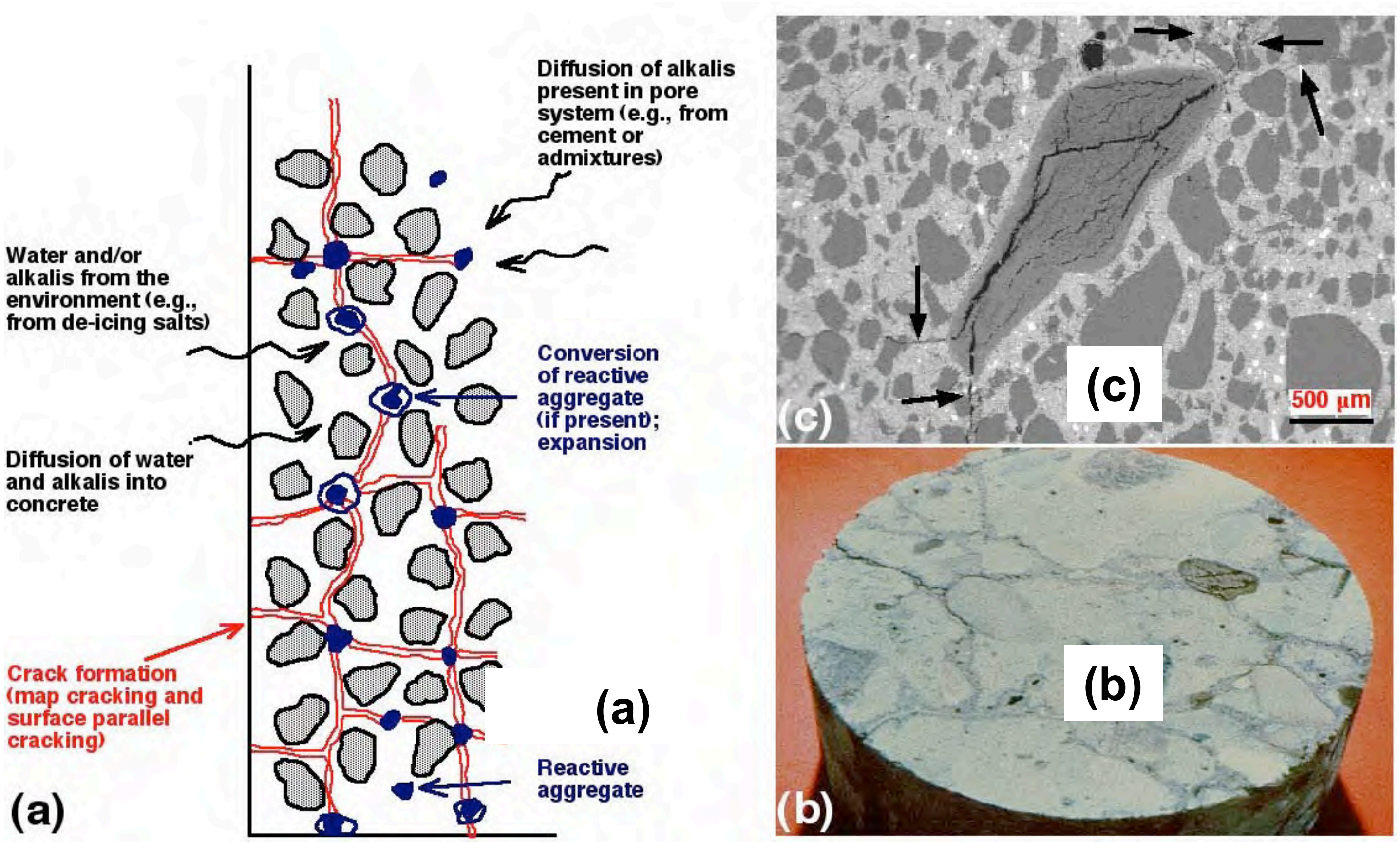
# Alkali-aggregate reactions

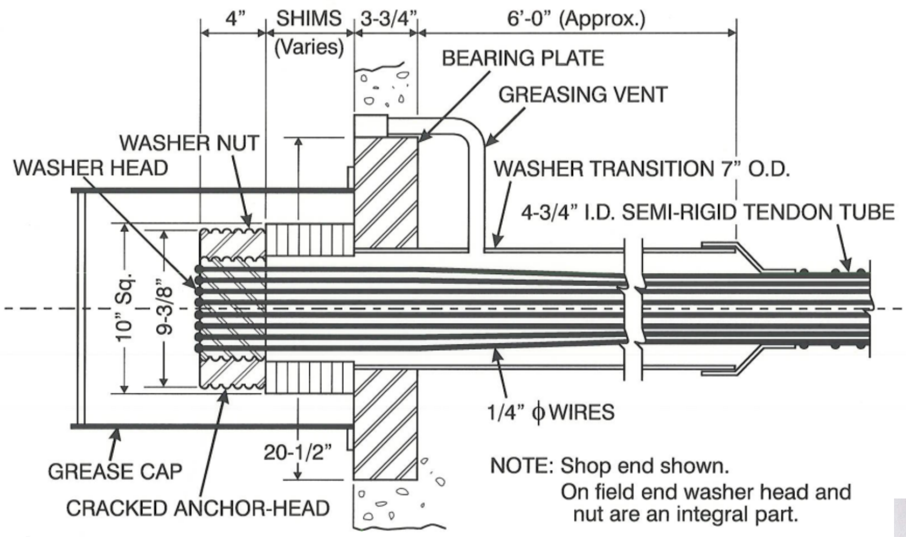


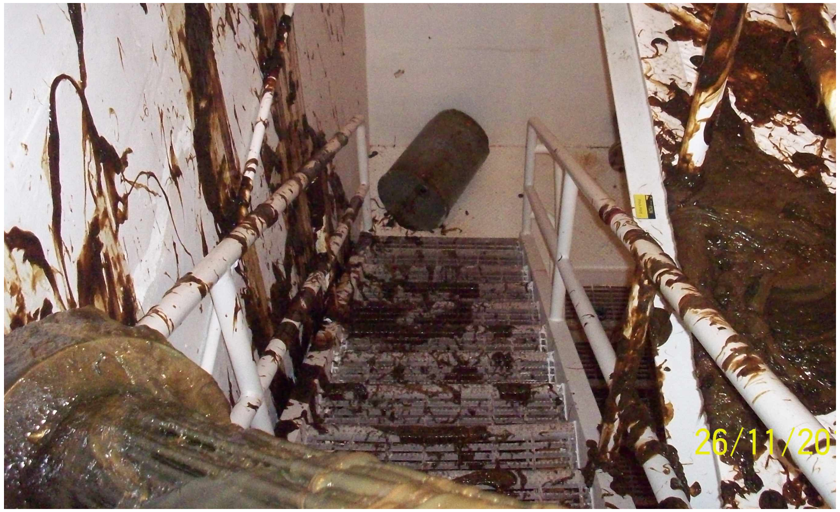

**(a) Mechanism**

**(b) Resulting gel that causes expansion and cracking**

**(c) Polished section showing internal cracking**

# Tendon anchor head failure




170 wire prestress system

# Concrete inspections identified areas of interest

- Licensees conduct periodic visual inspection of concrete structures, however the inspection criteria for visual inspection vary from plant to plant

- The GALL report recommends use of ACI 349.3R for frequency and quantitative inspection criteria.

- NRC issued Information Notice 2010-12 to inform licensees about recent issues involving corrosion of the steel liner of the reactor containment building

- NRC issued Information Notice 2010-14 to inform licensees about operating experience related to containment concrete surface condition examination frequency and acceptance criteria

# Concrete inspections identified areas of interest

- NRC issued Information Notice 2011-20 to inform licensees about potential for concrete degradation due to alkali-silica reaction

- NRC issued Information Notice 2013-04 to inform licensees of the occurrence of laminar subsurface cracks in reinforced concrete shield building

- NRC  issued Information Notice 2014-07 to inform Degradation of Leak-Chase Channel Systems for floor welds of metal containment shell and concrete containment metallic liner

# NRC Sponsored Concrete Research – A few examples

- In-service Inspection Guidelines for Concrete Structures ORNL/NRC/LTR-95/14, Dec 1995
- Ageing of Nuclear Power Plant Reinforced concrete Structures NUREG/CR-6424, March 1996
- Inspection of Inaccessible Regions of Containment Metallic Pressure Boundaries ORNL/NRC/LTR-02/02 June 2002
- Primer on Durability of Nuclear Power Plant Reinforced Concrete Structures NUREG/CR-6927, Feb 2007
- Elevated Temperature Effects on Concrete NUREG/CR-6900, March 2006 and NUREG/CR-7031, Dec. 2010
- Radiation Effects on Concrete NUREG/CR-7171, Nov 2013

# Expanded Materials Degradation Assessment (EMDA)Results

**In the EMDA Report (NUREG/CR-7153 Vol. 4), three important degradation modes identified for concrete structures.**

1. **Irradiation effects on concrete microstructures** (low knowledge but high significance)
2. **Alkali-silica reaction** (well documented in the scientific literature but need to assess its structural significance)
3. **Creep-Cracking interaction of the post-tensioned containment** (not visible on the surface; undetectable degradation mode)

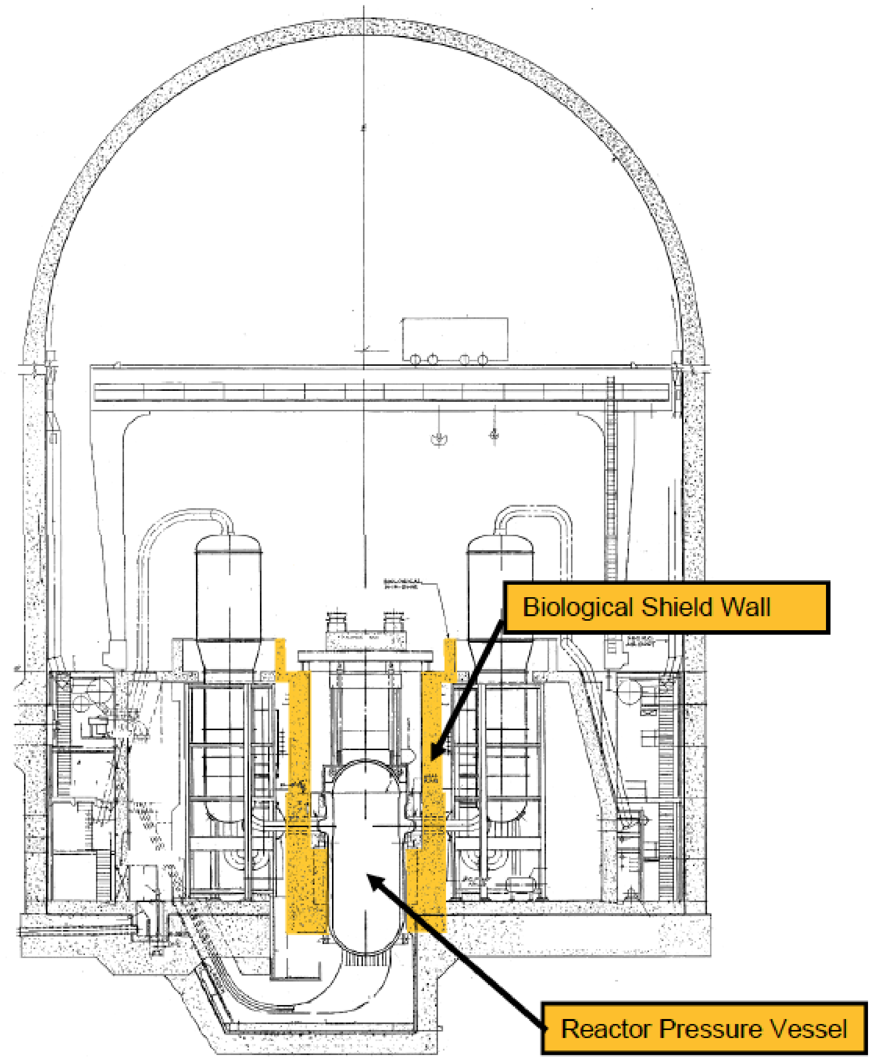
**Two highest degradation modes identified for steel components of the containment are:**

1. **The corrosion and stress corrosion cracking of the tendons**
2. **The corrosion of the inaccessible side of the liner (absence of a current in-service inspection technique)**

# Effects of Irradiation on Concrete

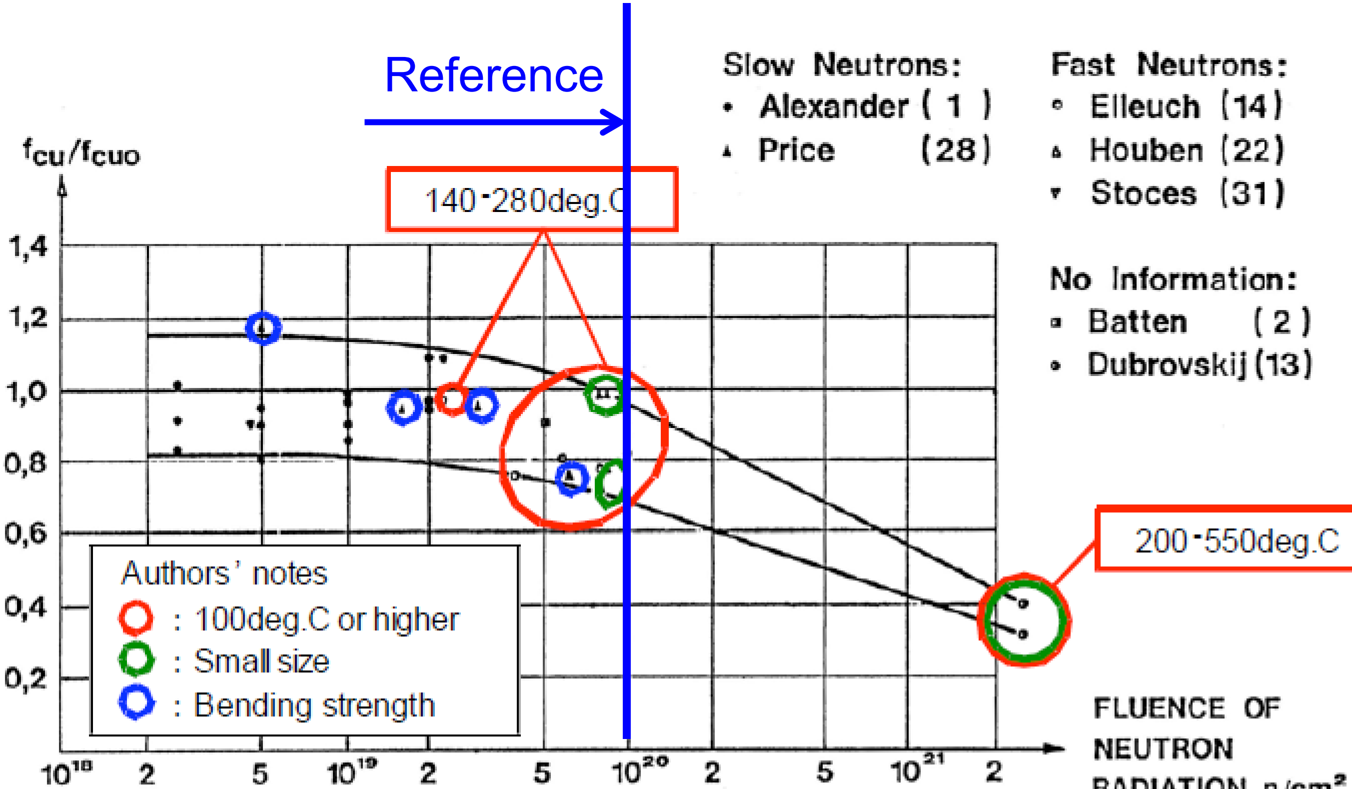
Data and information on irradiation effects on concrete microstructure and performance are limited

Area of Interest:
– RPV cavity
– RPV support pedestal
– Biological shielding



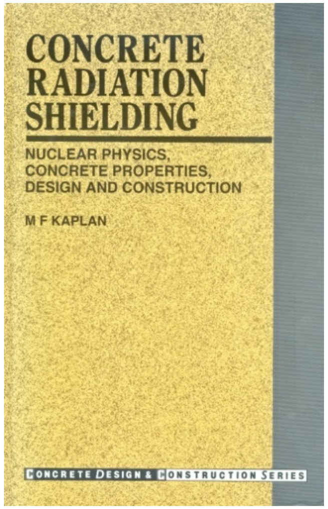

RPV - Reactor Pressure Vessel

# Effects of Irradiation on Concrete




Source: NUREG/CR-7171

**H.K. Hilsdorf, ACI SP-55, American Concrete Institute, 1978.**




**Literature**

**Sampling and Testing**

# Effects of Irradiation on Concrete – Research Strategy

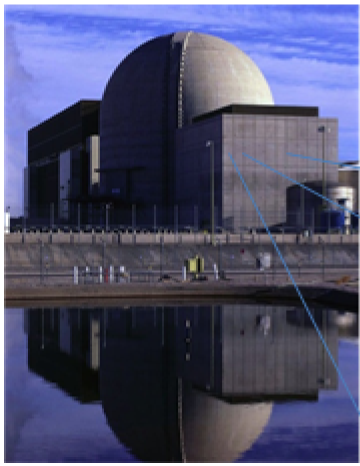
- Characterize the radiation field and determine fluence level in the biological shield wall and RPV support at 80 years or more
- Irradiate prototypical concrete and evaluate
- Harvest service irradiated concrete and evaluate
- Determine the effects of neutrons, gamma and temperature on concrete for potential degradation
- Develop mechanistic understanding of the effects of radiation on concrete
- Collaborate and leverage knowledge and capabilities

# Research sponsored by NRC- Effects of Irradiation on Concrete

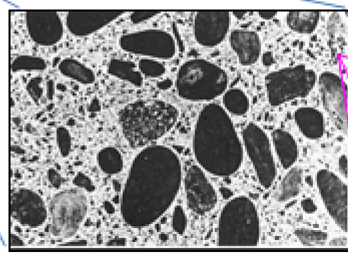
- NRC began to study the effects of irradiation on concrete since 2008.
- It started discussion within the NRC and also with U.S. industry, academic representatives, and Japanese researchers on this topic.
- NRC started a research program with Oak Ridge National Laboratory for light water reactors and also for new reactor designs.

# Research sponsored by NRC- Effects of Irradiation on Concrete

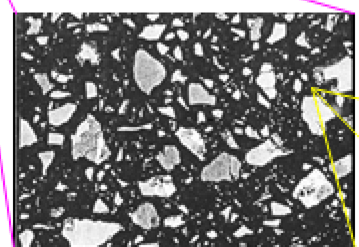
Internal structure of aggregates is more or less of crystalline nature while internal structure of cement paste is not. Responses of crystalline and non-crystalline materials to gamma rays and neutron radiation are different



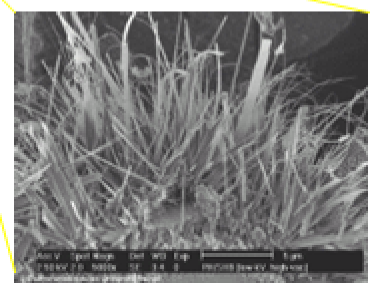
Macrostructure:
A reinforced concrete containment structure



Mesostructure
(Random distribution of gravels, sand particles, and cement paste)



Microstructure of cement paste (Random distribution of hydration products and pores)



Nanostructure of CSH

Approximately 70% of concrete volume is occupied by aggregate material and 30% by cement paste having a large amount of micro-pores

# Research sponsored by NRC-Effects of Irradiation on Concrete

NRC sponsored research published NUREG/CR 7171, Nov. 2013.

Conclusions:

- Use of elevated temperature as a proxy for irradiation exposure
- Obtaining and testing samples from biological shields and RPV supports of decommissioned NPPs or research reactors
- Impact of neutron and gamma exposure on NPP structures after 40, 60, 80, and 100 years operation
- Significance of nuclear heating associated with irradiation

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# Effects of Irradiation on Concrete - Other efforts

- NRC sponsored ORNL to prepare a report on "On-Going Research Program on Irradiated Concrete Conducted by DOE, EPRI and Japan Research Institutions: Roadmap, Achievements and Path Forward"

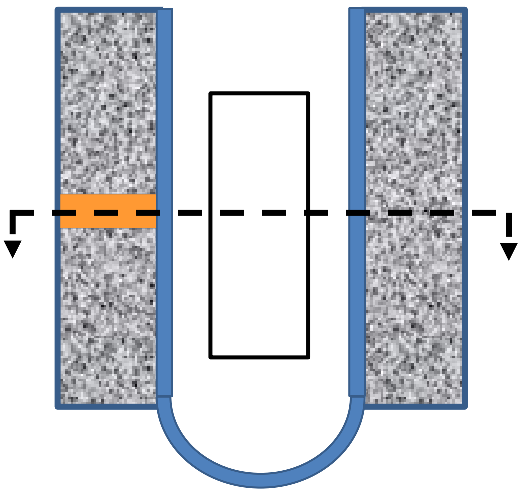
- International Collaboration on Effects of Irradiation on Concrete (ICIC) structures has been established – NRC is participating

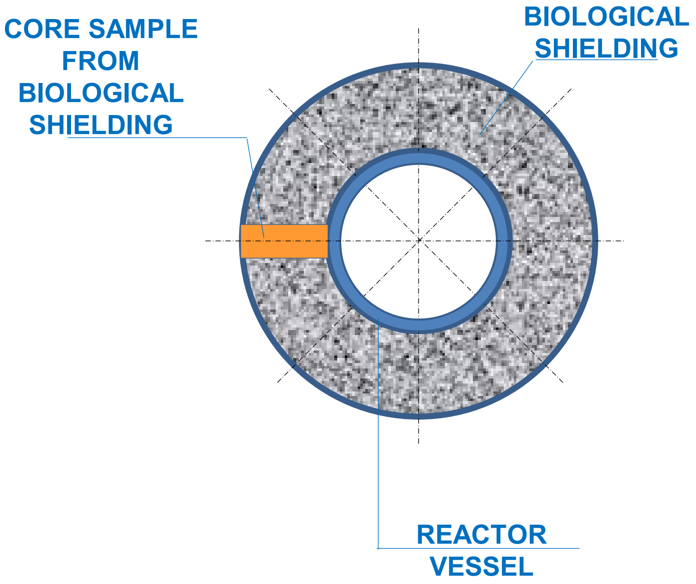
- Potential collaborative (NRC-DOE-EPRI) project for development of computational platform for quantitative evaluation of  structural significance

# Effects of Irradiation on Concrete - Other efforts

Potential harvest of concrete from decommissioned plants

- Zorita (26.5 EFPY and 38 years of service)
- Zion (15 EFPY and 24 years of service)
- Other






Zorita Concrete Project: Information from CSN

# Effects of Irradiation – Zorita Concrete Project

**Zorita Concrete Research Project - Radiation effects on concrete.**

**The plant operated from 1968-2006 with 26.5 effective full power years (EFPY)**

- High neutron fluence in a commercial service reactor
- Synergy with Zorita Reactor Internal Project (ZIRP)
- Decommissioning started in 2010, concrete coring planned for March 2015. Funded by the Spanish partners
- A formal cooperative agreement between NRC and CSN is in place
- Additional funding needed if additional sample/testing required

# Effects of Irradiation – Zorita Concrete Project

Continued

## Zorita Concrete Research Project

- NRC is informed through the NRC-CSN MOU
- NEA countries have also been informed through the Spanish delegate on the subgroup on concrete of IAGE/CSNI
- It was also discussed in IAEA June meeting for collaborative research project

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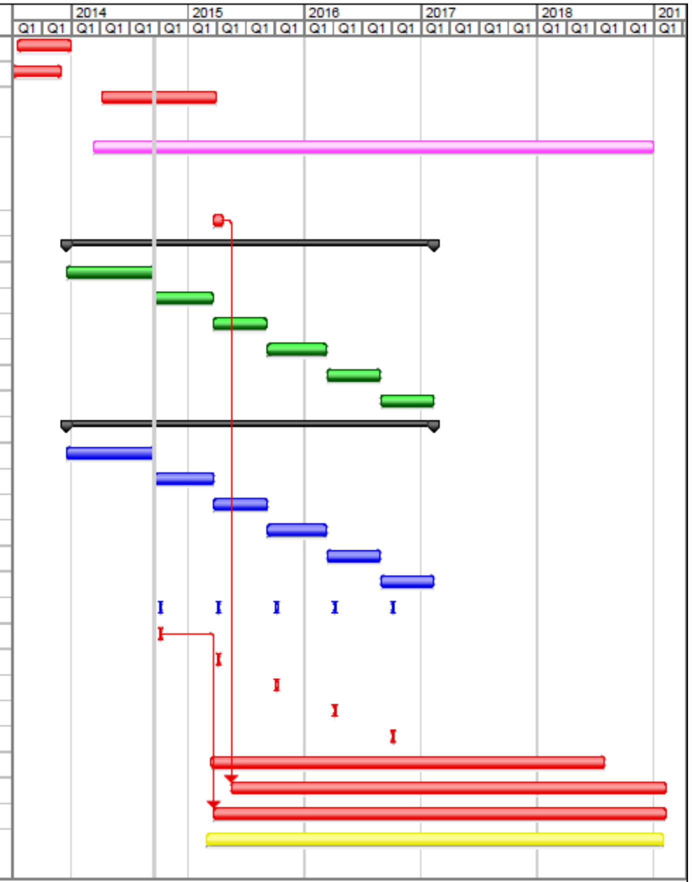
# Research Plan: Effects of Irradiation on Concrete

1. Current status and identifying the gaps
2. Bounding fluence for neutron and gamma
3. Stay informed
4. Participate multi-lateral collaborations to leverage knowledge and capabilities
   - Harvest concrete
   - Testing of the specimens
   - Evaluate degradation
   - Structural/mechanical properties
   - Computational framework for structural evaluation
   - NDE/NDT
5. Confirmatory testing/evaluation

# Effects of Irradiation on Concrete Research Timeline

| ID | | Task Name | Duration | Start | Finish | Predecessors |
|---|---|---|---|---|---|---|
| 1 | | EMDA Report - GAPs | 6 mons | Wed 07/17/13 | Tue 12/31/13 | |
| 2 | | NUREG/CR 7171 | 110 days? | Mon 07/01/13 | Fri 11/29/13 | |
| 3 | | Radiation Effects on Concrete - Ongoing Research Status | 257 days? | Mon 04/07/14 | Tue 03/31/15 | |
| 4 | | NRC Information Collection - ICIC/IAEA/CSNI/Zorita Concrete Research/ Japan Bilateral | 1254 days? | Wed 03/12/14 | Mon 12/31/18 | |
| 5 | | Zorita, Zion Concrete Harvesting | 1 mon | Tue 03/24/15 | Mon 04/20/15 | |
| 6 | | **EPRI Research** | **41.15 mons?** | **Wed 12/18/13** | **Fri 02/10/17** | |
| 7 | | EPRI Research P1 | 198 days? | Wed 12/18/13 | Fri 09/19/14 | |
| 8 | | EPRI Research P2 | 6.55 mons? | Fri 09/19/14 | Fri 03/20/15 | |
| 9 | | EPRI Research P3 | 6 mons? | Mon 03/23/15 | Fri 09/04/15 | |
| 10 | | EPRI Research P4 | 6.7 mons | Tue 09/08/15 | Fri 03/11/16 | |
| 11 | | EPRI Research P5 | 6 mons | Mon 03/14/16 | Fri 08/26/16 | |
| 12 | | EPRI Research P6 | 6 mons | Mon 08/29/16 | Fri 02/10/17 | |
| 13 | | **LWRS Research** | **41.15 mons?** | **Wed 12/18/13** | **Fri 02/10/17** | |
| 14 | | LWRS Research P1 | 198 days? | Wed 12/18/13 | Fri 09/19/14 | |
| 15 | | LWRS Research P2 | 6.55 mons? | Mon 09/22/14 | Mon 03/23/15 | |
| 16 | | LWRS Research P3 | 6 mons? | Tue 03/24/15 | Mon 09/07/15 | |
| 17 | | LWRS Research P4 | 6.7 mons? | Tue 09/08/15 | Fri 03/11/16 | |
| 18 | | LWRS Research P5 | 6 mons? | Mon 03/14/16 | Fri 08/26/16 | |
| 19 | | LWRS Research P6 | 6 mons? | Mon 08/29/16 | Fri 02/10/17 | |
| 20 | | **Review Research Findings** | **26.25 mons** | **Mon 10/06/14** | **Fri 10/07/16** | |
| 21 | | Review Research Findings 1 | 5 days | Mon 10/06/14 | Fri 10/10/14 | |
| 22 | | Review Research Findings 2 | 5 days | Mon 04/06/15 | Fri 04/10/15 | |
| 23 | | Review Research Findings 3 | 5 days | Mon 10/05/15 | Fri 10/09/15 | |
| 24 | | Review Research Findings 4 | 5 days | Mon 04/04/16 | Fri 04/08/16 | |
| 25 | | Review Research Findings 5 | 5 days | Mon 10/03/16 | Fri 10/07/16 | |
| 26 | | NRC-DOE-EPRI Collaborative Research | 881 days? | Mon 03/16/15 | Mon 07/30/18 | |
| 27 | | NRC Research on Harvested Concrete | 974 days? | Mon 05/18/15 | Thu 02/07/19 | 5 |
| 28 | | NRC Research - Confirmatory (EPRI/DOE/Zo | 1013 days? | Tue 03/24/15 | Thu 02/07/19 | 21 |
| 29 | | NRC-CSN Zorita Concrete Research under MOU | 51.2 mons? | Mon 03/02/15 | Thu 01/31/19 | |




Project: Radiation Plan V1
Date: Tue 09/16/14

| | | | | | |
|---|---|---|---|---|---|
| Task | | Milestone | | External Tasks | |
| Split | | Summary | | External Milestone | |
| Progress | | Project Summary | | Deadline | |

# On-going and Planned work: Effects of Irradiation on Concrete

On-Going and Planned work (Domestic and International) – Accelerated Irradiation of Prototypical Concrete

- LWRS Program at Oak Ridge National Laboratories
- EPRI-LTO Program
- Zorita concrete Project
- IAEA Collaborative Research Plan (possibility)

# Alkali Silica Reaction

EMDA report identified alkali-silica reaction degradation of concrete for assessing its potential consequences on the structural integrity

NRC began a research project at NIST this year on the ASR degradation mechanism.

The second half of RES’s presentation today will review the research plan in more detail.

# Creep-fracture and Posttensioned Containment

EMDA report also identified creep of the posttensioned containment as a knowledge gap.

For a posttensioned containment maintaining the prestressing force is very important.

Contributors for prestress loss include friction, slip at the end anchorage, elastic shortening, tendon relaxation, creep and shrinkage.

Out of these tendon relaxation, creep and shrinkage are related to ageing.

Sometime it is necessary to re-tension the tendons to regain the required level of prestressing. Periodic re-tensioning may introduce cyclic activation of primary creep and can damage the concrete. Creep-fracture could be a potential degradation mode for prestress concrete containment.

# EMDA Report: Creep-Fracture on Prestressed Concrete Containments

- Creep and shrinkage of concrete coupled with elastic shortening and relaxation of tendons can lead to various short term and long term losses of the prestressing forces on tendons
- Creep of concrete under complex three-dimensional states of stress around prestress duct may lead to creep-induced split cracking (delamination-like cracking) from combined hoop and vertical prestressing and evolve with time
- Split cracking or lamellar cracking may occur during initial prestressing, during re-tensioning, de-tensioning, or repair/replacement

# Round Robin Study on Containment Post-tensioning Methods – Grouted vs Greased

- OECD/NEA CAPS – Started in Oct 2010, Final Report – Review by the WG complete, to be submitted for OECD approval.

The objective of this research is to investigate the structural response of concrete containment with grouted and greased tendon system. The study includes the review of the following three tasks:

  - Study on Containment Structural Behavior for severe accident and Failure Modes
  - Comparison of Posttensioning and In-service Inspection Methods
  - Assessment of Durability and Long-Term Corrosion Protection

- Organization doing work: Sandia National Laboratories
- Final NUREG/CR under review

# Research Related to In-service Inspection (ISI)

- Review of current ISI methods for posttensioned concrete containment with grouted and ungrouted tendons and its applicability to newer higher strength materials.

- Review of methods of monitoring of the posttensioned containments by instrumentation.

- The results of this research will be used to update regulatory guides.

- The research was started in March 2012 and expected to be completed by December 2015.

# Nondestructive Examination (NDE)

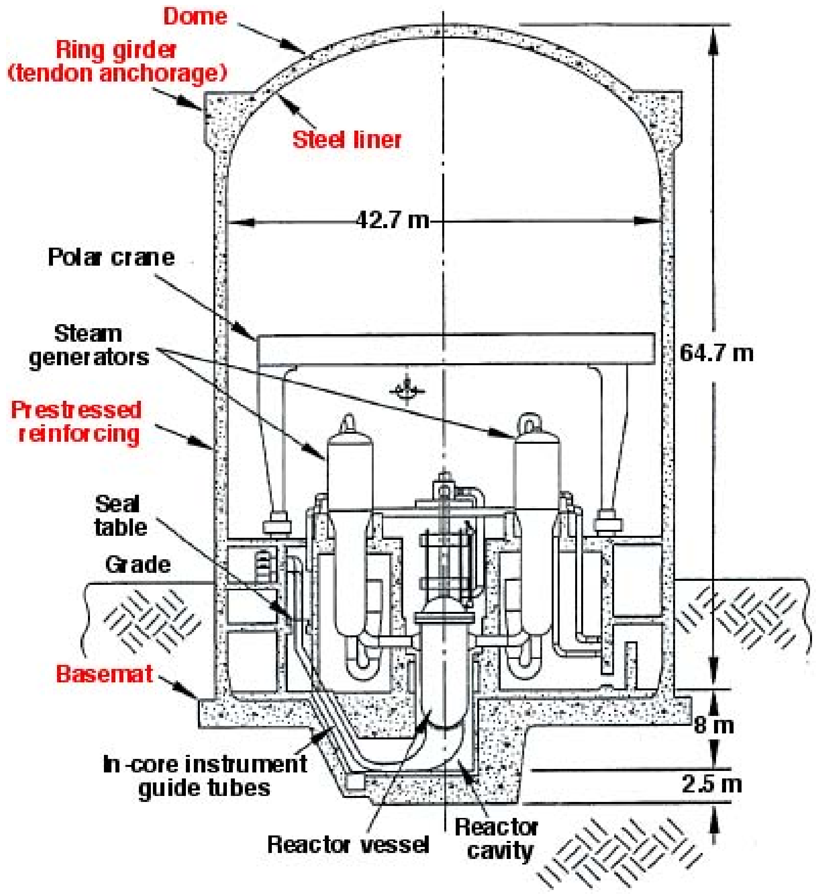
Extending plant life beyond 60 may likely increase the probability and severity of the known form of degradations. In addition, new mechanisms of degradation may come in to play. One of the main objective of LWRS program is to develop technologies and other solutions that can improve the reliability, sustain the safety over the subsequent period of operation of the nuclear power plants.

- As a part of that effort, a LWRS Concrete NDE Workshop was held at Oak ridge National Laboratory Conference Center, on July 31, 2012.

- NRC participated in the workshop - a roadmap for future research needs was developed under LWRS Program

- Report “Light Water Reactor Sustainability Nondestructive Evaluation for Concrete Research and Development Roadmap,” ORNL/TM-2012/360, September 2012

# Nondestructive Examination Improvements are desired




**PWR Large Dry**
**Prestressed Concrete Containment**

- **Thick, heavily reinforced concrete sections**
  - **As-built or current structural features**
  - **Flaw detection and characterization**
  - **Honeycomb and embedded items**
  - **Voids adjacent to liner**
- **Basemats and other inaccessible areas**
  - **Based on indirect approach (i.e., environmental qualification)**
- **Liners –**
  - **Global inspection methods**
  - **Inaccessible areas**
- **Prestressing tendons**
  - **Real-time techniques to monitor post-tensioning systems for tendon wire failures and level of stressing**

# Nondestructive Examination (NDE)

Gaps identified in the LWRS NDE Workshop

- Need to survey available samples
- Technique(s) to perform volumetric imaging on thick reinforced concrete sections
- Determine physical and chemical properties as a function of depth
- Techniques to examine interfaces between concrete and other materials
- Development of acceptance criteria – model and validation
- Need for automated scanning system for any of the NDE concrete measurement systems

# Subsequent License Renewal GALL Revision

- License renewal guidance documents are being revised for subsequent license renewal (SLR)
- There are 8 Structural Aging Management Programs (AMPs) in the GALL.
- RES structural staff are the technical leads for 7 of them.
- Findings of the EMDA report are factored in the revision process

# Concrete Degradation - Dry Cask Storage System (DCSS)

- A new project has just started for evaluation of concrete degradation modes for spent fuel dry cask storage systems

- The project has two phases:

  - Regulatory program review for first 60 years of system operation for SFST

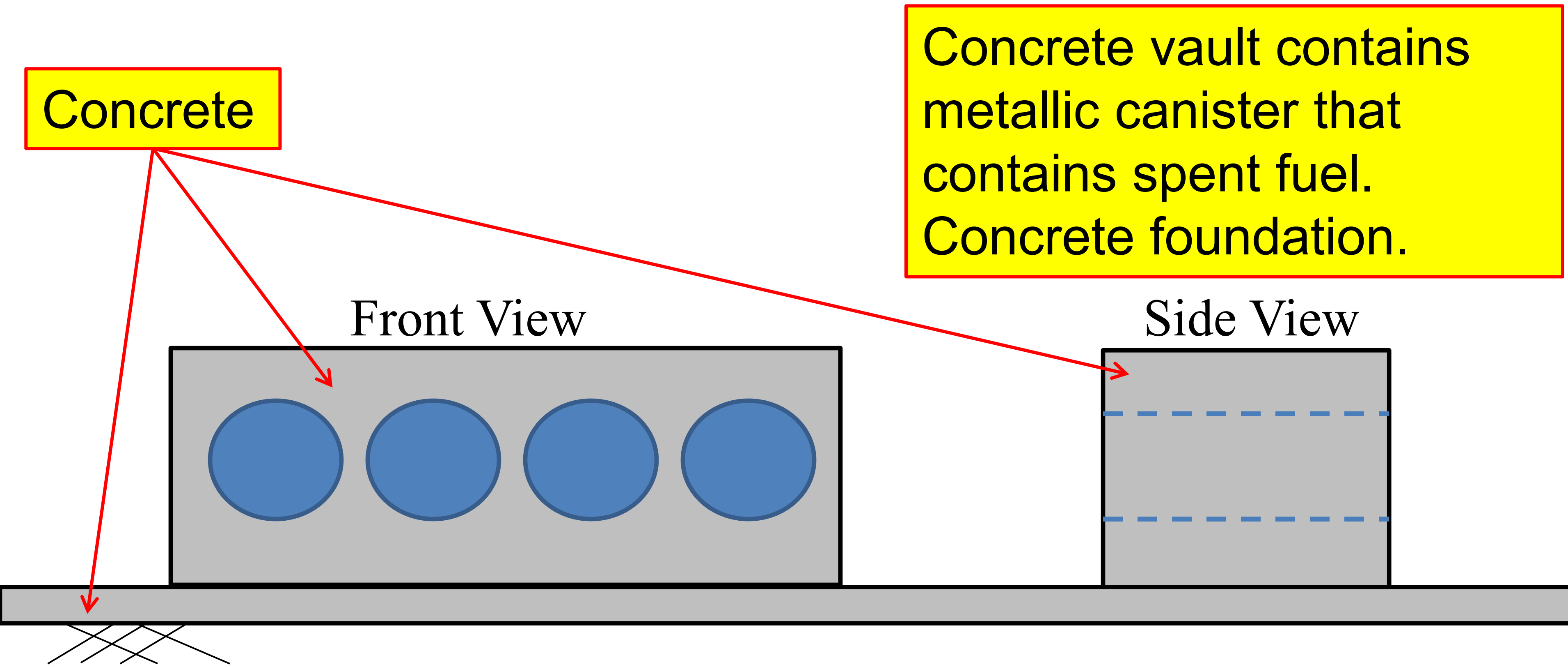
  - Regulatory program review for operation up to 300 years for SFAS

- Expert panel being planned to evaluate concrete degradation modes for dry cask storage up to 300 years – Planned for Nov/Dec - 2014

**SFST – Spent Fuel Storage and Transportation Strategies**

**SFAS - Spent Fuel Alternative**

# Horizontal Vault DCSS



# Participation in Codes, Standards and International Committees

- ASME Codes – Section III Div. 2 – Concrete Containment – joint committee with ACI 359
- ASME Section XI – In-service Inspection
- ACI 349
- Nuclear Energy Standard Coordination Collaboration
- American Society of Nondestructive Examination

# Participation in Codes, Standards and International Committees

- OECD NEA CSNI Concrete Working
- RILEM Technical Committee on ASR Degradation of Nuclear Concrete Structures
- International Collaboration on Irradiated Concrete
- Bilateral agreement with Japan
- MOU with Spain

**OECD NEA CSNI – Organization for Economic Co-operation and Development Nuclear Energy Agency Committee on the Safety of Nuclear Installations**
**RILEM – International union of laboratories and experts in construction materials, systems and structures**

# Contact RES/DE/SGSEB

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# Thanks

Discussion
Q&A

# Concrete Degradation Research
## Introductory Remarks


**Jacob Philip**

***Senior Geotechnical (Civil) Engineer***
***RES/DRA/ETB (301) 251-7471, jxp@nrc.gov***


***September 19, 2014***

***Advisory Committee for Reactor Safeguards***

# Background

**RES/DRA/ETB**

- **Two central issues – both focused on the materials properties of concrete (service life)**
  - **Long term performance of concrete waste isolation structures (LLW, Entombment, WIR) and waste forms (Saltstone) – NIST, and Cement Barriers Partnership (MOU among NRC, DOE and NIST) (FSME user needs starting in early 90's)**

  - **Degradation of nuclear power plant concrete structures (NRR user need on alkali-silica reaction, ASR) and Non Destructive Testing (NDT) and Sensor Technology for Concrete Structures for concrete service life prediction**

# Todays discussions

- **Current research on ASR**
  - **Dr. Ken Snyder – Overview of concrete degradation**
  - **Dr. Fahim Sadek and Dr. H.S. Lew – Experimental investigations of concrete structures affected by ASR**
  - **Dr. Ken Snyder – Material investigations supporting bulk experiments**
- **Cementitious Barriers Partnership**
  - **Dr. David Kosson – Overview of CBP activities**

# International Activities

- **RILEM technical committee on ASR degradation of nuclear concrete structures**
- **OECD/NEA/CSNI collaborative program on concrete degradation**
- **Joint international workshop at NIST, July, 2015**

# Concrete Degradation

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Materials and Structural Systems Division
Engineering Laboratory

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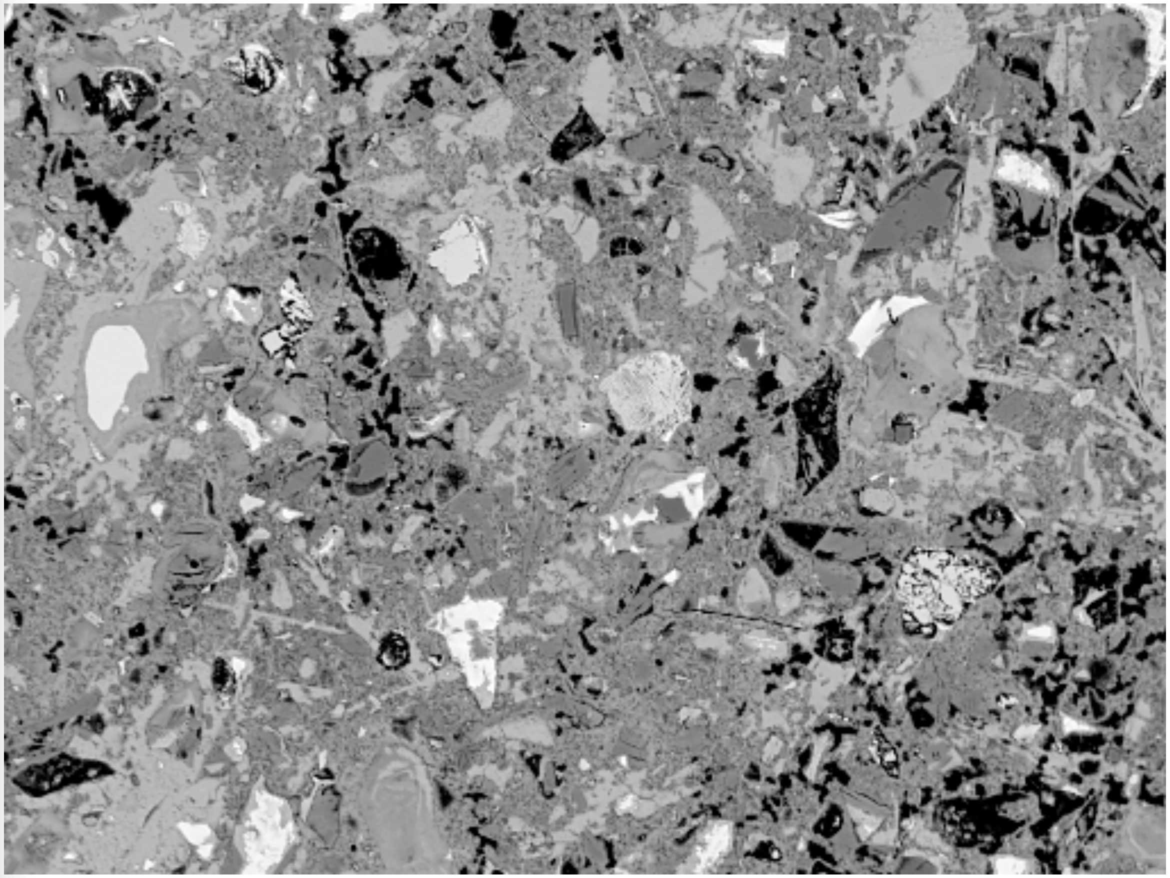
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

# Presentation Overview

- Overview of Concrete Degradation
- Underlying Mechanisms: Physical & Chemical
- Impact on Durability & Strength
- NIST-NRC Activities
- ASR: Mechanism / Tests / Detection

# Hydrated Paste Under the Microscope



500 μm

Reaction continues for months or years

Paste = Cement + Water + Hydration

Water plays a critical role:
- It is required for the reaction
- Loss of water can cause cracking

| | |
|---|---|
| C-S-H | 50% |
| Portlandite | 35% |
| Hydrogarnet | 7% |
| Ettringite | 3% |
| Hydrotalcite | 2% |
| AFm | 1% |

Poorly Ordered    Crystalline

*Hydrated paste is a multi-phase porous material, with the pores in contact with all the hydrated phases.*

*The pore solution contains dozens of dissolved species and has a pH in the range 13 - 13.5*

# Degradation Processes

- Corrosion of Steel Reinforcement
- Alkali-Aggregate Reaction:
  - Alkali-Silica Reaction (ASR)
  - Alkali-Carbonate Reaction (ACR)
- Sulfate Attack
- Freeze-Thaw
- Leaching: loss of material
- Others…

The cracking created by one degradation process could accelerate a subsequent process.

# Chemical Attack Primer

- Most often initiated by interactions with the environment
- Involve transport through the hardened cement paste
  - diffusion, permeation, sorption, conduction, etc.
- Typically involve chemical reactions with mineral phases:
  - Phases within the paste
  - Phases within the aggregate
- Involve expansive reaction products, or leaching
- Expansive forces/loss of material, lead to stresses
- Sufficient stress creates cracks in the paste
- Cracks reduce mechanical strength
- Cracks increase the rate of transport

# Degradation Defenses

- Reduce the severity of the environment: *new location*
- Isolate the concrete from the environment: *coatings*
- Reduce the rate of transport: *tighter microstructure*
- Delay the onset of reaction: *corrosion inhibitors, AEA**
- Reduce the extent of the reaction: *minimize the reactants*
- Increase the capacity to resist the stresses: *tougher/fibers*

*Some approaches eliminate the problem, others merely delay the inevitable.*

* air entraining agent

# NIST-NRC Activities

Service Life Modeling: Cementitious Materials

- Supported performance assessment of engineering cementitious barriers
- Simulated electro-diffusive transport and chemical reaction (4sight)
- Incorporated synergistic effects of simultaneous degradation mechanisms
    - leaching and corrosion of steel reinforcement
- Related changes in the microstructure (reaction) to changes in transport coefficients
- Used parameter uncertainty
- Validated with laboratory measurements and published data
- Explored the use of Kalman filtering to improve parameter estimation
    - discussed its use as a monitoring tool

Status:

- Superseded by commercial SIMCO software (STADIUM)
- STADIUM advancing under the Cementitious Barriers Partnership (CBP)
- CBP: NRC; NIST; DOE; SIMCO; and Vanderbilt University (Nashville)
    - NIST: New models to relate changes in microstructure to changes in transport

# Alkali-Silica Reaction (ASR)

- Alkali hydroxides react with susceptible silicates
- These phases can be found in siliceous aggregates
  - e.g., chert, opal, microcrystalline or strained quartz
  - n.b., can also be found in some calcareous aggregates

- The reaction requires water
- The reaction product is an alkali-silica gel
- The gel incorporates water and grows in volume

The reaction can lead to excessive expansion and cracking

# Alkali-Silica Reaction: In Practice

**Environment:** moisture, wet/dry cycling
**Transport:** sorption and vapor diffusion
**Reactants:** alkali hydroxides, susceptible silicates
**Resultants:** alkali-silica gel

Strategies:

- Reduced water infiltration
- Reduce available alkalis through materials screening
- Create tighter microstructures by changing the mix design
- Use low alkali cements
- Test for reactive aggregates

# Alkali-Silica Reaction: Tests

## Standardized Tests:

ASTM C289 (Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates)

ASTM C227 (Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)

ASTM C1260 (Potential Alkali Reactivity of Aggregates: Rapid Mortar-Bar Test)

ASTM C1293 (Length Change of Concrete Due to Alkali-Silica Reaction)

ASTM C1567 (Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method))



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# Alkali-Silica Reaction: Gel Formation

## Aggregate-Paste Interface:

Expansive Gel Penetrates the Paste

Porosity Filling vs. Crack Formation

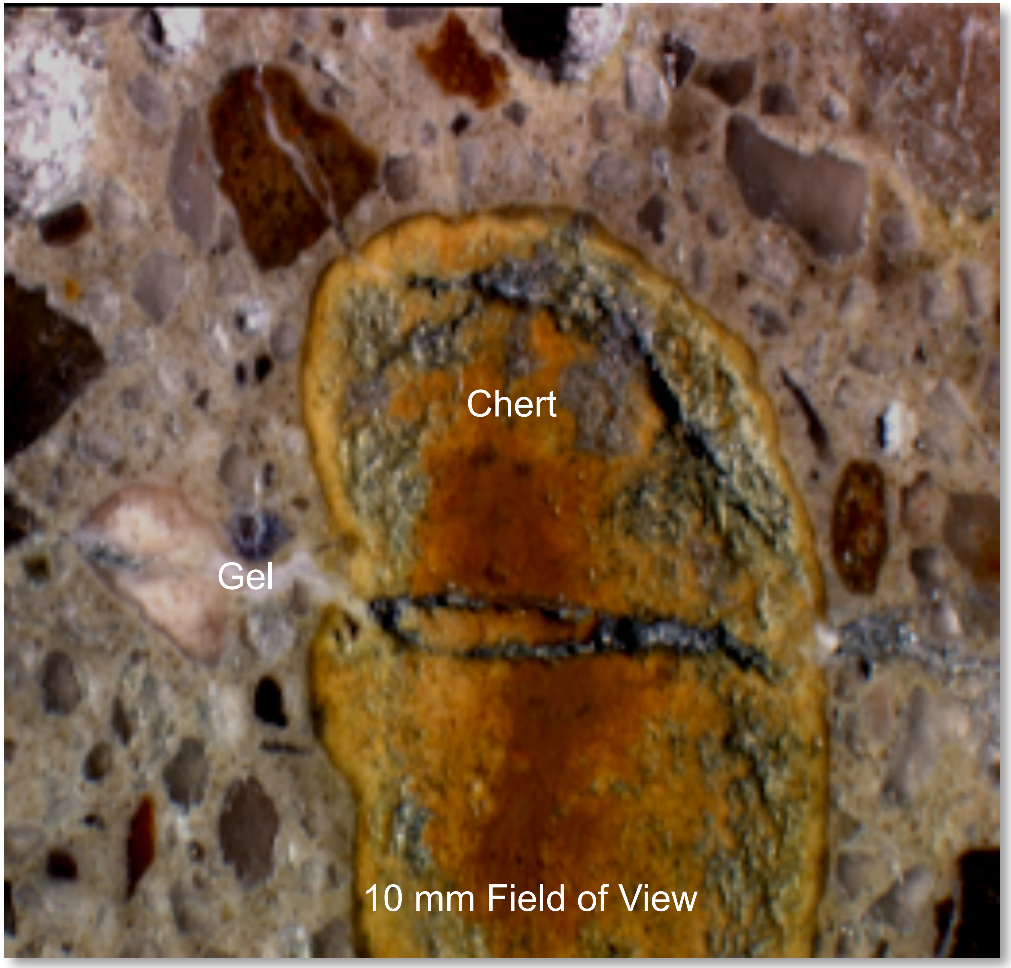
- Depends…

Porosity Filling Dynamics:

- Rate of gel production
- Porosity/Permeability of paste
- Viscosity of the gel

Potential Strength Gain?

- During porosity filling, but before crack formation
- Cementing properties of gel (in crack) is uncertain

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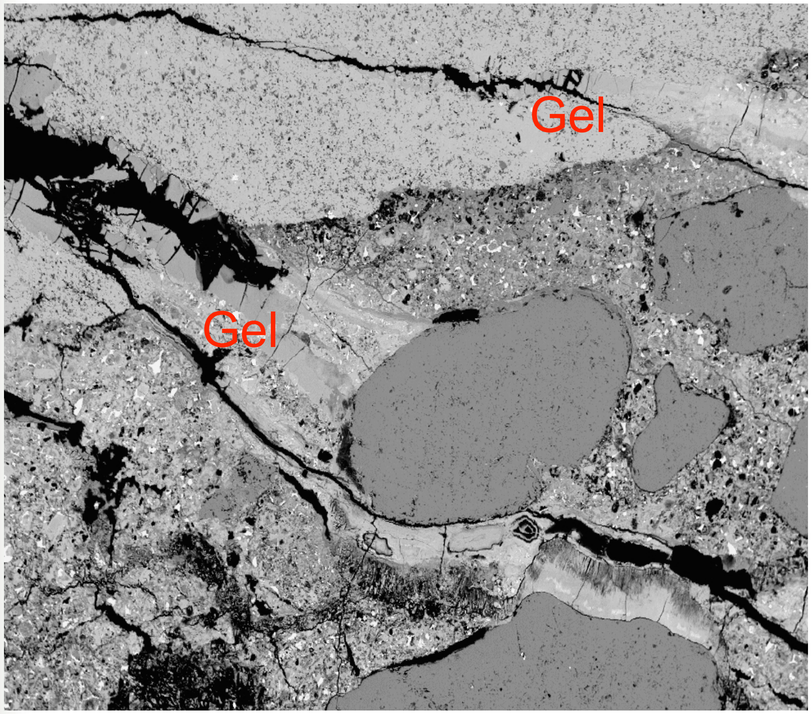
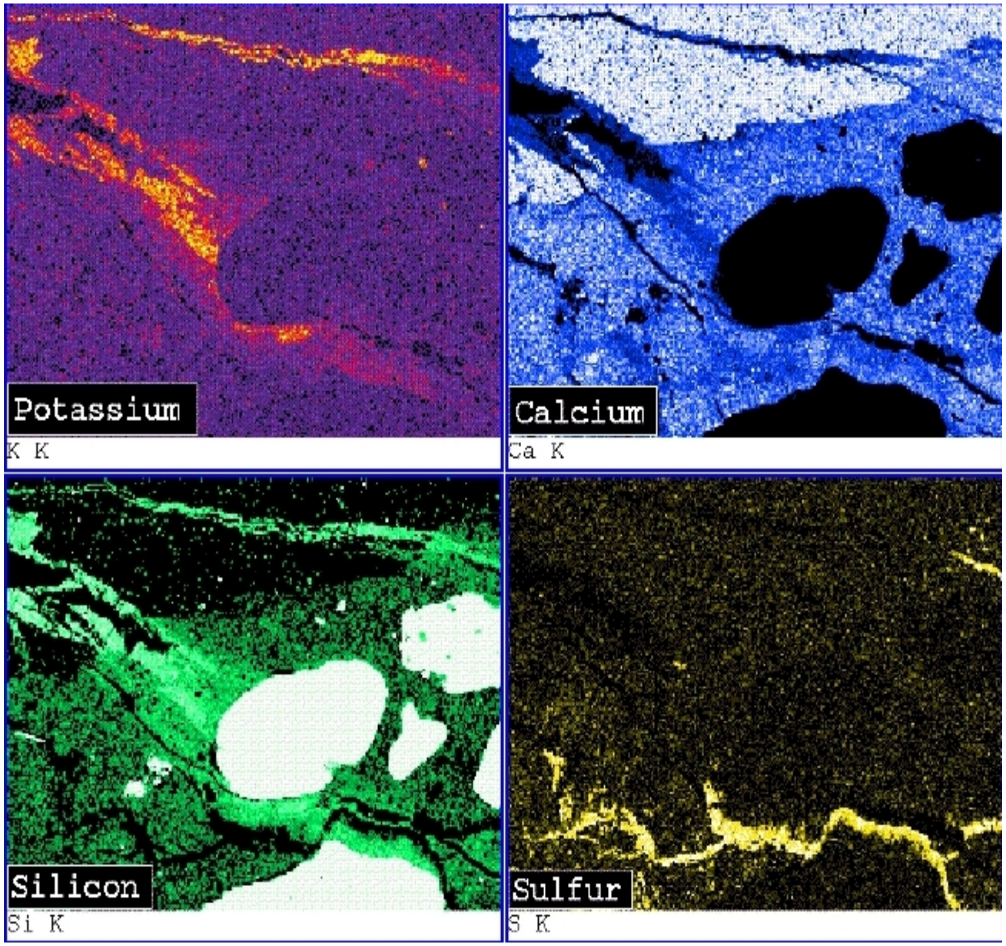
# Alkali-Silica Reaction: Detection

SEM imaging for identification of reaction gel

Backscattered Image




X-ray µ-Probe Elemental Mapping




Potassium seems to be a unique identifier for the ASR gel

# Structural Performance of Nuclear Power Plant (NPP):

# Concrete Structures Affected by Alkali-Silica Reaction (ASR)

Advisory Committee on Reactor Safeguards

Structural Analysis/Plant License Renewal Subcommittee Meeting

Concrete Degradation

September 19, 2014

H.S. Lew and Fahim Sadek

Materials and Structural Systems Division

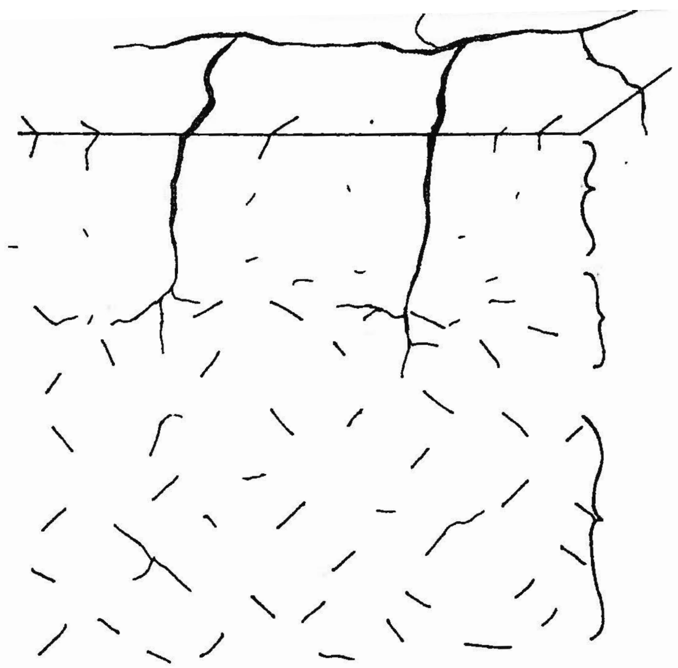
National Institute of Standards and Technology

National Institute of Standards and Technology

U.S. Department of Commerce

# Surface Cracking due to ASR

Surface cracks



Macro cracks in the direction normal to surface

Micro cracks parallel to surface

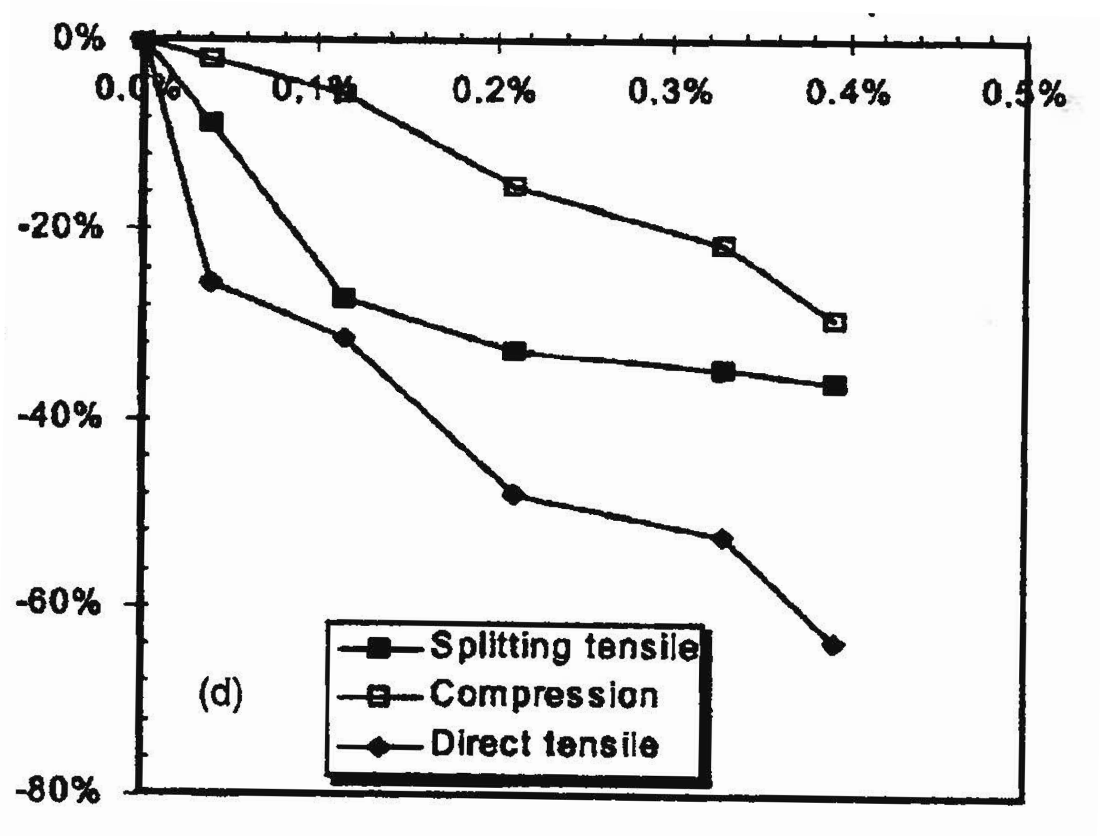
Random micro cracks unless restrained to expansion

- **ASR** can occur over time between the highly alkaline cement paste and reactive non-crystalline (amorphous) silica, found in many common aggregates.
- This reaction causes the expansion of the altered aggregate by the formation of a swelling gel of Calcium Silicate Hydrate.
- This gel increases in volume with water and exerts an expansive pressure inside the material, which may cause spalling and loss of strength of the concrete.

# Loss of strength and stiffness due to ASR

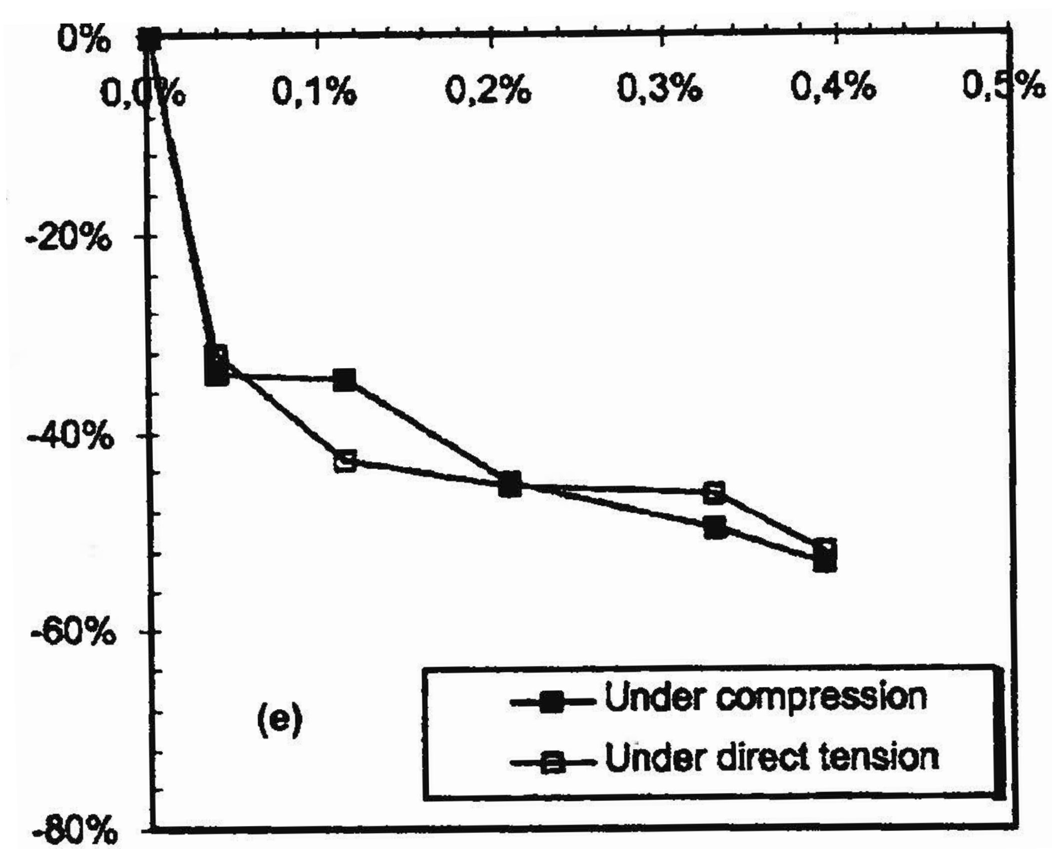
Expansion

Loss in strength




Expansion

Loss in modulus of elasticity



# Mechanical Properties of ASR-affected Concrete

**Normal Concrete**

$$f_{ct} = 6.7\sqrt{f'_c} \qquad \text{(psi)}$$

$$f_r = 7.5\sqrt{f'_c} \qquad \text{(psi)}$$

$$E_c = 33\, w_c^{1.5}\sqrt{f'_c} \qquad \text{(psi)}$$

$$l_d = \Phi f\left[\left(f_y/f_{ct}\right)\alpha\,\beta\,\gamma\right] d_b$$

**ASR-affected Concrete**

$$f_{ct} = A\sqrt{f'_c} \qquad \text{(psi)}$$

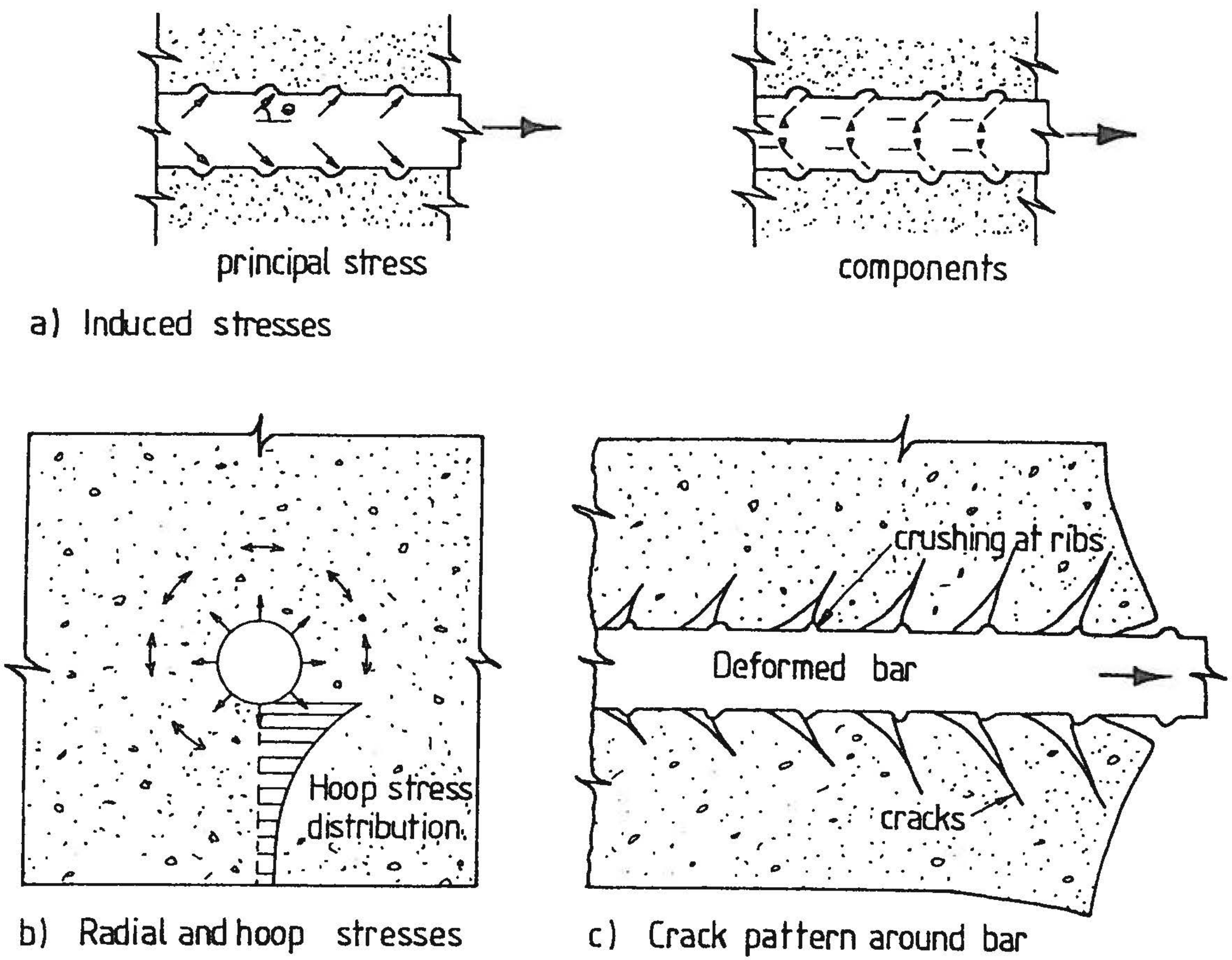
$$f_r = B\sqrt{f'_c} \qquad \text{(psi)}$$

$$E_c = C\, w_c^{1.5}\sqrt{f'_c} \qquad \text{(psi)}$$

$$l_d = \Phi f\left[\left(f_y/f_{ct}\right)\alpha\,\beta\,\gamma\right] d_b$$

# Loss of bond strength

## Bond (anchorage) Strength



# Overall Study Objective and Outcome

**Objective:**

To develop a technical basis and regulatory guidance for NRC to evaluate ASR-affected concrete structures. The research will assess the structural performance of ASR-affected concrete structures for design basis static and dynamic loading and load combinations through its service life, including the period of extended operation for the 20 year license renewal period.

**Outcome:**

A methodology to determine, for an existing ASR-affected structure;

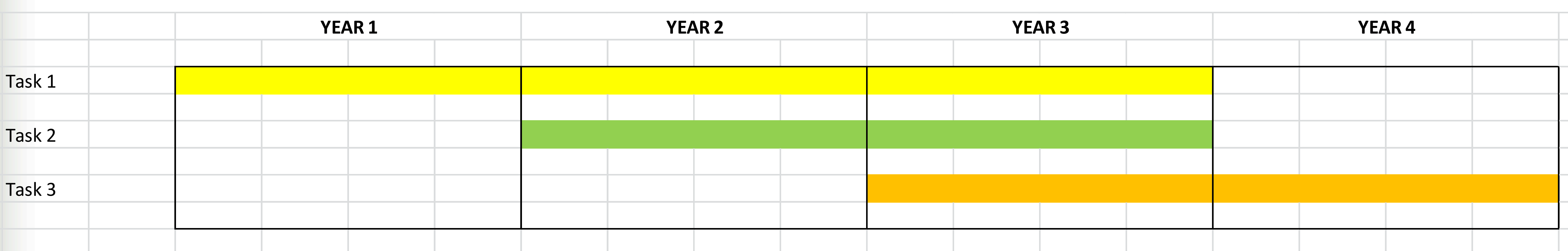
- Current structural capacity to resist static and dynamic loads, and
- Estimate of future structural capacity to resist static and dynamic loads.

# Technical plan

**Task 1:** Assessing In-Situ Mechanical Properties of ASR-Affected Concrete

**Task 2:** Assessing Development and Lap-Splice Lengths of Reinforcing Bars in ASR-Affected Concrete

**Task 3:** Seismic Response Characteristics of ASR-Affected Concrete Structural Members



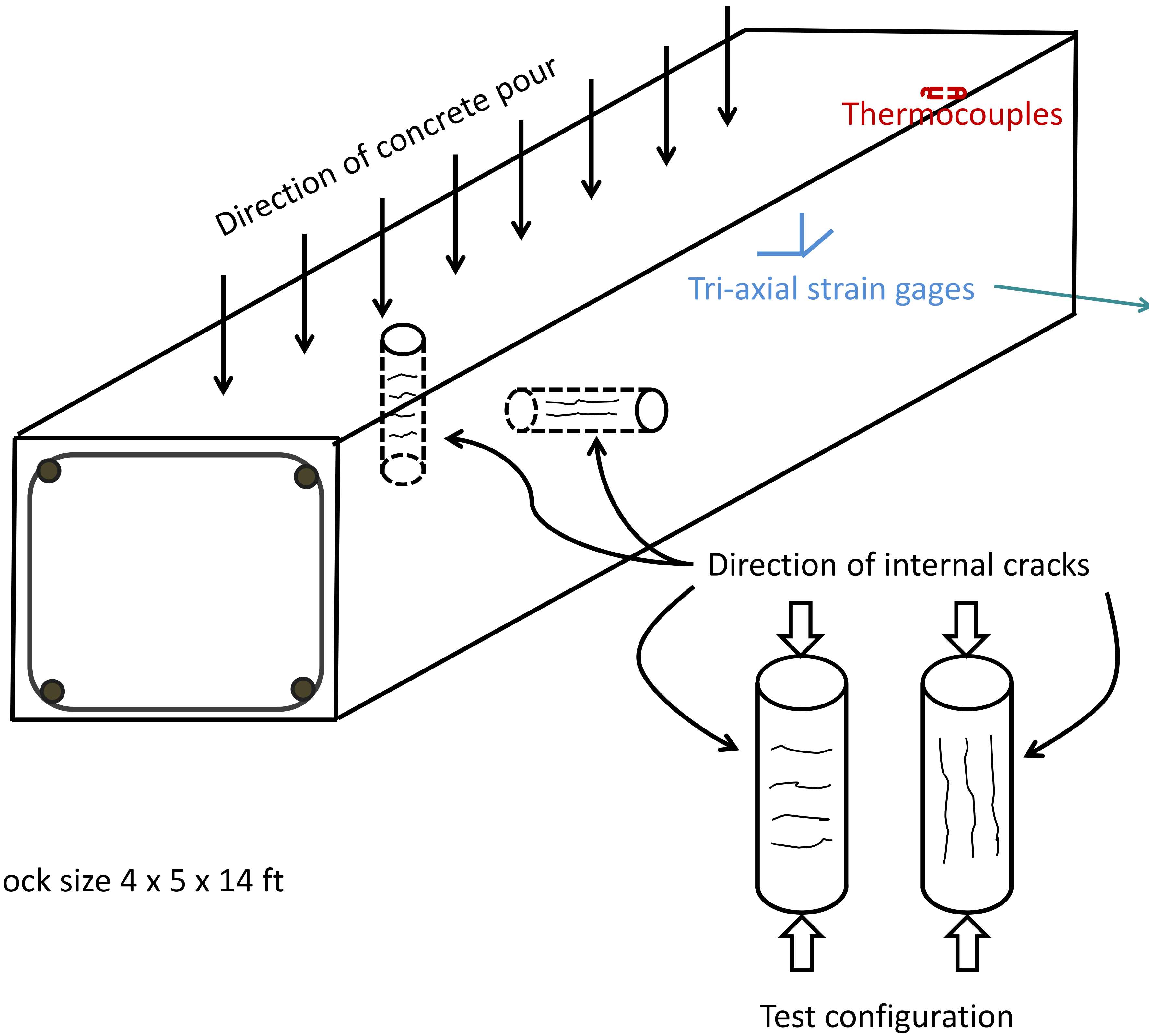
# Task 1: Assessing In-Situ Mechanical Properties of ASR-Affected Concrete

**Objective**:

To establish

- the relationship between expansion due to ASR and (1) concrete mechanical properties and (2) surface cracking of concrete, and
- the effectiveness of hoop reinforcement (i.e., stirrups) in confining expansion of concrete due to ASR.

# Task 1: Assessing In-Situ Mechanical Properties of ASR-Affected Concrete



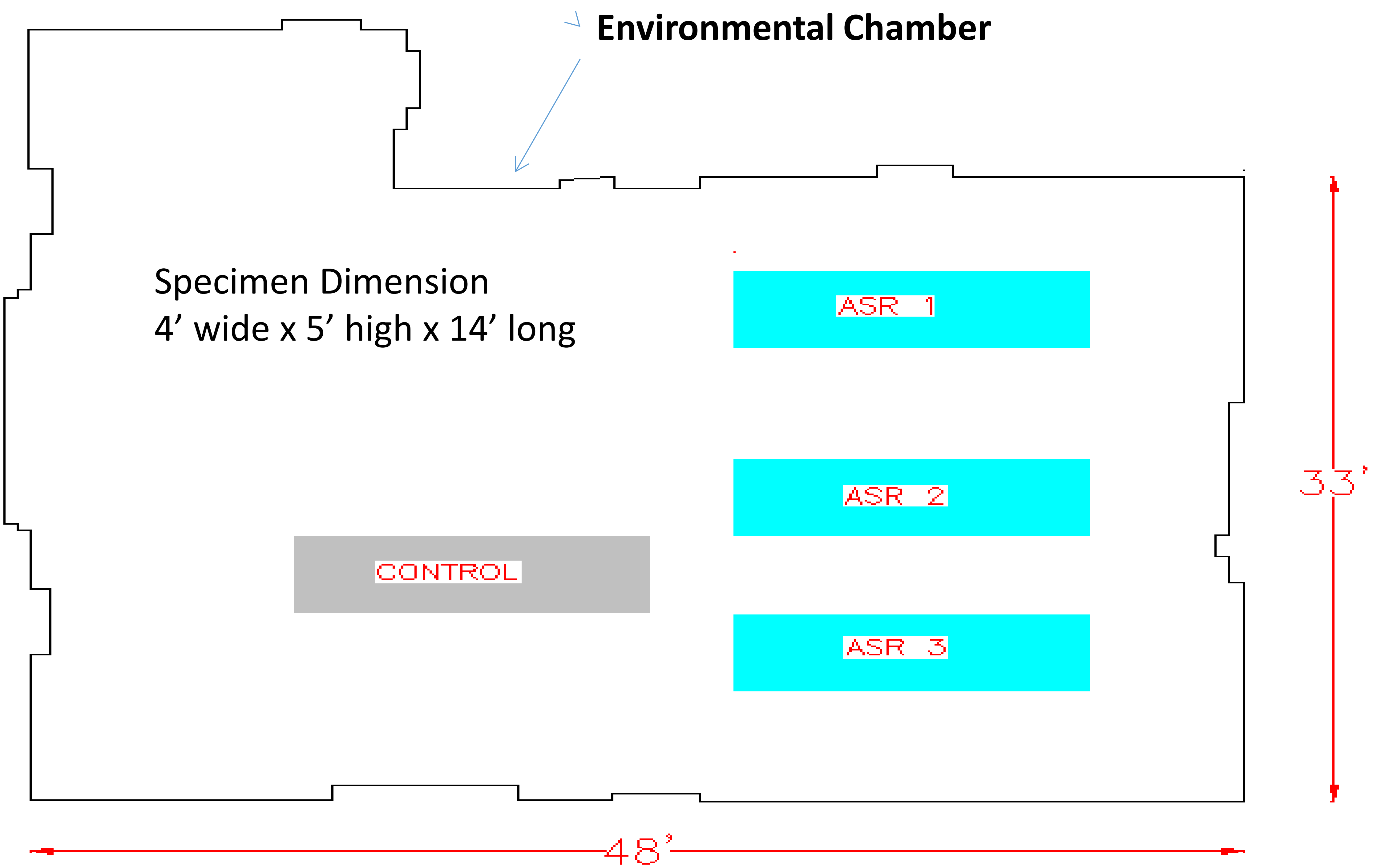

Block size 4 x 5 x 14 ft

# Task 1: Assessing In-Situ Mechanical Properties of ASR-Affected Concrete

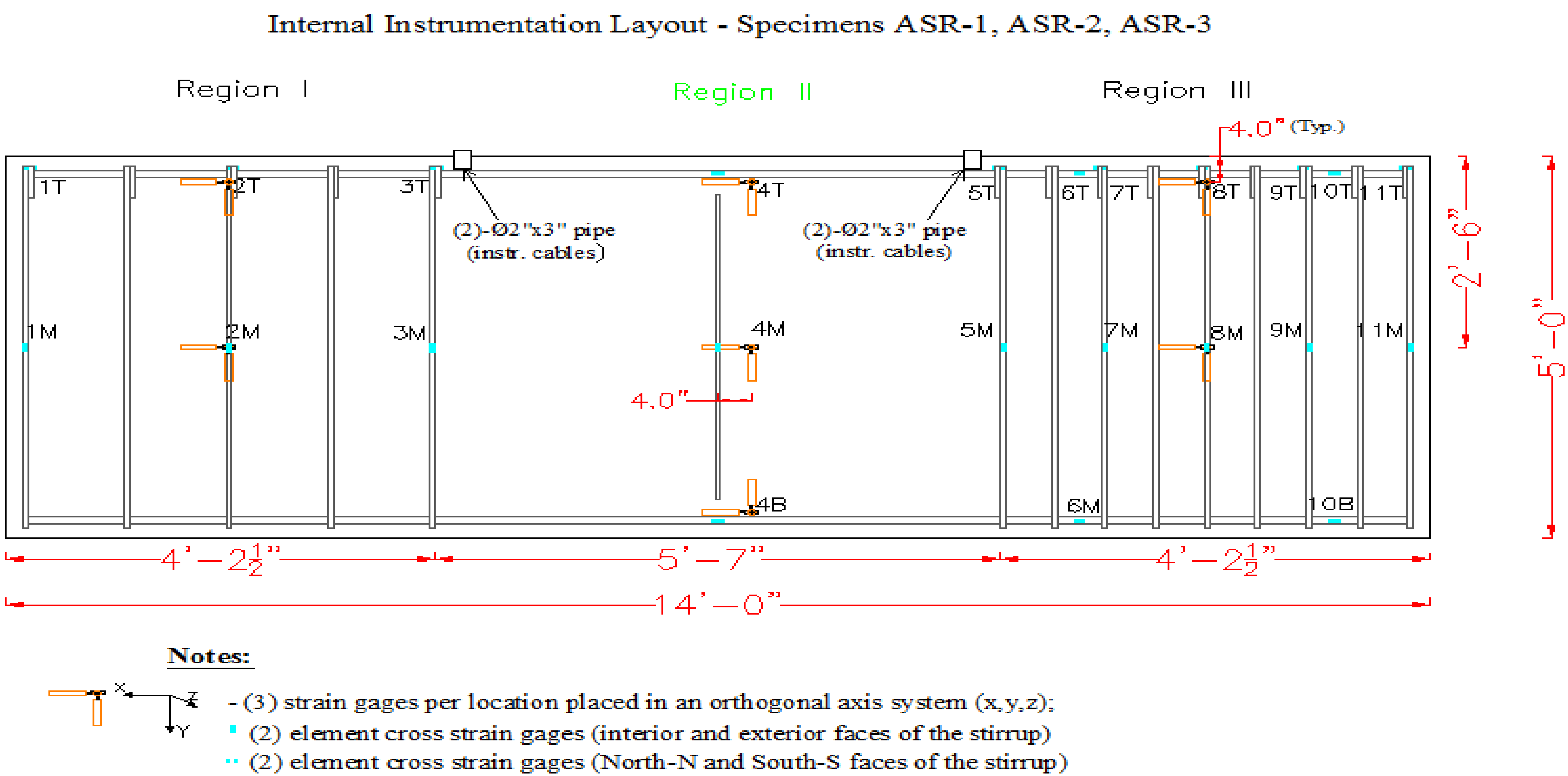
**Approach**:

- Three large concrete block specimens made with three different reactive aggregates along with a control (non-reactive) block specimen will be cast. The three large block specimens will be fabricated with hoop stirrups placed at different spacings.
- Blocks will have tri-axial strain gauges embedded at selected locations to measure internal expansion of concrete due to ASR and overall expansion of the blocks using laser tracking system and demountable mechanical (DEMAC) gauges.
- Cores will be removed from the block specimens, and compressive and tensile tests under confinement pressure will be performed to determine the mechanical properties of the concrete as the ASR reaction progresses.
- Advanced computational modeling of the concrete blocks will be conducted to correlate the state of strain at the center of the block with surface cracking at various levels of reaction/expansion. The modeling results will be validated using measurements and observations from the test blocks.

# Specimen Layout in Curing Chamber

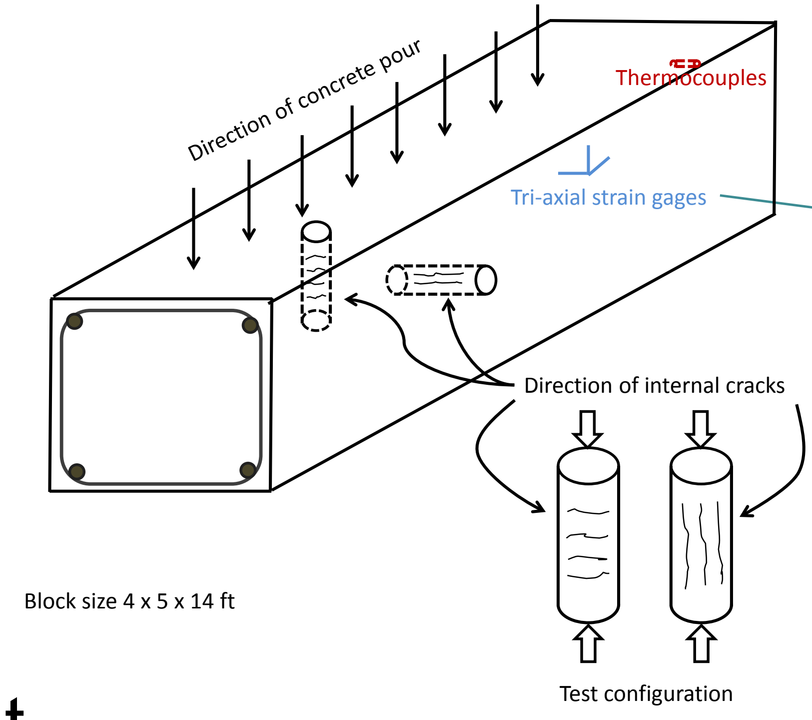


# Reinforcement Layout



# Instrumentation Plan

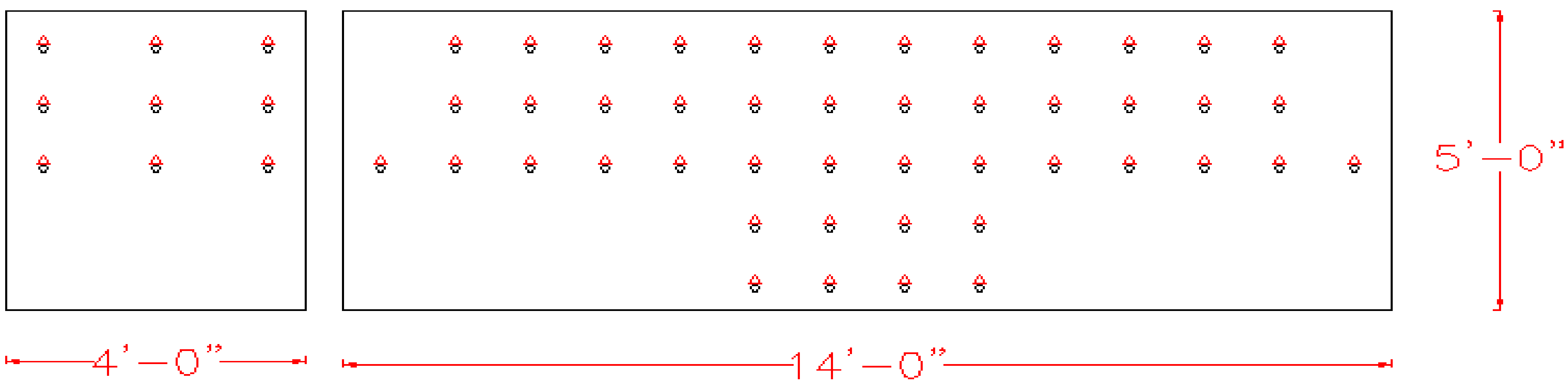
## **Strain Measurement Instruments**:




- ❑ Core concrete strain measurement
  - Tri-axial transducers
- ❑ Concrete surface strain measurement
  - DEMAC (Demountable Mechanical) gauges
  - Laser tracking device
- ❑ Reinforcing bar strain measurement
  - SR-4 strain gauges

# Surface Strain Measurement

DEMEC and Laser targets Layout – ASR1, ASR2 and ASR3 Specimens
Side View and End View




**Notes:**

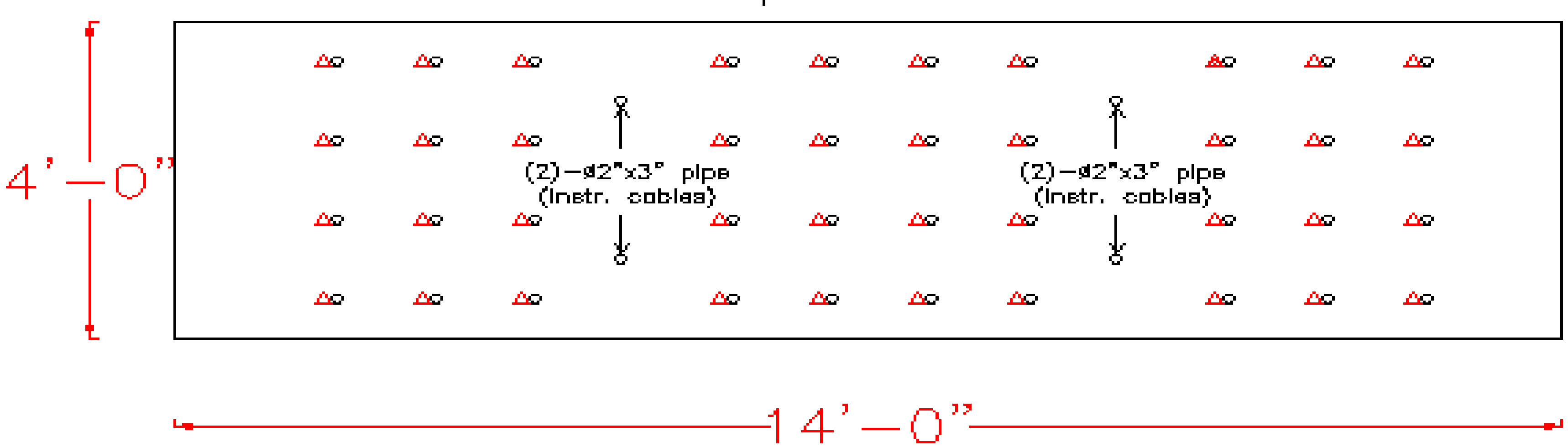
△ DEMEC target
∘ Laser target

Laser targets are following the same layout as DEMEC targets, with a 1.5" center to center offset.

A total of 450 DEMEC targets for ASR-1, ASR-2 and ASR-3 Specimens

A total of 450 Laser targets for ASR-1, ASR-2 and ASR-3 Specimens

DEMEC and Laser targets Layout – ASR1, ASR2 and ASR3 Specimens
Top View

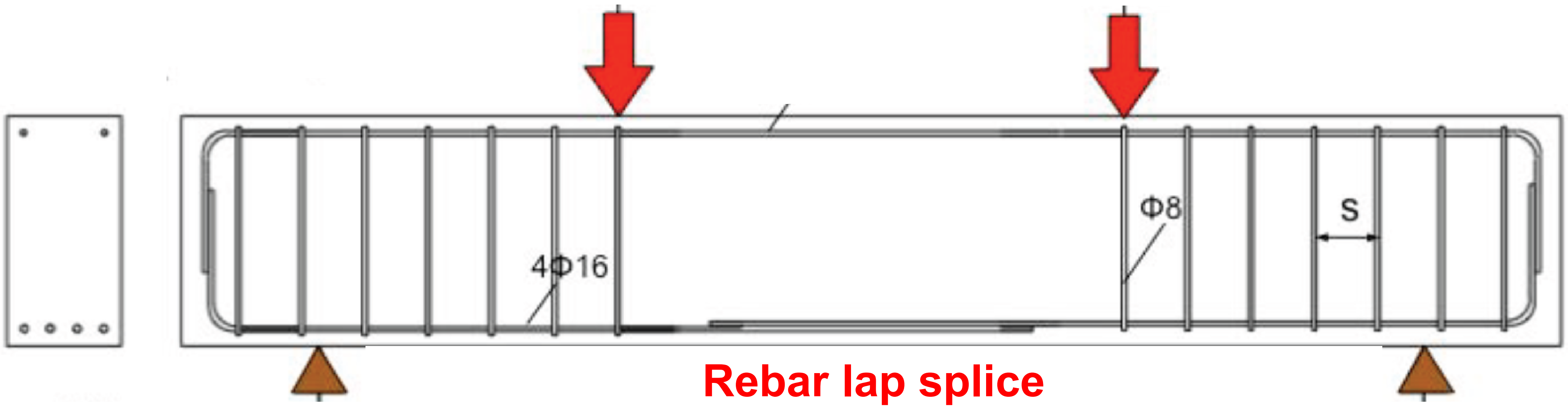


## Task 2: Assessing Development and Lap-Splice Lengths of Reinforcing Bars in ASR-Affected Concrete

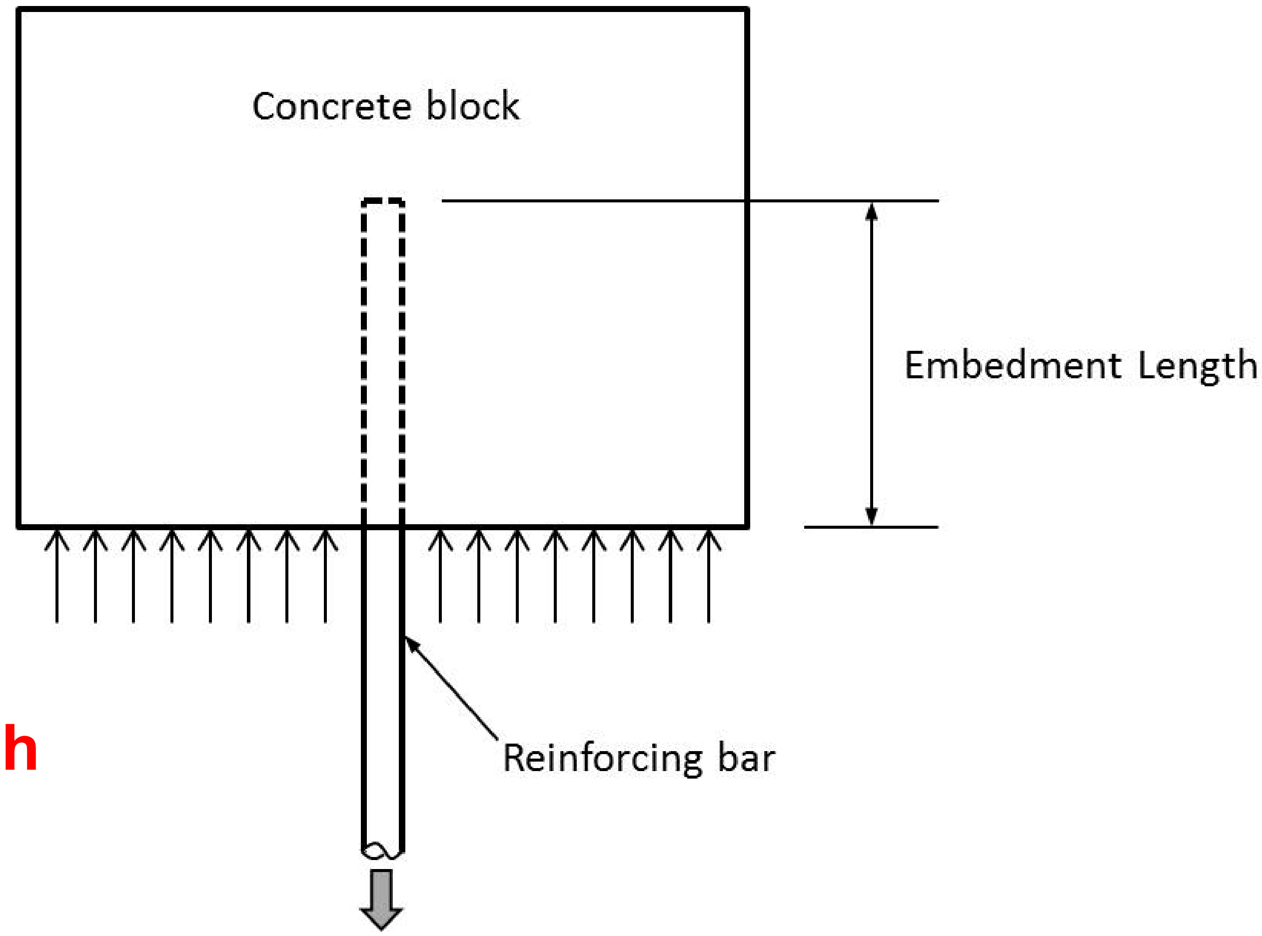
**Objective**:

To develop a methodology for assessing the effects of ASR on development length of steel reinforcement including (1) lap splices in flexural members, and (2) axially loaded reinforcing bars.  The methodology will address the degree of loss of anchorage and flexural capacities.

# Task 2: Assessing Development and Lap-Splice Lengths of Reinforcing Bars in ASR-Affected Concrete




**Rebar lap splice**




**Rebar embedment length**

# Task 2: Assessing Development and Lap-Splice Lengths of Reinforcing Bars in ASR-Affected Concrete

## **Approach**:

(a) Effect of ASR on lap splices of flexural reinforcement

- Cast 16 rectangular ASR-reactive reinforced concrete beam specimens along with two additional non-reactive beam specimens. Two different sizes of reinforcing bars will be used.
- Lap splices will be placed in the constant moment region of four-point loading test setup with and without transverse reinforcement. Spliced reinforcing bars will be instrumented with strain gauges to detect the loss of bond strength.
- Perform static four-point loading tests periodically over a period of two years. Results of the tests including load, strain, and deflection measurements will help determine the degradation in bond strength as the ASR reaction takes place.

## **Approach**:

(b) Effect of ASR on embedment length of reinforcement

- Cast 16 rectangular ASR-reactive reinforced concrete block specimens along with two additional non-reactive block specimens. A single reinforcing bar will be embedded in the block. Two different sizes of reinforcing bars will be used.

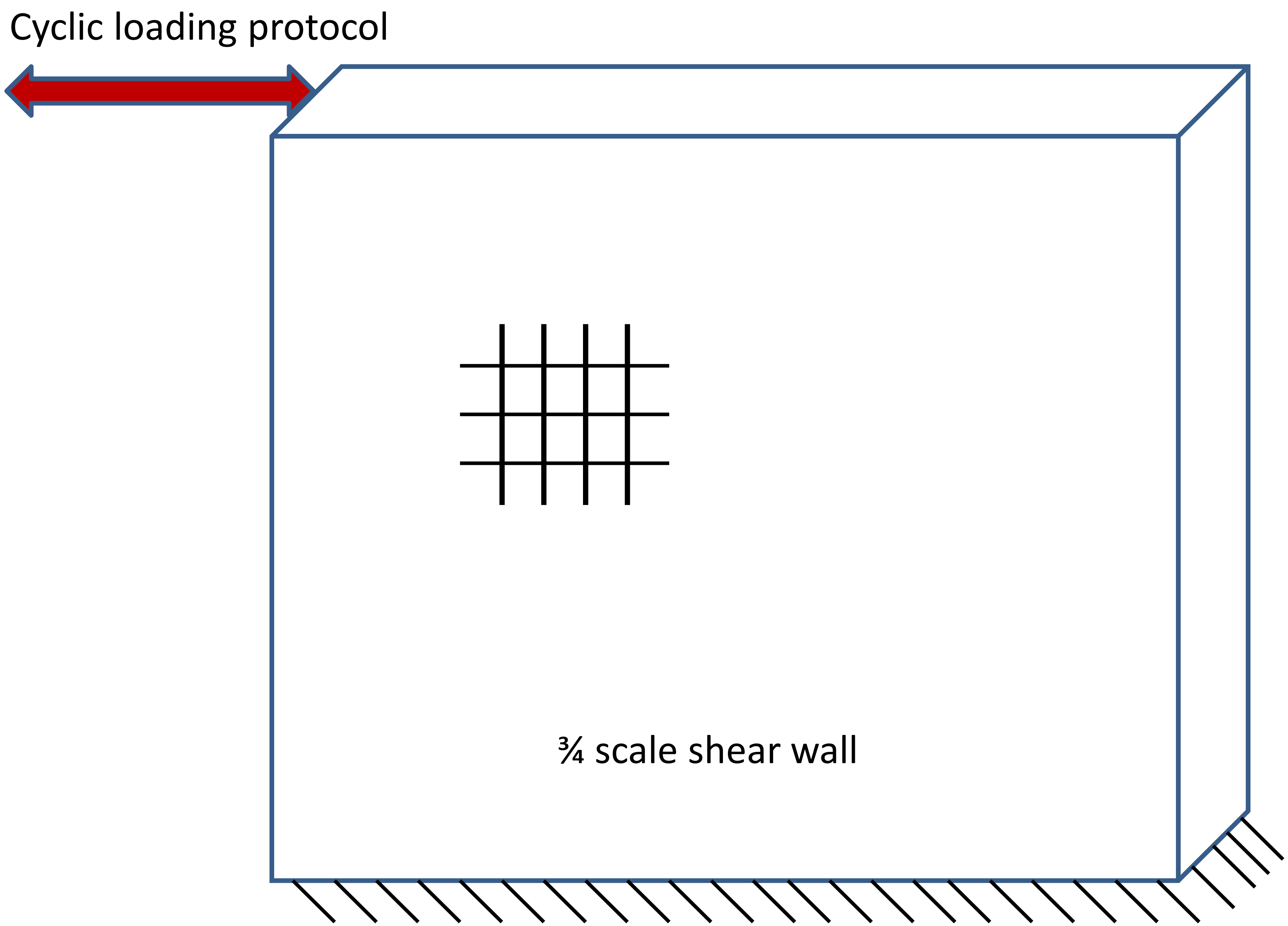
- Perform simple pullout tests periodically over a period of two years. The results of the test will include loss of pullout strength as the specimens experience expansion due to ASR effects.

# Task 3: Seismic Response Characteristics of ASR-Affected Concrete Structural Members

**Objective**:

To develop a methodology for assessing the degradation of seismic resistance of structural members and systems due to ASR.

# Task 3: Seismic Response Characteristics of ASR-Affected Concrete Structural Members



# Task 3: Seismic Response Characteristics of ASR-Affected Concrete Structural Members

**Approach**:

- Design and cast four rectangular ¾ scale shear wall specimens; one with non-reactive material as control specimen and three with ASR-reactive material.
- Periodically perform loading tests of the specimens which will include vertical (gravity) loads along with cyclic displacement of the shear wall specimens over a period of two years.
- Results of the tests will include the hysteresis loops of the walls, strains on reinforcing bars and concrete, along with damage patterns. Results will help determine the effects of ASR on the energy dissipation capacity of shear walls.

# QUESTIONS ?????

# NRC-NIST Effort

**Scoping Study:**

Snyder, K.A. and Lew, H.S., *Alkali-Silica Reaction Degradation of Nuclear Power Plant Concrete Structures: A Scoping Study*, NUREG/CR ####, April 2013.

**NRC-NIST IAA:**

Structural Performance of Nuclear Power Plant (NPP) Concrete Structures Affected by Alkali-Silica Reaction (ASR), May 2014.

# Task 1: Assessing In-Situ Mechanical Properties of ASR-Affected Concrete

## **Outcomes**:

The testing and analysis of Task 1 will provide protocols for (1) estimating the extent of ASR, (2) estimating the resulting volume expansion and corresponding internal pressure development, (3) performing expansion analysis of the concrete specimen, and (4) estimating the mechanical properties of ASR-affected concrete structural members.

## **Deliverable**:

A methodology for determining the effect of ASR degradation on the mechanical properties of in-situ concrete in structural members and the effects of hoop reinforcement in confining expansion of concrete due to ASR.

.

# Task 2: Assessing Bond and Anchorage of Reinforcing Bars in ASR-affected Concrete

## Outcomes:

The testing  and associated results of Task 2 will provide a methodology for assessment of the deterioration of bond strength in ASR-affected concrete structures, including (1) the required length of lap splices of tension reinforcement in beams and (2) the required length of embedment of axially loaded reinforcing bars in concrete.

## Deliverable:

A procedure that can be used to assess the loss of bond strength due to ASR.

.

# Task 3: Seismic Response Characteristics of ASR-Affected Concrete Structural Members

## **Deliverable**:

A methodology for assessing the loss of stiffness and of energy absorption capacity due to ASR for structural members and assemblies.

.

# Materials Performance of Concrete Structures Affected by Alkali-Silica Reaction (ASR)

## Advisory Committee on Reactor Safeguards

Structural Analysis/Plant License Renewal Subcommittee Meeting

Concrete Degradation

September 19, 2014


Kenneth A. Snyder

Materials and Structural Systems Division

National Institute of Standards and Technology


National Institute of Standards and Technology
U.S. Department of Commerce

# ASR: Materials Component

## Broad Objectives:

- The extent to which the reaction has progressed
- The rate of the progress
- The impact on other degradation mechanisms

## Support to the Structural Objectives:

Predicting future properties of the reinforced structure

- Predict the time-dependent behavior of the reaction
  - use to predict future stresses/strains

# Task 4: Overview

## Estimating the Degree of the Reaction:

**Objective:** Develop methodology for estimating the degree of internal expansion due to ASR.

**Plan:**

- Relate the degree of internal expansion the degree of the reaction
- Identify/Quantify reactive phases in raw materials
- Identify/Quantify reactive phases in hydrated materials
- Identify/Quantify reaction products in hydrated materials

**Deliverable:** The methodology for estimating the degree of the reaction and relating it to expansion.



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# Task 4: Details

**Task 4a:** Identify expansive minerals and mixtures

- Procure materials and cast mortar bars
- Identify/Quantify ***expansive minerals*** in raw/hydrated materials

**Task 4b:** Procedure refinement on mortar specimens

- Measure expansion over time
- Quantify reactive phases and ***reaction products***
- Cast concrete prisms

**Task 4c:** Procedure refinement on concrete specimens

- Measure expansion over time
- Quantify reactive phases and reaction products
- Relate degree of reaction to extent of expansion

# Task 5: Overview

## Predicting Future and Ultimate ASR Expansion:

**Objective:** To develop test methods for predicting the future degree of ASR reaction in existing concrete structures.

**Plan:**

- Develop 'order of magnitude' model: one significant digit / large uncertainty
- Start with primary factors: temperature, alkalinity, & volume fraction
- Estimate ultimate degree of reaction/expansion
- Validate with concrete

**Deliverable:** The methodology for estimating the future rate of the ASR reaction and the ultimate expansion.

# Task 5: Details

**Task 5a:** Primary Factors: temperature, alkalinity, & volume fraction

- Cast mortar bars and vary the primary factors
- Measure expansion and develop order-of-magnitude formula

**Task 5b:** Procedure refinement on mortar specimens

- Cast expansive mortar bars
- Cut thin slabs from bars and expose to alkaline solution
- Compare subsequent slab expansion to remaining mortar bar expansion

**Task 5c:** Procedure refinement on concrete specimens

- Vary the primary factors, monitor expansion
- Cut thin slabs and expose to alkaline solution
- Compare subsequent slab expansion to remaining prism expansion

# Task 6: Overview

## ASR Effects on Transport of Ions through Concrete

**Objective:** To develop a methodology for assessing the influence of ASR on the remaining service life of affected concrete.

**Plan:**

- Monitor ingress and resistivity of cracked samples
- Validate with concrete specimens

**Deliverable:** The methodology for assessing the expected service life of ASR affected concrete.

# Task 6: Details

**Task 6a:** Strategies for Using Mortar Resistivity

- Expose expansive prisms to chloride environments
- Monitor chloride ingress and concrete resistivity
- Relate changes to rate of ingress (transport) to changes in resistivity

**Task 6b:** Validation in Concrete Mixtures

- Expose expansive concrete prisms to chloride environments
- Monitor changes in concrete resistivity
- Compare measured ingress to predicted ingress

# Cementitious Barriers Partnership
## Project Overview and LeachXS/Orchestra

David S. Kosson and Kevin G. Brown

Vanderbilt University and CRESP

Cementitious Barriers Partnership

September 19, 2014

CBP
Cementitious Barriers Partnership

# Project Team Members

**Vanderbilt University & CRESP**
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**Savannah River National Laboratory (SRNL)**
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**Energy Research Centre of The Netherlands (ECN) & CRESP**
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**National Institute of Standards and Technology (NIST)**
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**Nuclear Regulatory Commission (NRC)**
D. Esh, M. Furman, J. Phillip

**SIMCO Technologies, Inc. (Canada)**
E. Samson, J. Marchand

*Project Leadership Team

**DOE-EM Project Manager: Pramod Mallick**

# Project Goal

Develop a reasonable and credible set of tools to predict the structural, hydraulic and chemical performance of cement barriers used in nuclear applications over extended time frames (e.g., up to and >100 years for operating facilities and >1000 years for waste management).

- Mechanistic / Phenomenological Basis
- Parameter Estimation and Measurement
- Boundary Conditions (physical, chemical interfaces)
- Uncertainty Characterization

# Primary Near-term Applications

- Hanford
  - Single shell tank integrity
  - C-Tank Farm – HLW tank closure assessment
  - Integrated Disposal Area PA
  - Source term from Cast Stone (secondary waste, LAW supplemental treatment)
  - In-situ grouting performance
- Savannah River
  - Saltstone Performance
  - Disposal vaults and other concrete facilities
- Nuclear Energy
  - Dry cask storage performance
  - License extensions

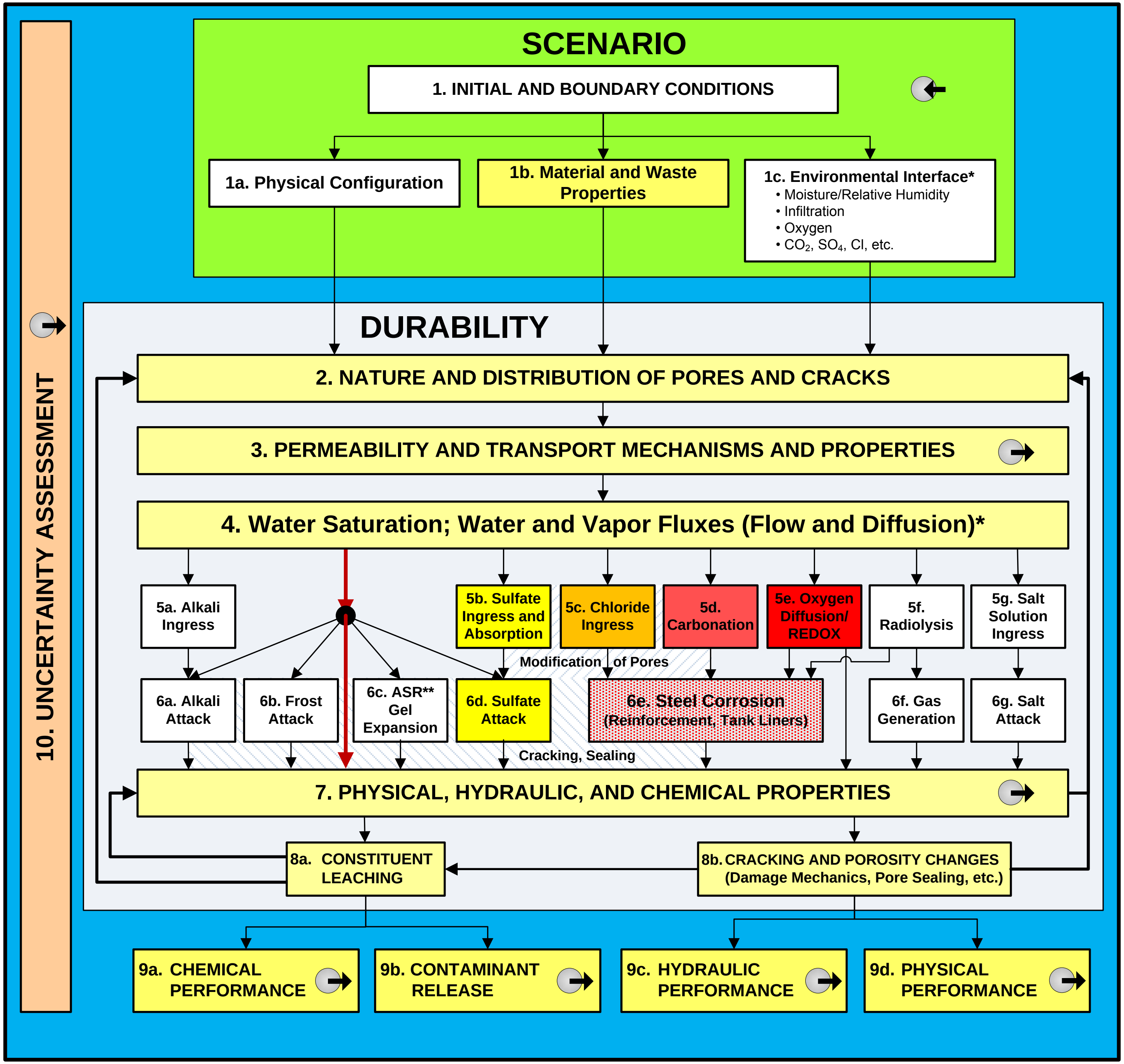
# Key Questions

- Waste Forms and Disposal Systems
  - What is the rate of release for radionuclides and contaminants under a range of scenarios?
  - What is the evolution of system pH?
  - What are the effects of cracking?
  - What is the rate and impact of aging processes (oxidation (Tc-99), carbonation, leaching)?
- Structural Systems Performance
  - What is the service life?
  - What are the impacts of ingress of aggressive species (chloride, sulfate, carbon dioxide)?

# Technical Strategy / Approach

- **Reference Cases** – provide basis for comparison and demonstration of CBP tools
  - Cementitious waste form in concrete disposal vault with cap
  - Grouted high-level waste (HLW) tank closure
  - Used nuclear fuel pool, dray cask storage (future)
  - Nuclear processing facilities closure / D&D (e.g., canyons)
  - Grouted vadose zone contamination
  - Materials – surrogate low-activity waste (LAW) cementitious waste form, reducing grout, reinforced concrete (historical), reinforced concrete (future)
- **Extension/enhancement of existing tools** – CEMHYD3D/THAMES, STADIUM, LeachXS/ORCHESTRA, GoldSim Performance Assessment (PA) framework
- **Coordinated experimental and computational program**
  - Conceptual model improvement
  - Define test methods and parameter measurements
  - Model validation

→ **CBP Software ToolBox Version 2.0 Release (January 2014)**




# Specifications, Properties, and Phenomena for the Evaluation of Performance of Cementitious Barriers

## Key Processes

### Current

Chloride
Sulfate
Carbonation
Decalcification
Leaching

### In-development

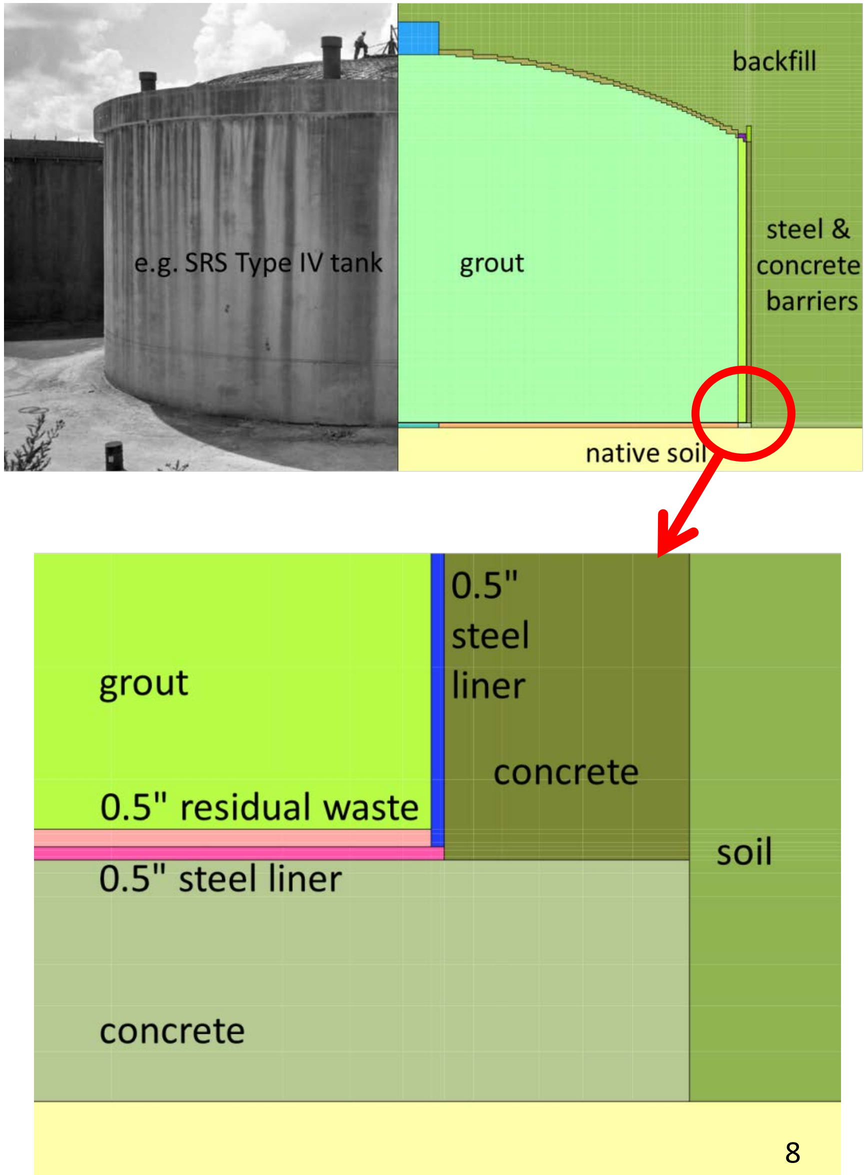
Cracking
Oxidation
Properties estimation
Variable saturation
Alkali-silica rxn

# Motivation: Stabilize Residual High-Level Waste

**200+ High-level waste (HLW) tanks require waste removal and closure:**

- Tanks in service:
  - Capacity of ca. 4 million liters
  - Carbon steel liner within a reinforced concrete shell
- Tank closure
  - HLW retrieved to extent practical and filled with grout
  - Grout – cement mixed with supplementary materials
  - Grout intended to provide structural stability and to retain residual radionuclides

**Challenge** – predict timeframe and radionuclide rate of release



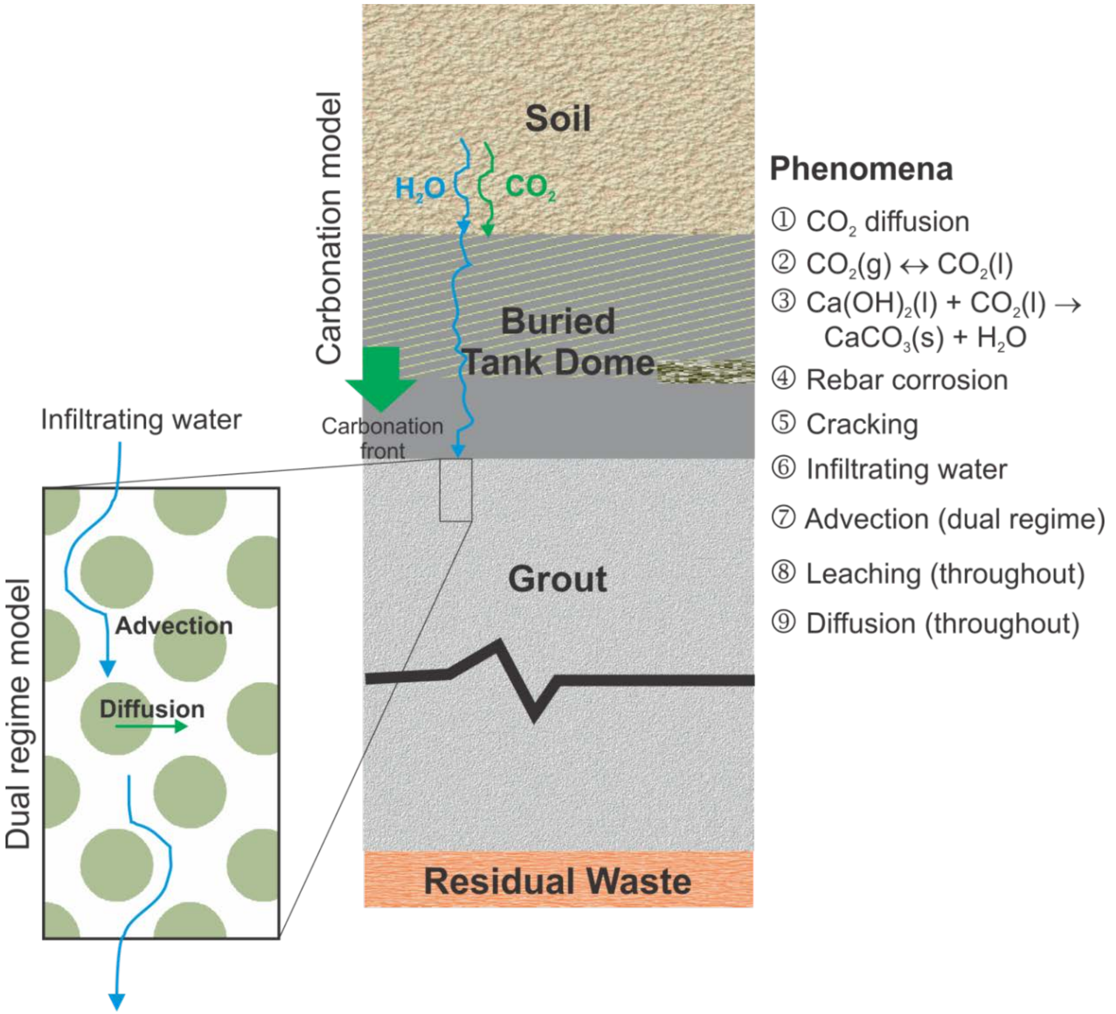

Source: SRNL-STI-2012-00372

# Primary Degradation Mechanisms

**Important degradation phenomena that can lead to radionuclide release:**

- Dome:
  - $CO_2$ ingress (carbonation) and major constituent leaching
  - Depassivation of embedded steel (pH<9) and cracking leading to water infiltration
- Grout:
  - Cracking allowing water percolation, constituent leaching, and release to environment
  - Grout: $CO_2$/$O_2$ ingress resulting in pH change and respeciation of grout and waste constituents (future)

- LeachXS/ORCHESTRA used to model phenomena



# Mineral Set

**Thermodynamic model**

- LeachXS/ORCHESTRA
  - Solves system of equations:
    - Conservation of mass
    - Laws of mass action
  - Yields solid, aqueous, and gaseous speciation
- C-S-H
  - Ideal solid solution with Tobermorite- and Jennite-like end-members (Lothenbach et al., 2008)
- Adsorption models, Organic complexation
- Additional minerals included in the model for trace species
  - As, B, Ba, Cd, Cr, Cu, Sb, Se, Sr, Th, V, Zn
  - Tc, U, Cs, etc.

*Major Mineral Phases*

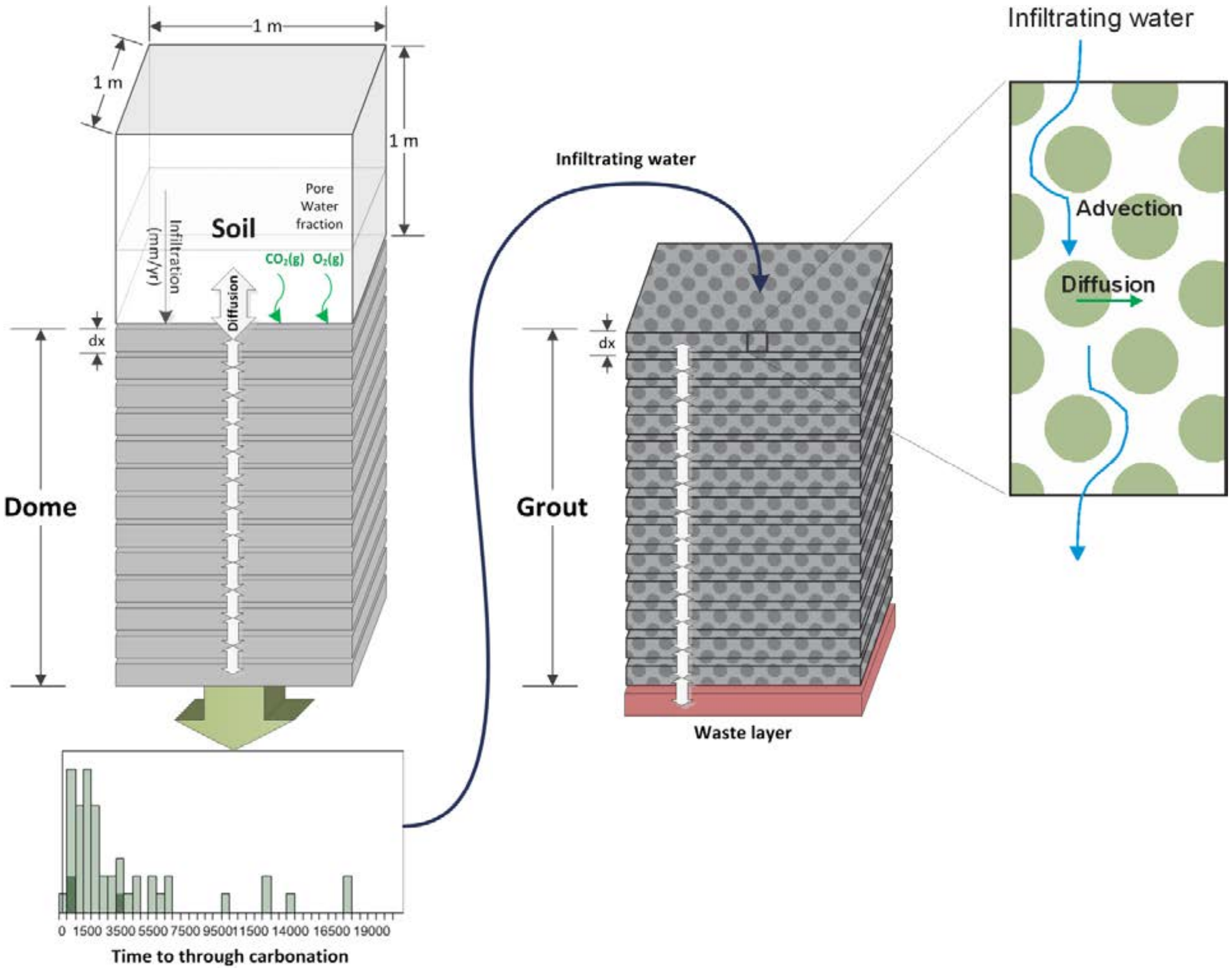
| | | |
|---|---|---|
| $Mg(OH)_2$ *Brucite* | $Ca(OH)_2$ *Portlandite* | $CAH_{10}$* *Unnamed meta-stable phase* |
| $CaSO_4 \cdot 2H_2O$ *Gypsum* | $CaCO_3$ *Calcite* | $C_3AH_6$* *Hydrogarnet* |
| $SiO_2$ (am) *Amorphous Silica* | $C_2ASH_8$* *Strätlingite* | $C_3FH_6$* *Fe-hydrogarnet* |
| $Al(OH)_3$ (am) *Amorphous Aluminum hydroxide* | $C_2FSH_8$* *Fe-Strätlingite* | $C_4AH_{13}$* *Hydroxy AFm* |
| $Al_2O_3$ *Alumina* | $C_2AH_8$* *Unnamed meta-stable phase* | $C_4FH_{13}$* *Fe-hydroxy AFm* |
| $Fe(OH)_3$ (am) *Amorphous Iron hydroxide* | $C_2FH_8$* *Unnamed meta-stable phase* | ***Solid Solution:*** $C_{1.67}SH_{2.1}$* *Jennite* $C_{0.83}SH_{1.3}$* *Tobermorite* |
| $K_2Ca(SO_4)_2 \cdot H_2O$ *Syngenite* | $CaSO_4$ *Anhydrite* | |

* Notation: C = CaO, A = $Al_2O_3$, F = $Fe_2O_3$, S = $SiO_2$, H = $H_2O$

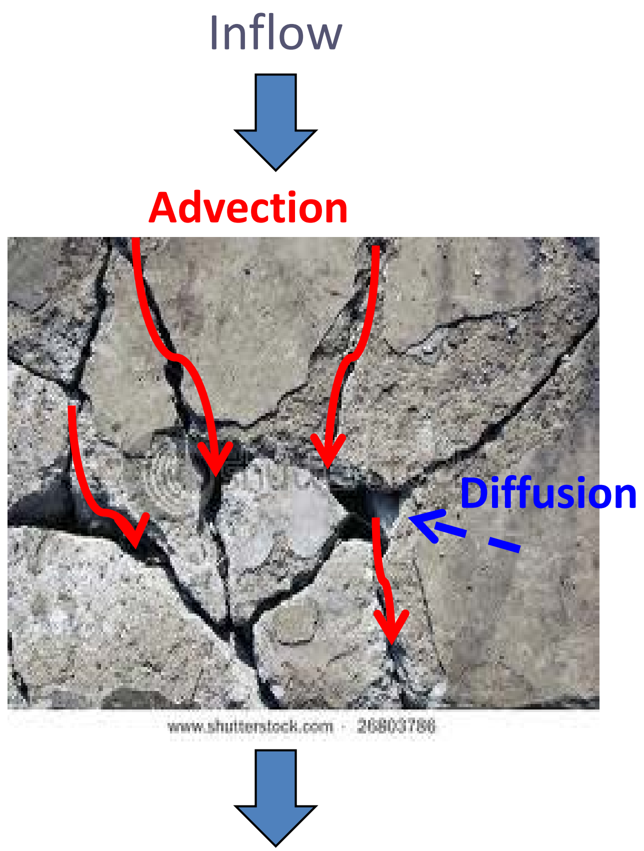
# Modeling Approach

**Decouple carbonation of the dome from transport in the grout (dual regime reactive transport) model**

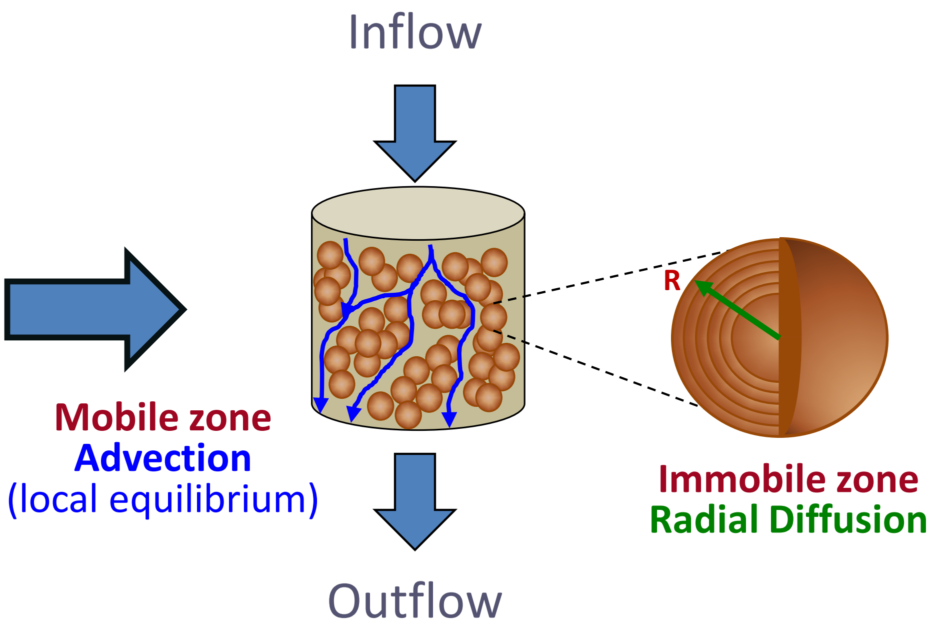
- Carbonation of dome is a very slow process (e.g., << 1mm/yr)
- Transport in the grout assumed negligible until dome is carbonated and cracked (allowing infiltration)
- Thus, stochastically model dome carbonation to generate distribution of times until cracked
- Time distribution then used to delay impact on cracked grout pH using dual regime model

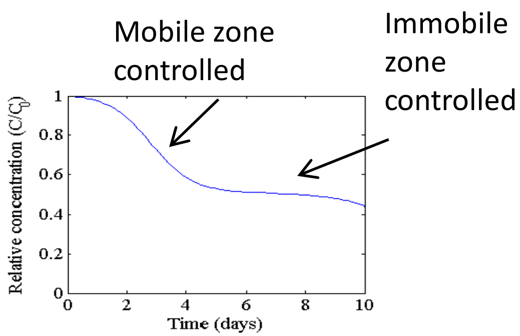


# Flow through Heterogeneous Media




## Advection – radial diffusion approach




- Refined mobile-immobile approach
- Can capture micro-macro pore and particle size distributions

CBP Cementitious Barriers Partnership

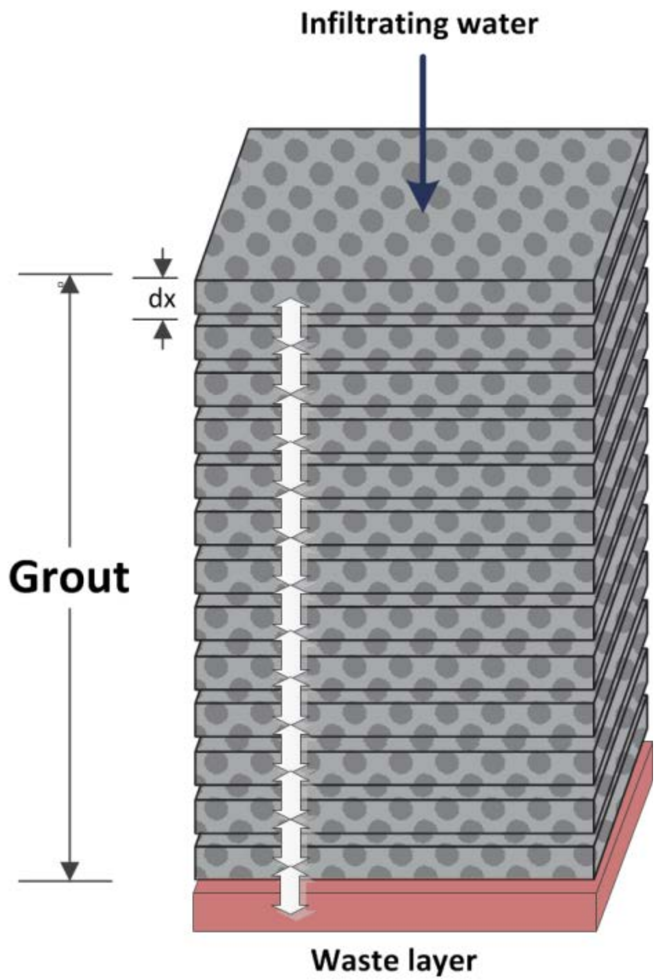
# Probabilistic Grout Analysis

## Non-Stochastic Parameters

- Grout thickness 10.5 m (SRS Type IV Tank)
  - Varies between 9 and 16 m (Sites, et al. 2006)

## Stochastic Parameters

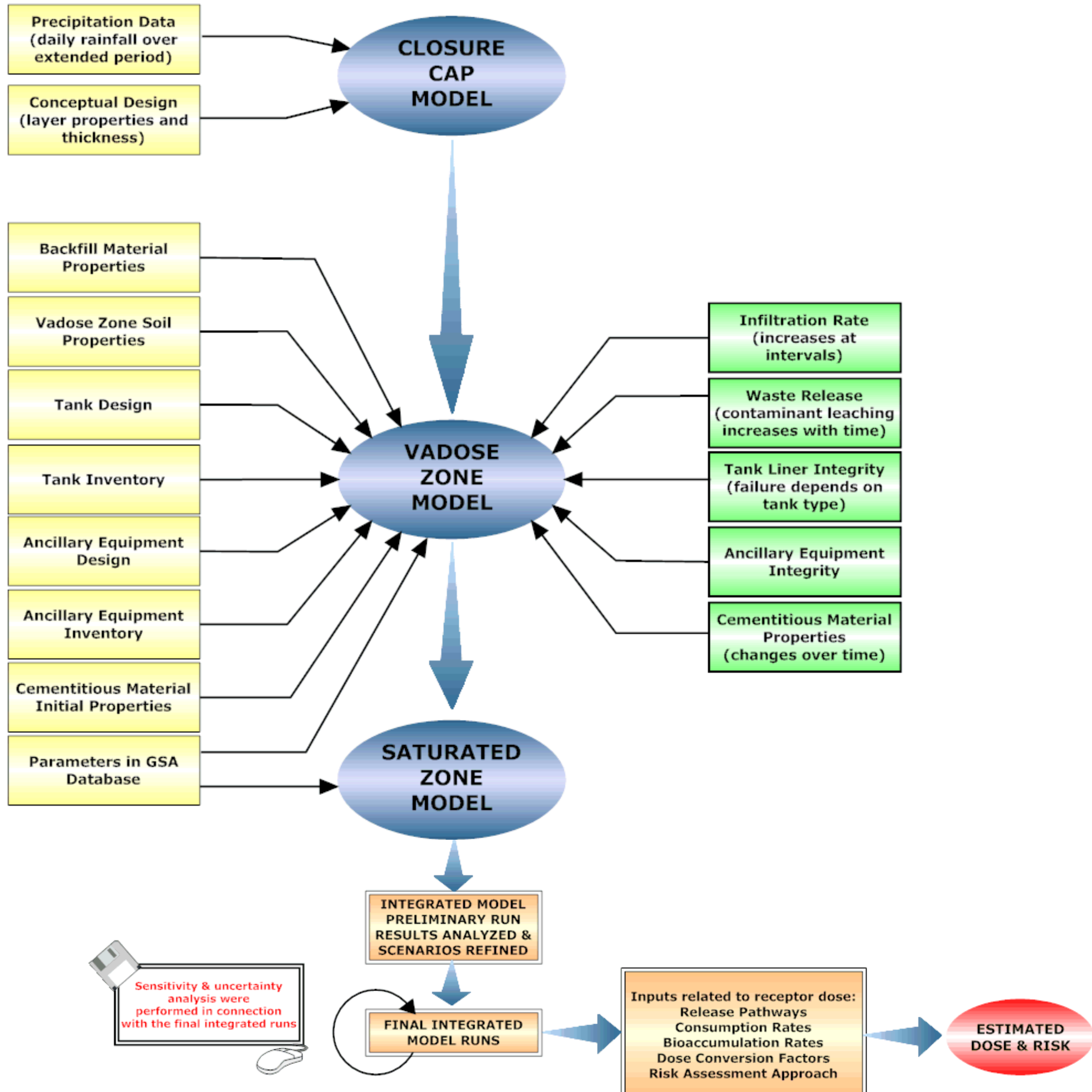
- Crack spacing – U(1,2) m
  - Sarkar, *et al.* (2013)
- Infiltration Rate – N(0.18, 0.051) m/yr
  - Distribution of 1,000-yr rates (WSRC-STI-2007-00184)
- Total porosity: $\phi_t$ – U(0.20, 0.30)
  - Sarkar, *et al.* (2013)
- Immobile zone porosity: $\phi_{im}$ – N(0.221, 0.013)
  - Information from WSRC-STI-2006-00198
- Mobile volume fraction: U(0.10,0.20)
  - Sarkar, *et al.* (2013)
- Solid composition: N(mean, ±10%)
  - Sensitivity evaluation



# PA Challenges: Model Integration

## Model integration

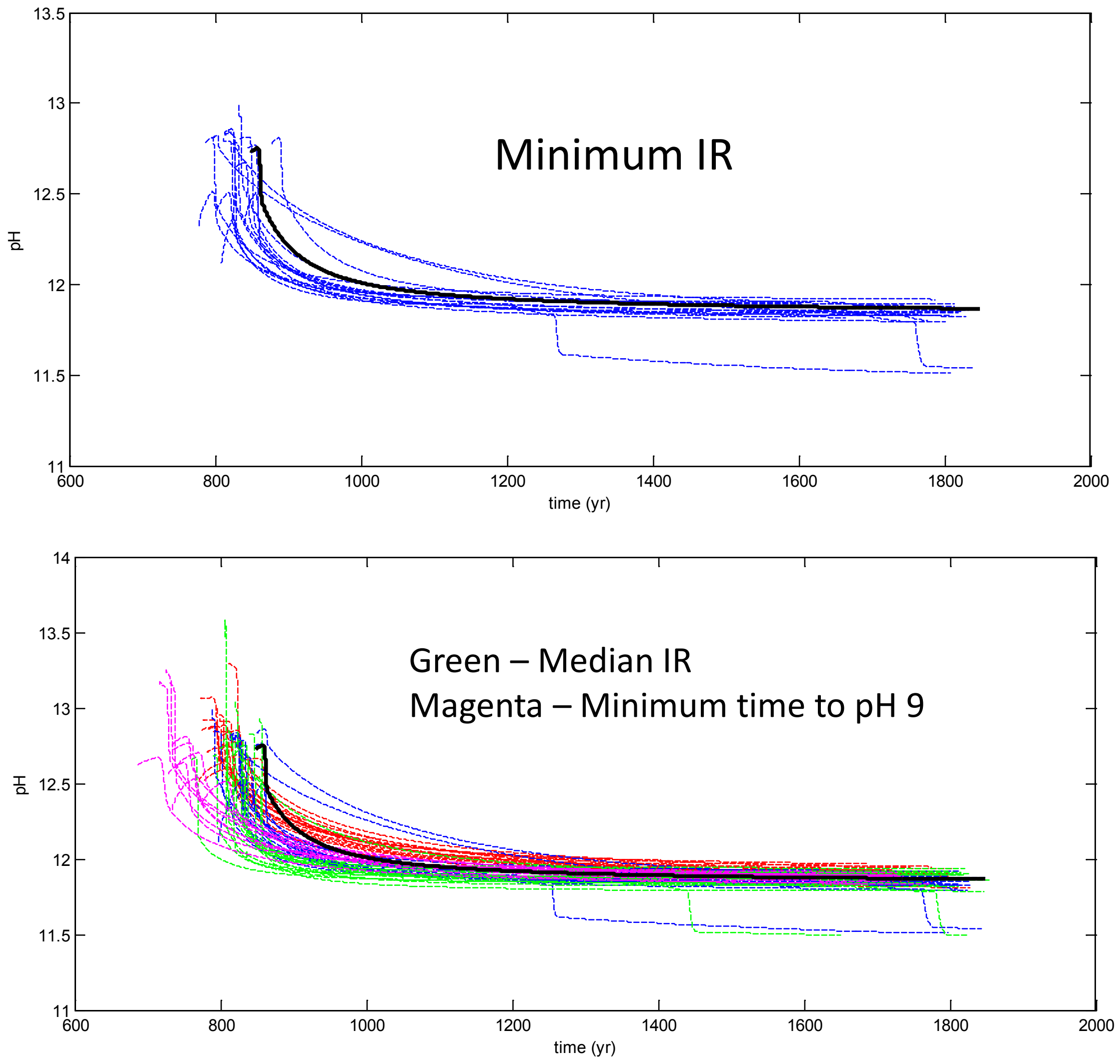
- Phenomena
- Regions
- Varying fidelity / abstraction
- Benchmarking




SRNL-STI-2012-00372

# Coupled Analysis Results (2)

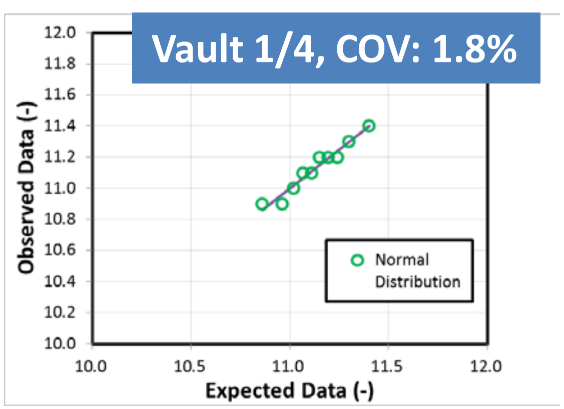
- Simulated pH response at grout – waste layer interface
- Upper graph (blue) indicates sensitive pH response *at minimum infiltration rate*
- Lower graph indicates sensitive pH response *depending on infiltration rate*
  - Similar sensitive response found at median (green) infiltration rate
  - Waste layer not impacted until after 700 years (and likely much longer)
- Significant pH effects over the first two millenia tend to be observed as the infiltration rate is lower
  - Longer simulations required to better evaluate

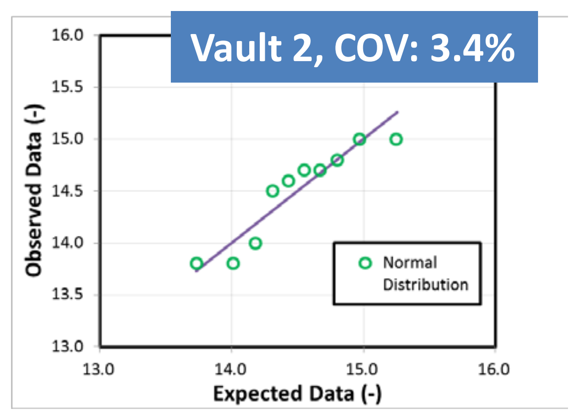


# Concrete characterization

## Porosity measurements (ASTM C642)

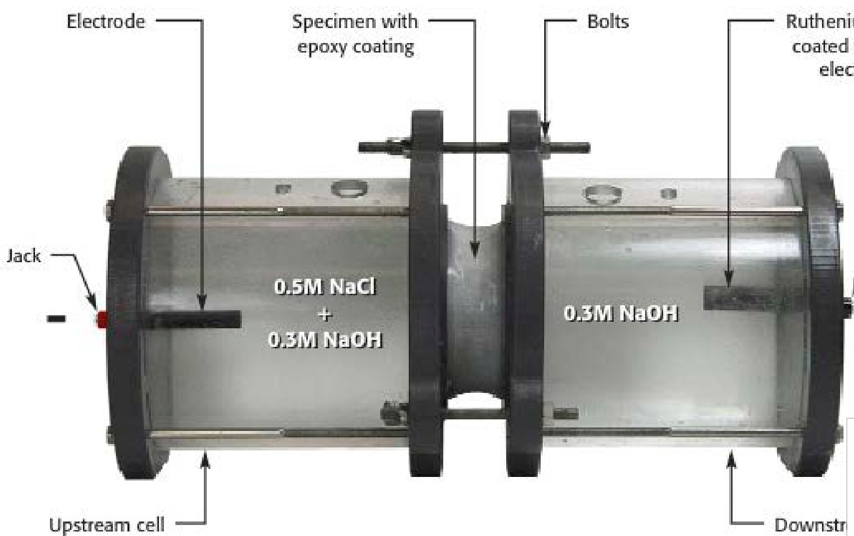
| Age of samples | Vault 1/4 (%) | Vault 2 (%) |
|---|---|---|
| 28 days | 11.4 | 13.1 |
| 91 days | 11.3 | 14.3 |
| 1 year | 11.4 | 14.2 |
| 2 years | 11.1 | 14.5 |



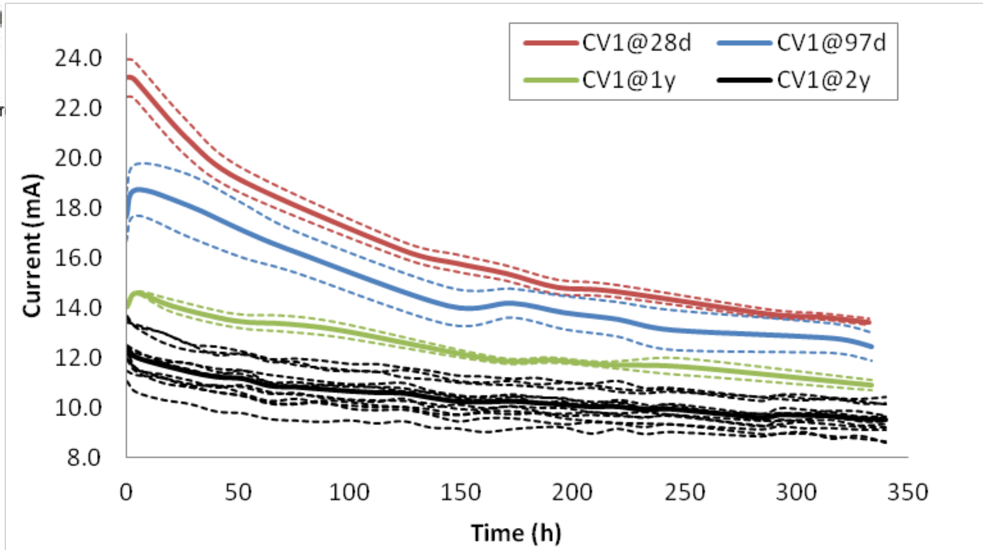



# Concrete characterization

## Diffusion coefficient measurements (migration test)

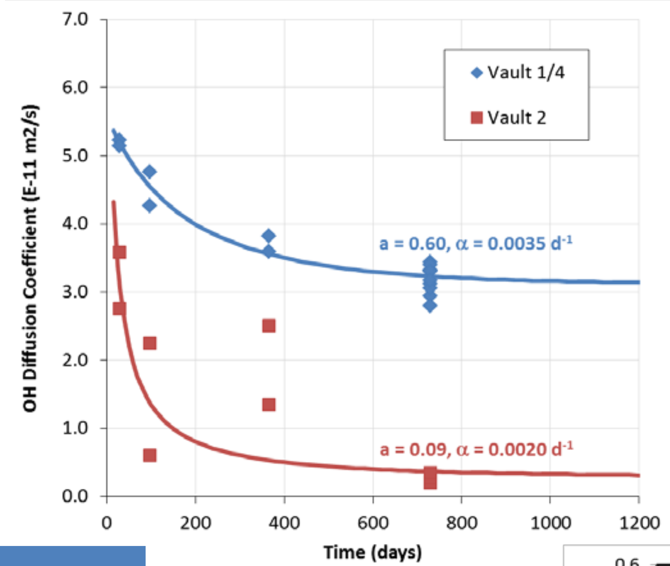



### Vault 1/4



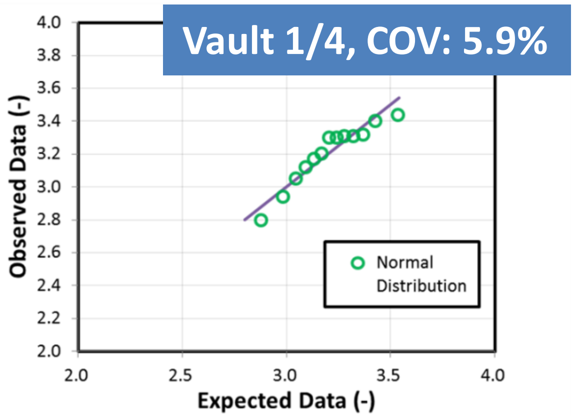
# Concrete characterization

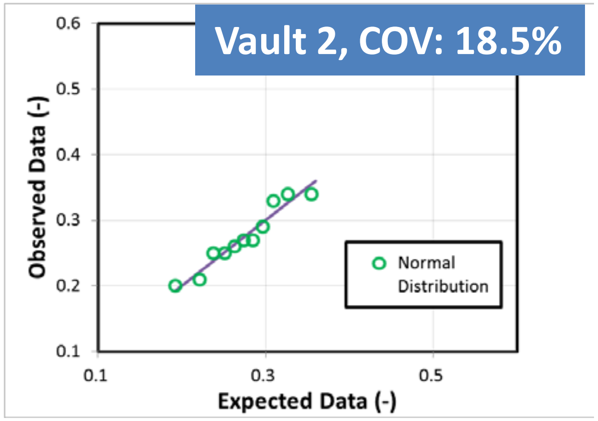
## Diffusion coefficient measurements (migration test)




Avg. τ @ 2 yrs: 0.0061

Avg. τ @ 2 yrs: 0.0005

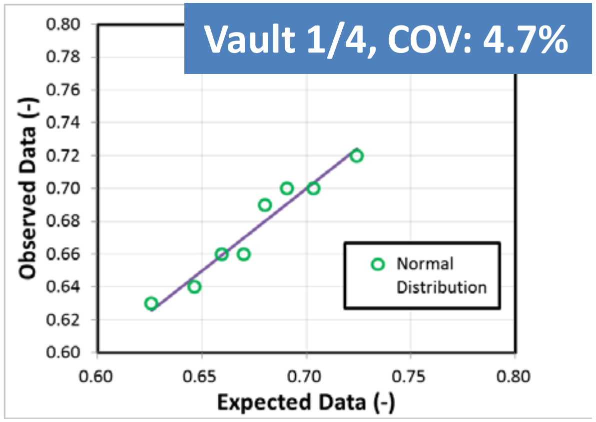


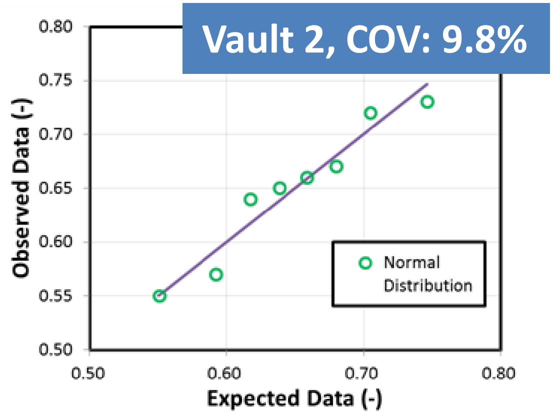



# Concrete characterization

## Permeability measurements (drying test)

| Age of samples | Vault 1/4 (E-22 $m^2$) | Vault 2 (E-22 $m^2$) |
|---|---|---|
| 91 days | 1.27 | 1.04 |
| 2 years | 0.68 | 0.65 |



# L E A F

Leaching Environmental Assessment Framework

## A Decision Support System for Beneficial Use and Disposal Decisions in the United States and Internationally…

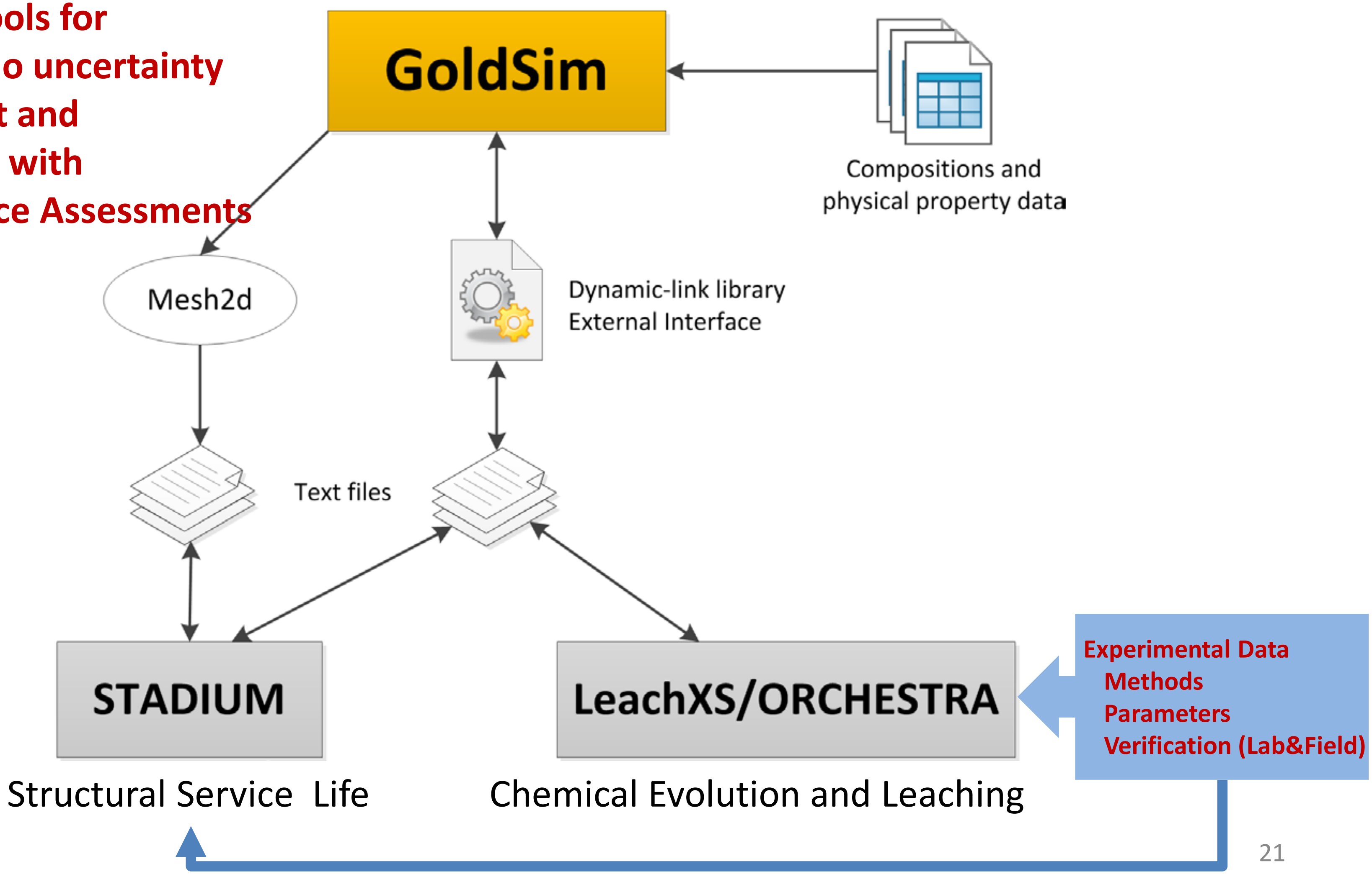
- Four leaching test methods
- Data management tools
- Geochemical speciation and mass transfer modeling
- Quality assurance/quality control for materials production
- Integrated leaching assessment approaches

… designed to identify characteristic leaching behaviors for a wide range of materials and scenarios.

More information at http://www.vanderbilt.edu/leaching

# Summary of the CBP Software ToolBox

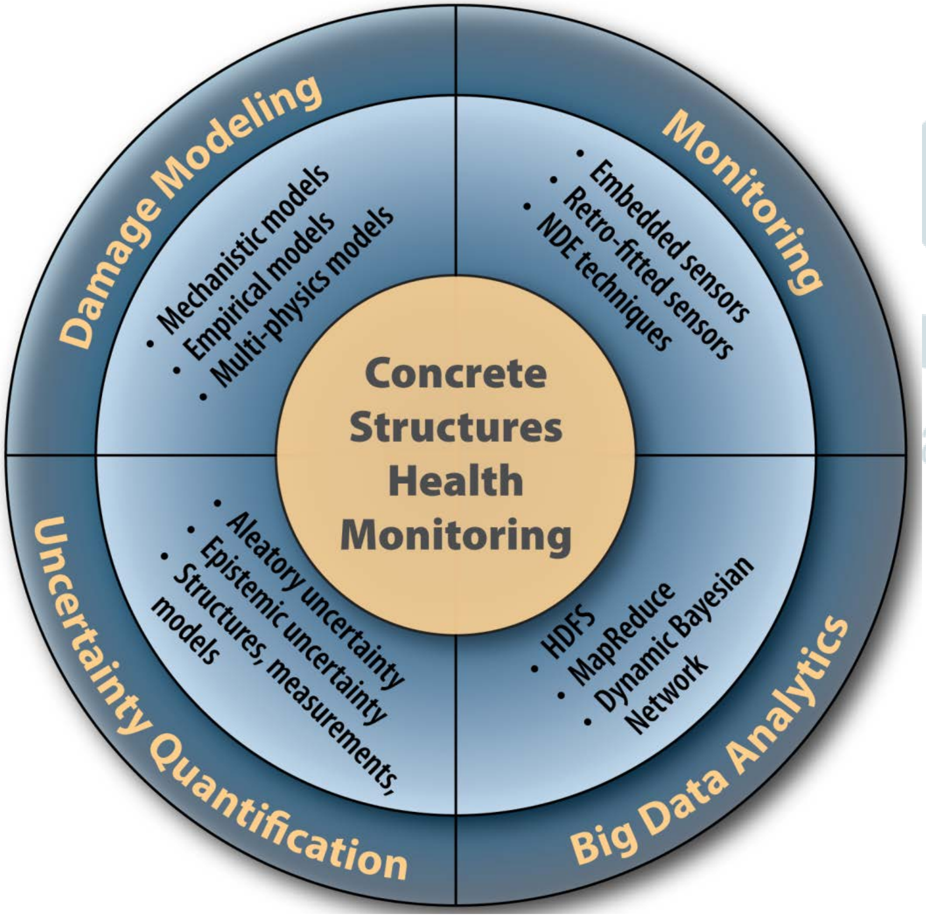
Provides tools for
Monte Carlo uncertainty
assessment and
integration with
Performance Assessments



Idaho National Laboratory

# Research Initiative: Concrete Structural Health Monitoring Framework

- A systematic approach proposed to assess and manage aging concrete structures requires an **integrated** framework




Idaho National Laboratory
Operated by Battelle Energy Alliance

VANDERBILT UNIVERSITY

Oak Ridge National Laboratory
Managed by UT-Battelle for the Department of Energy

- Leverage existing modeling efforts
- Interaction amongst damage mechanisms
- Multiple NDE techniques
- Perform diagnosis & prognosis

# Uncertainty Quantification

- Aleatory uncertainty
  - Natural variability
    - System properties
    - Operating environments

- Epistemic uncertainty
  - Data uncertainty
    - Sparse, imprecise, qualitative, faulty, or missing data
    - Big data (data quality, relevance, processing)
  - Model uncertainty
    - Model form, model parameters, solution errors

- Bayesian network suitable for uncertainty integration
  - Facilitates both diagnosis and prognosis

# *Path Forward*

- Assemble effective individual techniques for damage modeling, health monitoring, data analytics, and uncertainty quantification
  - Initial focus on ASR damage

- Consider multiple damage mechanisms in concrete structures
  - Demonstrate for small structural components

- Integrate multi-physics simulation, full-field imaging, data analytics, and uncertainty quantification
  - Demonstrate for large structures

- Develop risk management framework
  - Demonstrate for representative structures

# Concrete Durability, Repair Strategies and Their Limitations

Paul Brown, Ph.D.
Professor of Materials Science & Engineering, Penn State Univ.

President Chemhydration, LLC
contact: chemhydration@aol.com

# I. Concrete viewed from a materials perspective

Concrete is not in chemical equilibrium
with its surroundings.

We wish to avoid concrete achieving chemical
equilibrium.

We rely on kinetic limitations
(typically diffusion control) for this avoidance.

Concrete is inherently flawed:
Porous (permeable)
Cracked

# Evaluation of concrete

Is there evidence of deterioration?

What are the criteria on which an assessment of deterioration are based?

**Visual inspection**
**Strength determinations**
**Petrographic analyses**
**Other (half cell detns, NDE techniques)**

What is the mechanism of deterioration?

# Evaluation of concrete, cont

Is the mechanism still active?

If so, will the anticipated rate of deterioration meaningfully compromise the integrity of the structure prior to the end of its service life?

What is an appropriate repair, if any?

What is an appropriate schedule for future inspections?

# Factors that can affect concrete aging

I. Mix design

- Concrete materials (aggregate)
  - ASR
  - ACR
  - Unsoundness
- Strength
- Permeability

II. Placement/curing

- Strength
- Permeability
- Cracking (plastic & drying)
- Delayed expansive reactions (DEF)

# Factors that can affect concrete aging

III. Service Environment

Carbonation

Leaching

Acid (chemical) attack

Freezing-thawing

Sulfate attack

Physical salt attack

Corrosion of embedded metals

(ASR)

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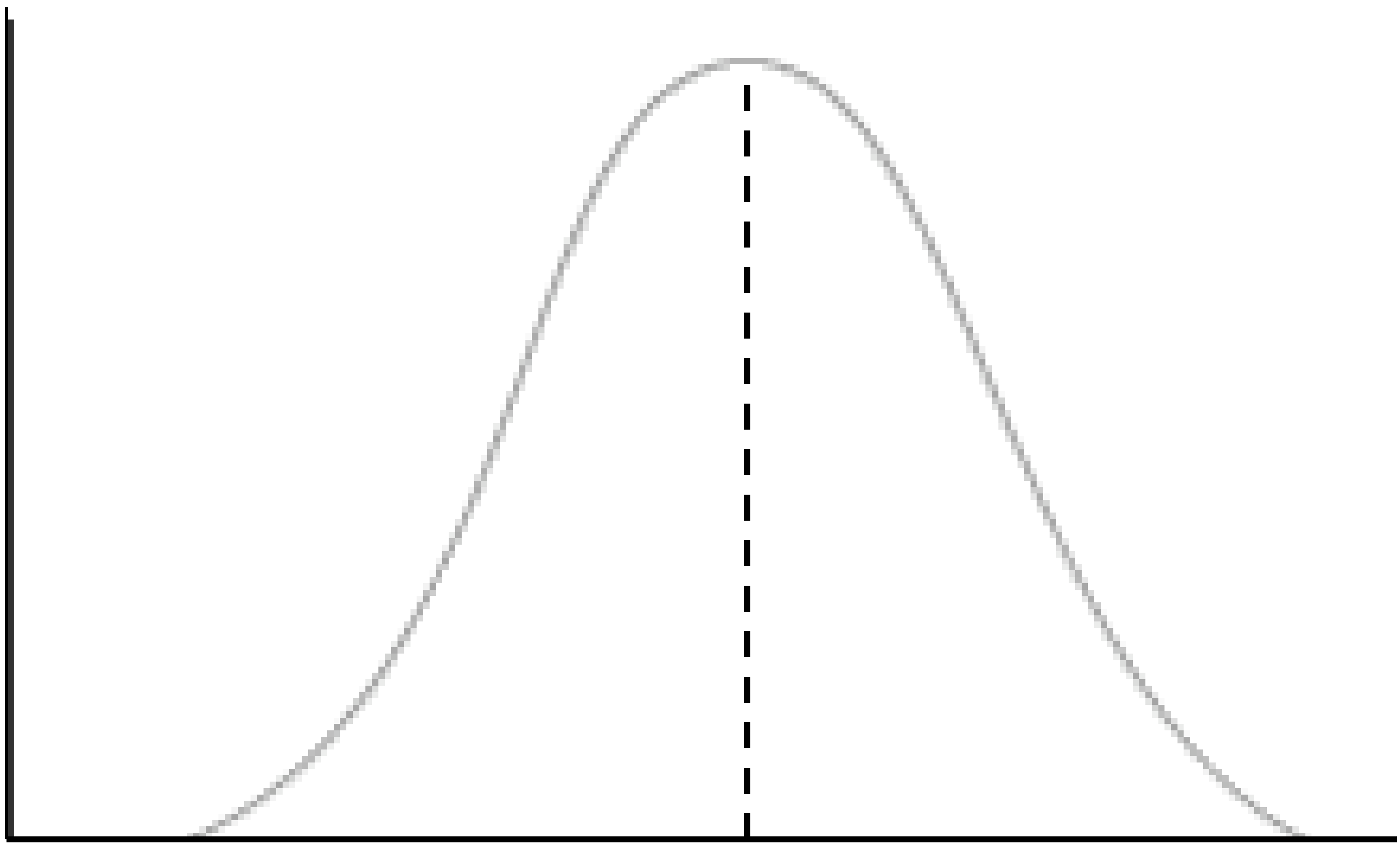
Concrete
Degradation Mtg
9-19-14

# II. Factors Affecting Concrete Strength

# 28 day compressive strength

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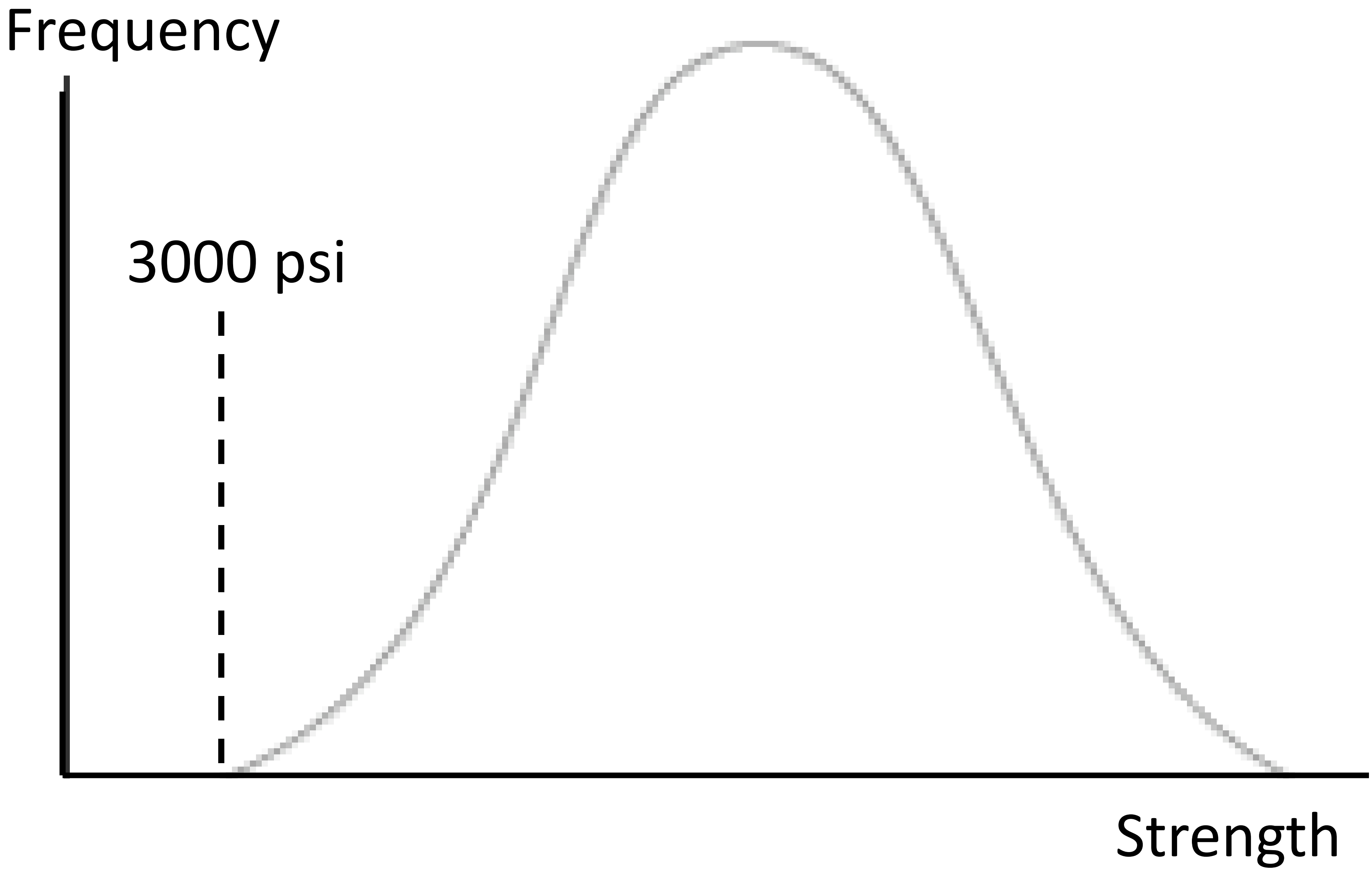


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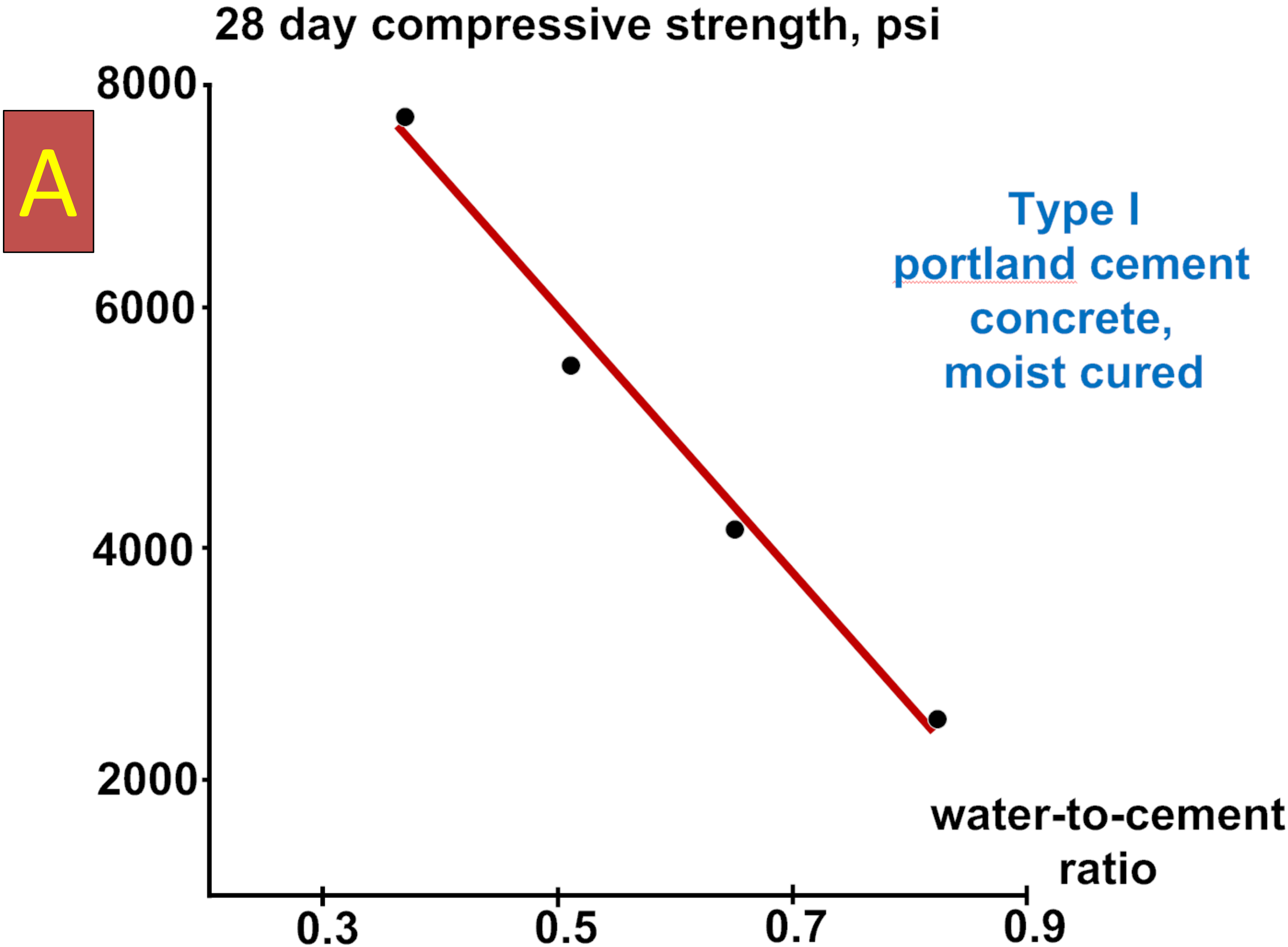
# Factors affecting long-term strength

- A Mix design
- B Curing regime
- C Core handling
- D Degradation phenomena


28 day compressive strength, psi
8000
6000
4000
2000
A
Type I
portland cement
concrete,
moist cured
water-to-cement
ratio
0.3
0.5
0.7
0.9

B

# Effect of curing duration on compressive strength

| Duration Of curing | 28 day break | 90 day break | 180 day break |
|---|---|---|---|
| 3 days | 27 MPa | 26 MPa | **25** MPa |
| 7 days | 32 | 31 | 28 |
| 14 days | 35 | 35 | 34 |
| 28 days | 32 | 39 | **37** |

w/c ratio 0.5

50% difference due to curing only

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B

# Effect of curing duration on compressive strength

| Duration Of curing | 28 day break | 90 day break | 180 day break |
|---|---|---|---|
| 3 days | 27 MPa | 26 MPa | 25 MPa |
| 7 days | 32 | 31 | 28 |
| 14 days | 35 | 35 | 34 |
| 28 days | 32 | 39 | 37 |

Effect of testing wet vs testing dry

C

# Effect of core handling on compressive strength

## Δ dry vs wet testing

| Low strength concrete | Higher strength concrete |
|---|---|
| +15-25% | +8-15% |

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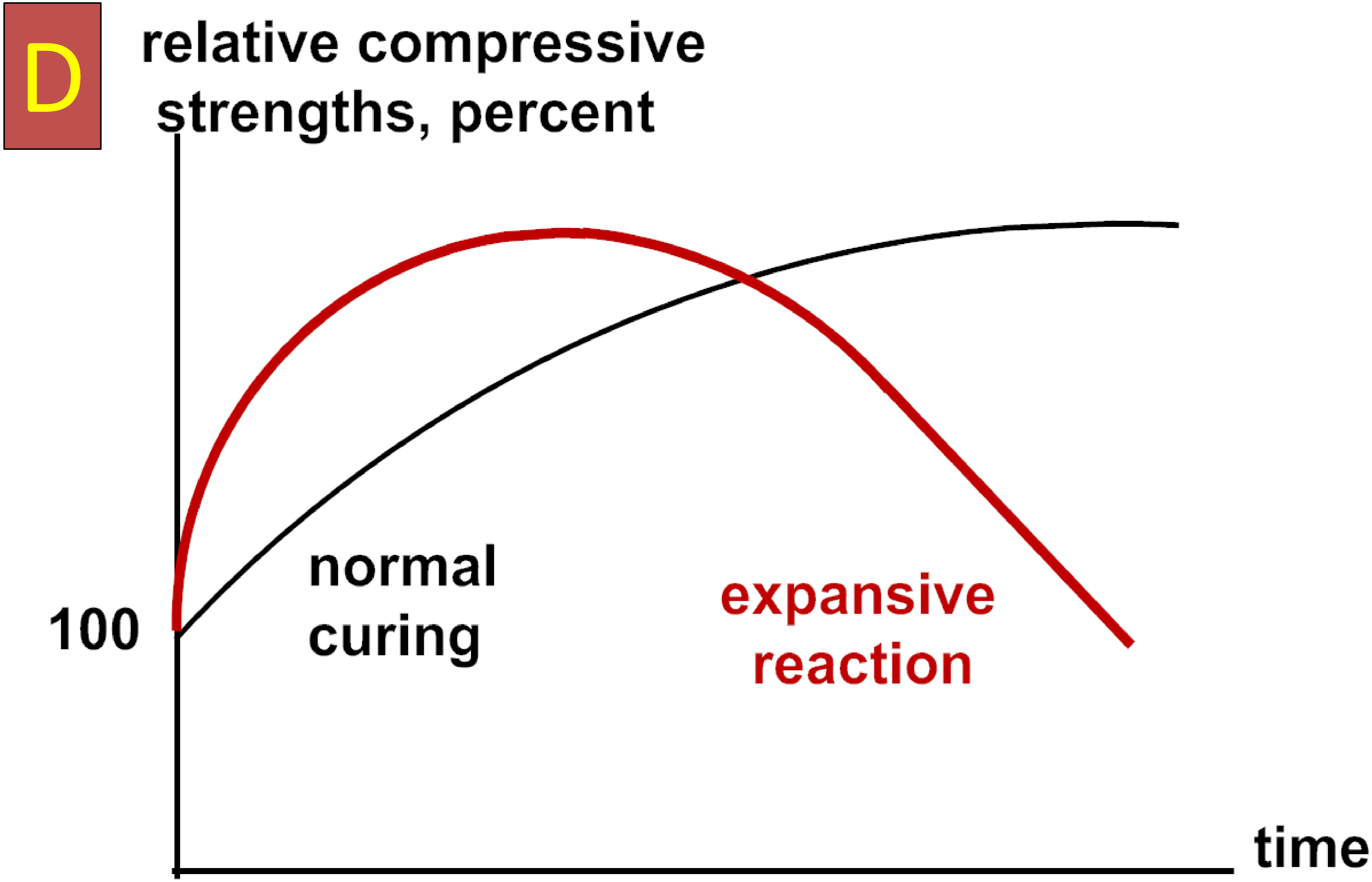
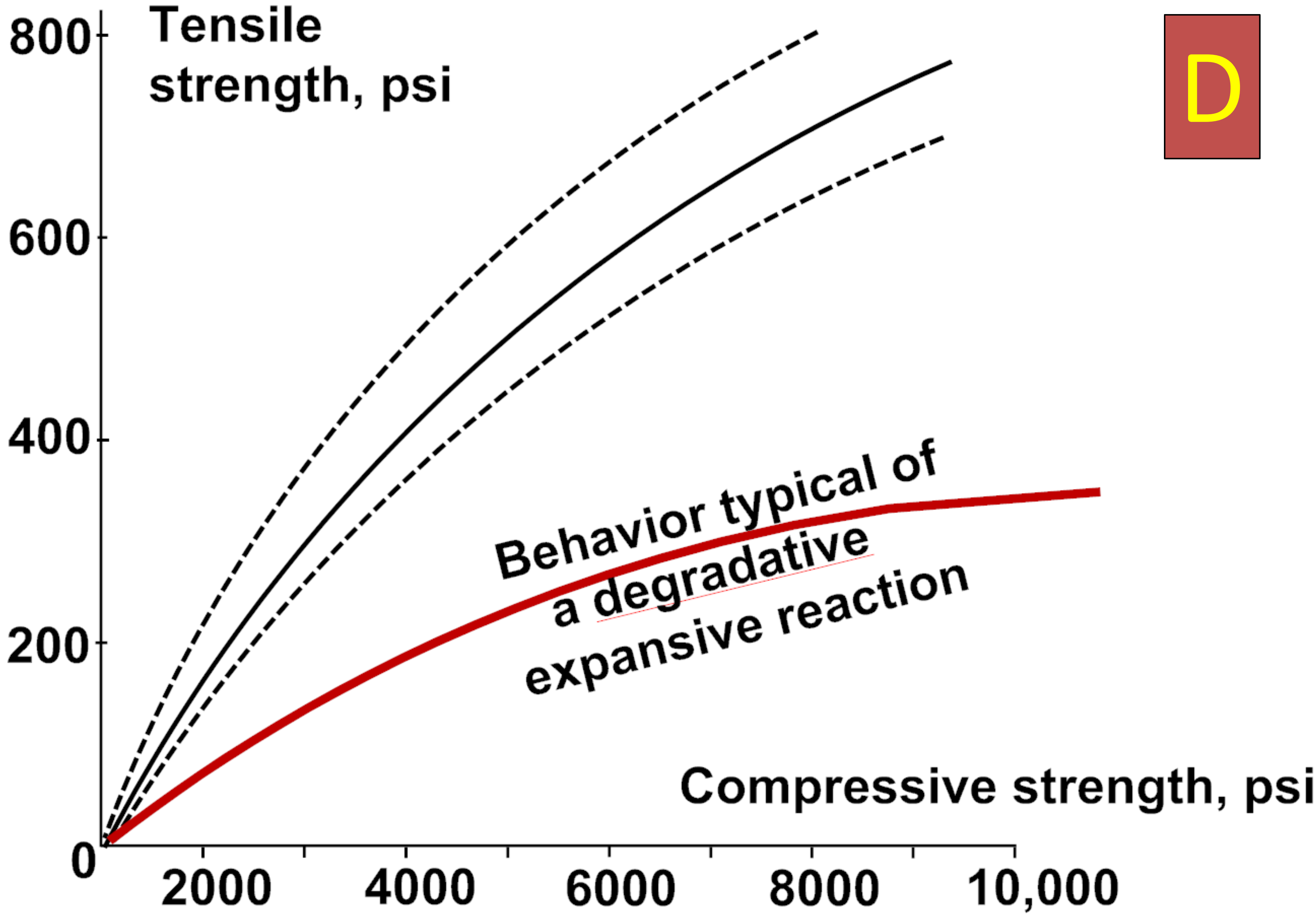

D
relative compressive
strengths, percent
100
normal
curing
expansive
reaction
time

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# III. Why concrete generally contains cracks

# Volume Change with Hydration

*Hydration of tricalcium silicate*

$$2Ca_3SiO_5 + 7H_2O \rightarrow Ca_3Si_2O_7.4H_2O + 3Ca(OH)_2$$

## Molar volumes:

| | | | |
|---|---|---|---|
| 2(72.4) | 7(18) | 153 | 3(33.1) |

## Sums of solid volumes:

| | | | | | |
|---|---|---|---|---|---|
| Volume of Reactants | 144.8 | + | 126 | = | 270.8 |
| Volume of Products | 153 | + | 99.3 | = | 252.3 |
| Net Volume Reduction | | | | = | -18.5 |

# Two types of volume change occur during cement hydration

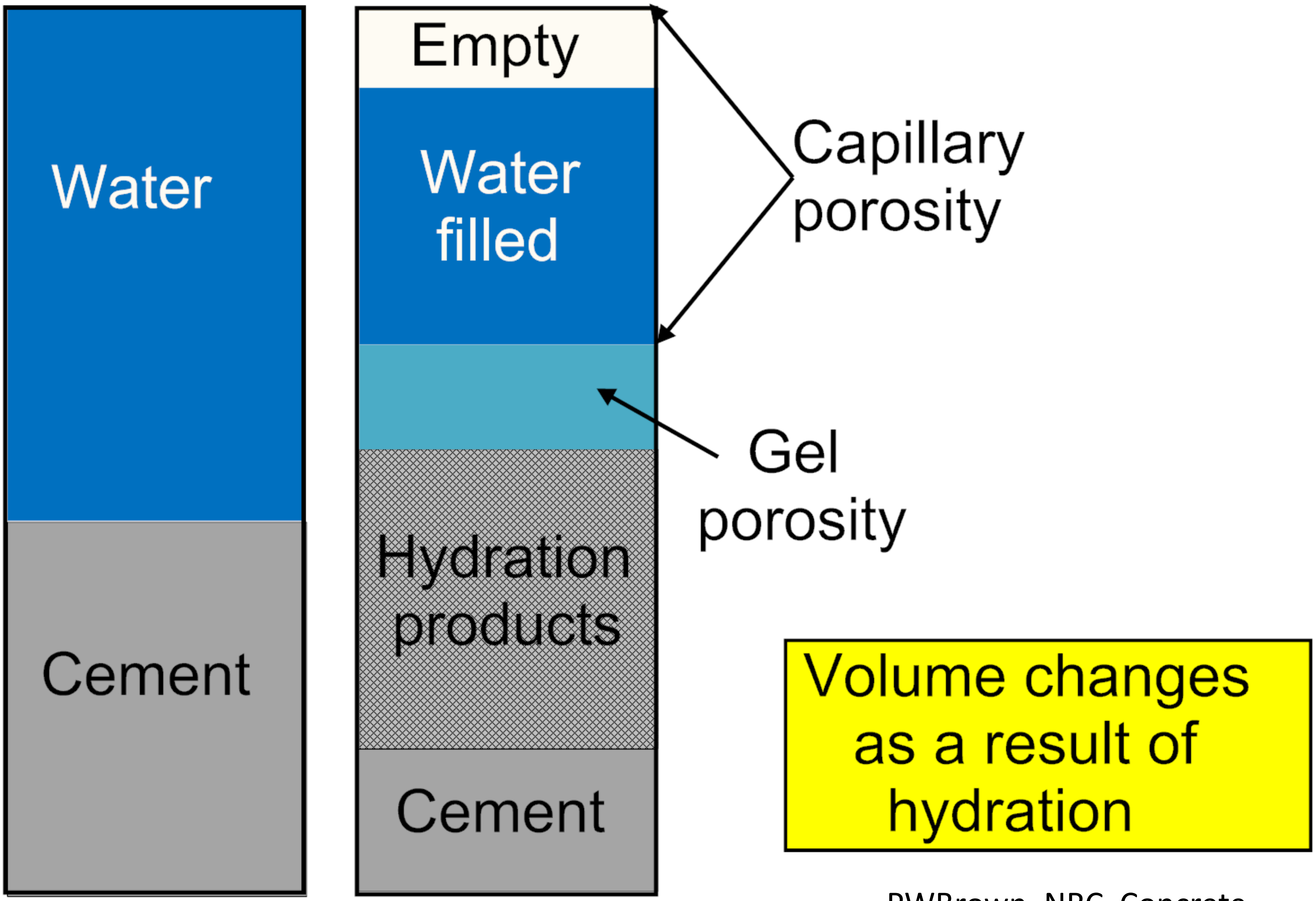
Using tricalcium silicate hydration as an  example:

The volume of solids increases from 145 to 252

**This is responsible for strength gain.**

The total volume of solids + liquids decreases from 271 to 252.

**This called chemical shrinkage and it is responsible for cracking**.

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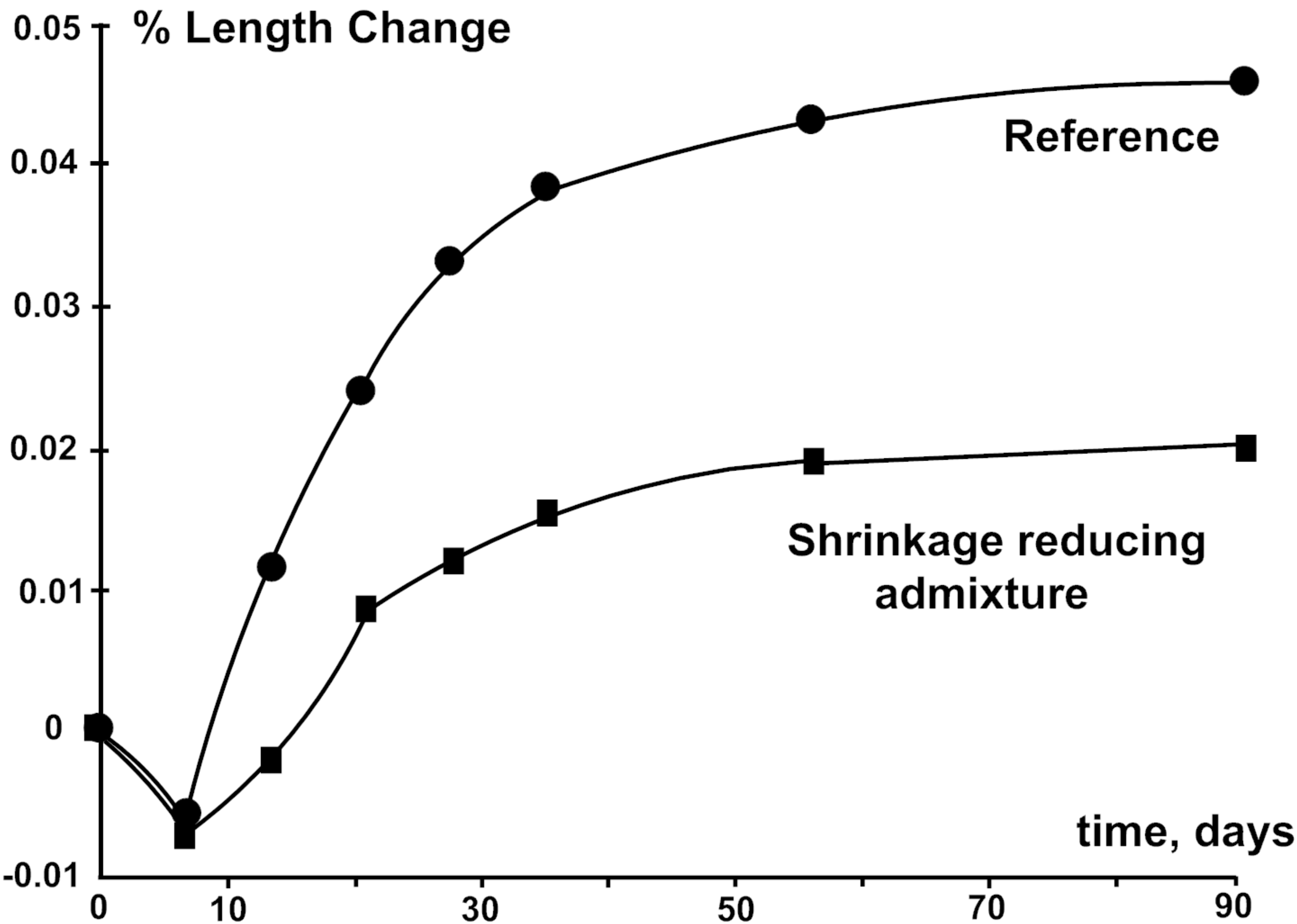


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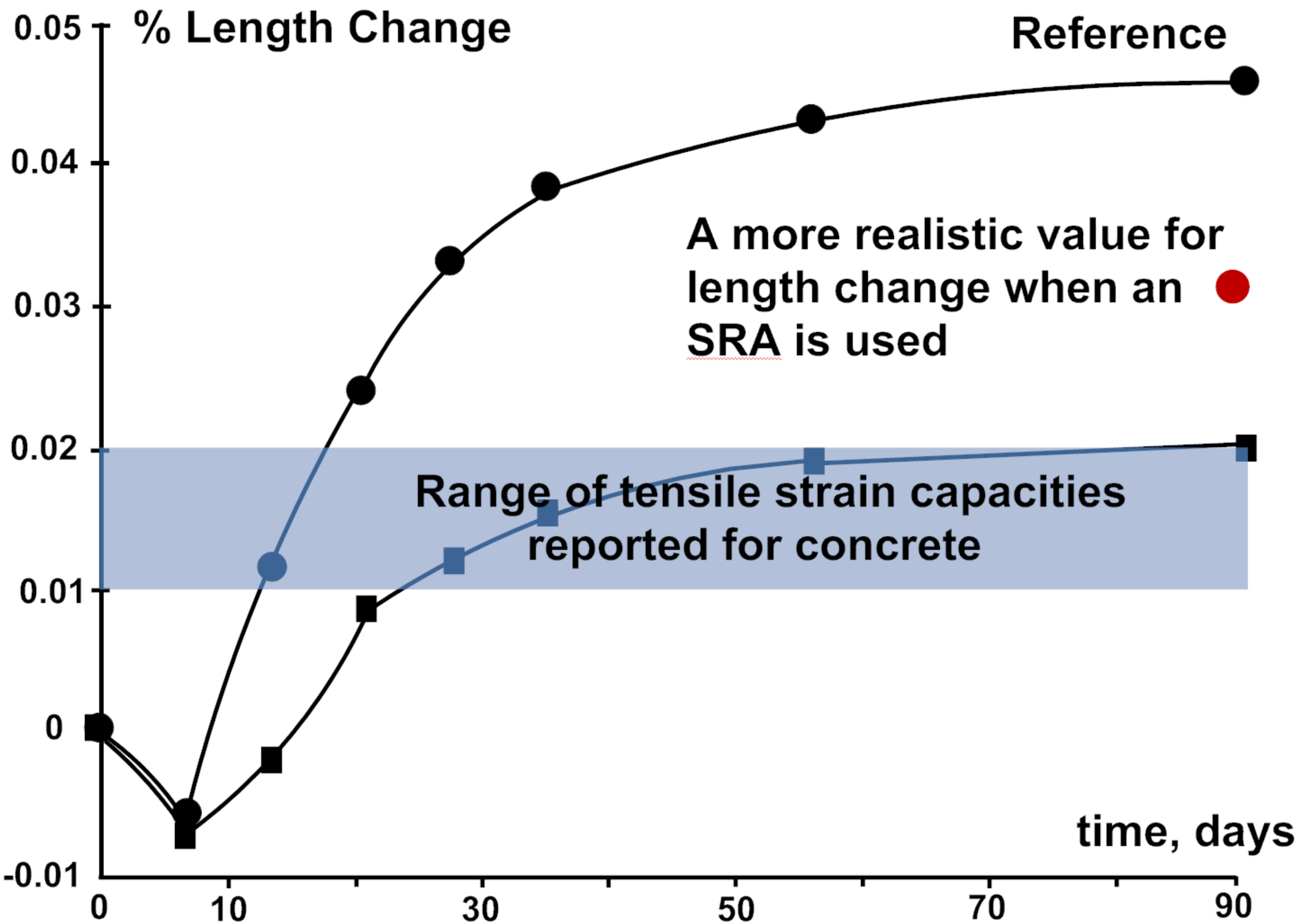


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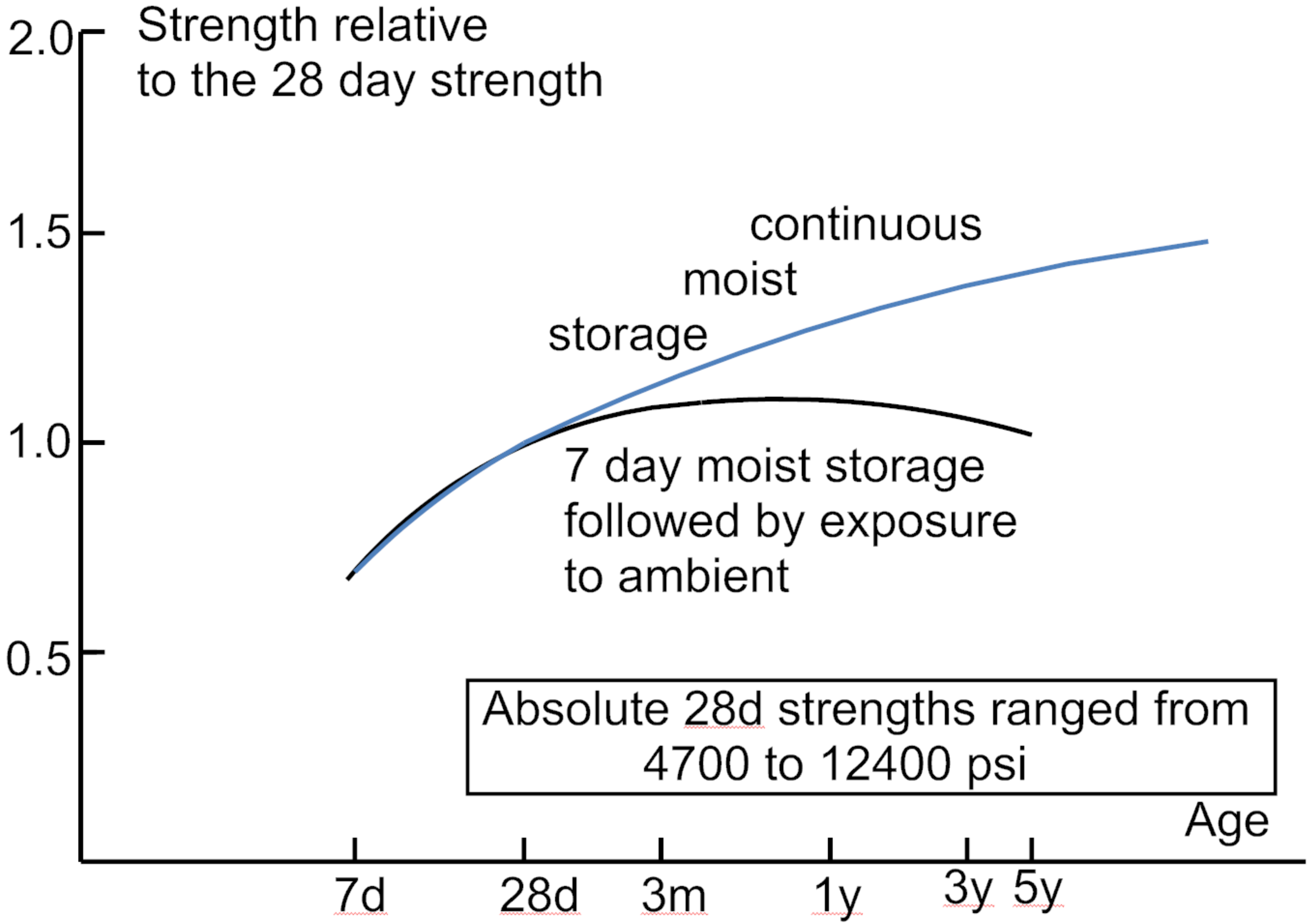
# But then the concrete dries out

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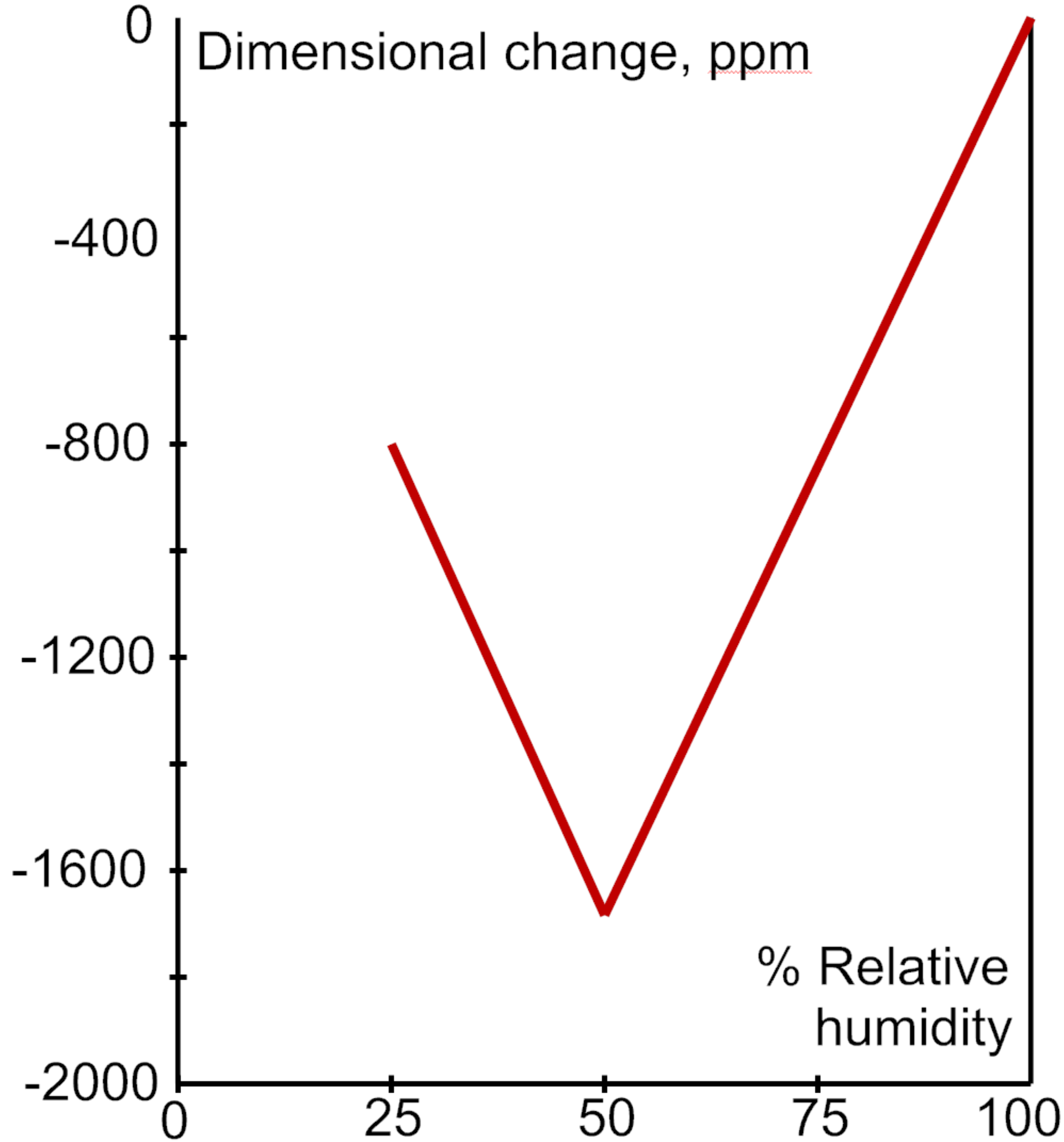
# Mortar

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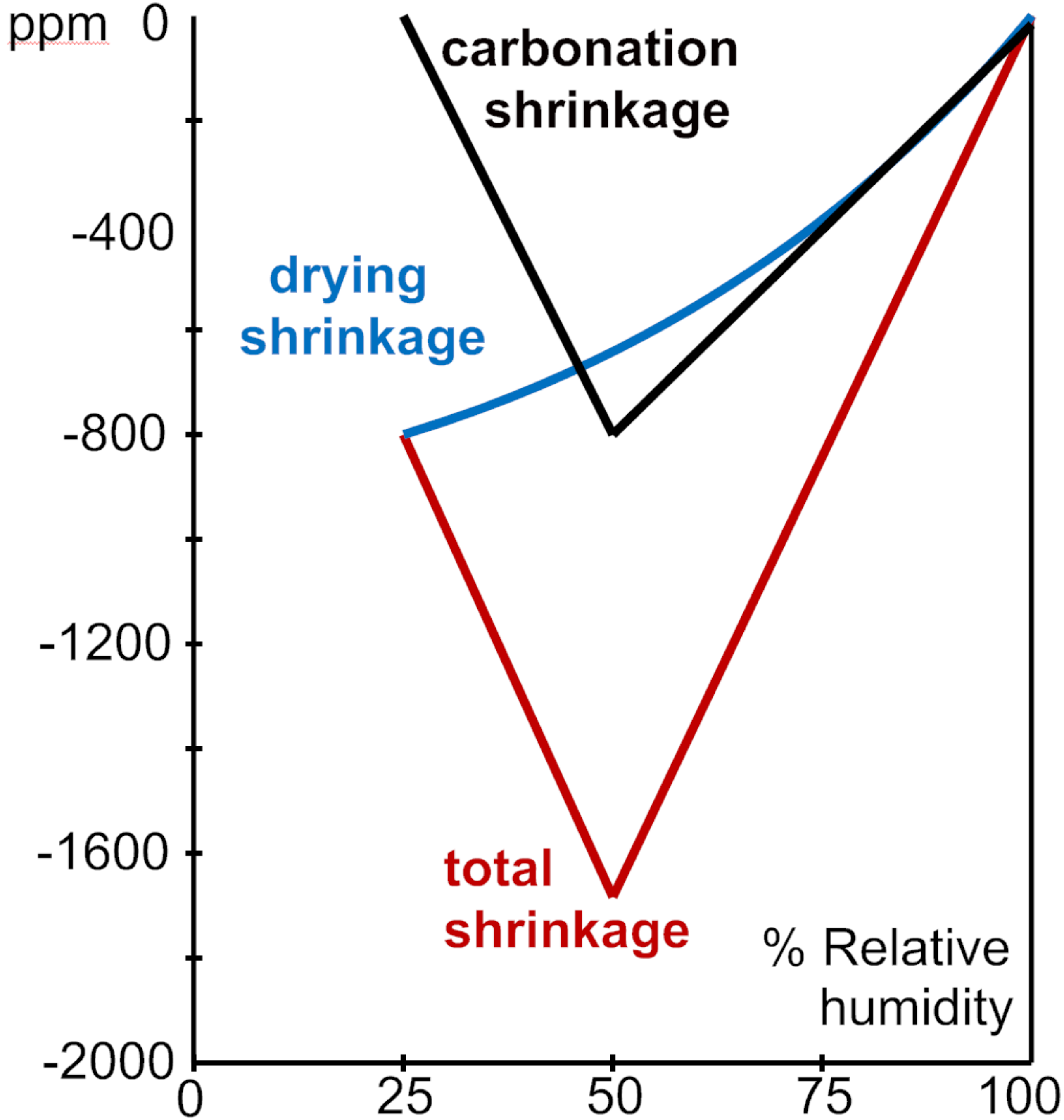


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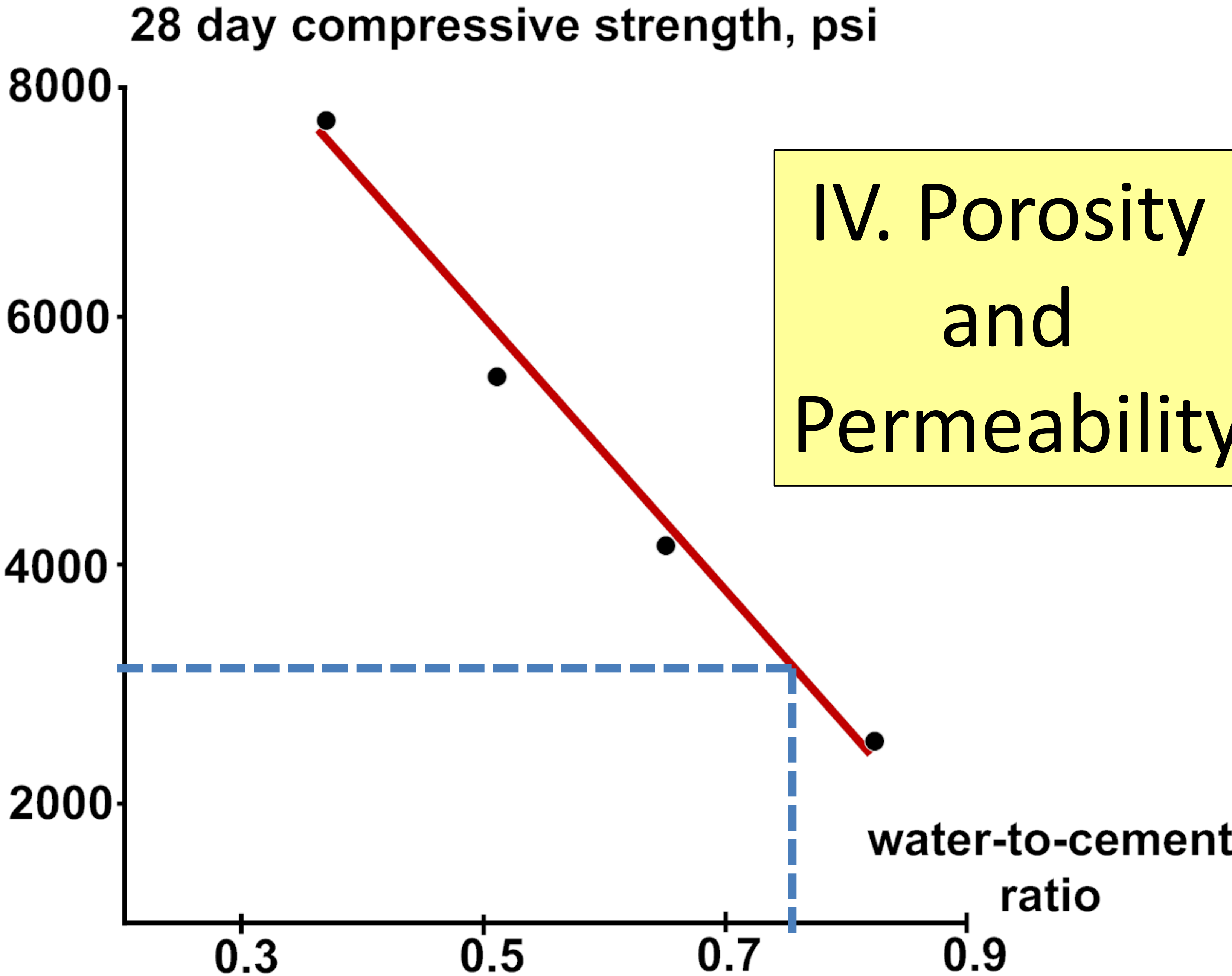
NRC Concrete
Degradation
Mtg 9-19-14




# IV. Porosity and Permeability

# Relationship between w/c ratio & porosity

| W/C Ratio by Mass | Capillary Porosity % by Volume |
|---|---|
| 0.40 | 8 |
| 0.45 | 14 |
| 0.50 | 19 |
| 0.55 | 24 |
| 0.60 | 28 |
| 0.65 | 32 |
| 0.70 | 35 |
| 0.75 | 38 |
| 0.80 | 41 |

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Degradation
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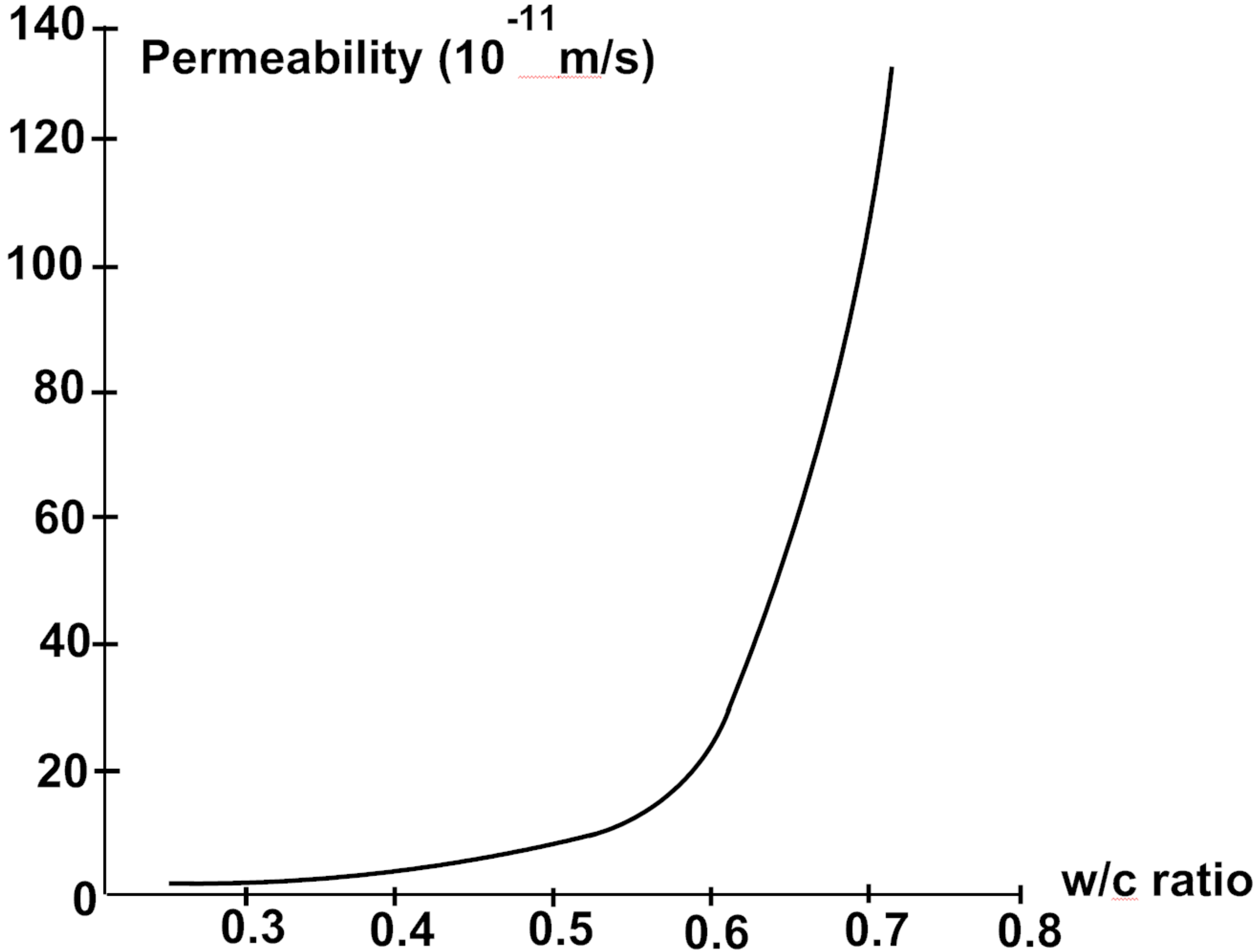
# Relationship between w/c ratio & permeability



# V. Degradation reactions

Carbonation
Leaching
Acid (chemical) attack
Freezing-thawing
DEF
Sulfate attack
Physical salt attack
Corrosion of embedded metals
ACR
ASR

# Degradation reactions

Carbonation

Surficial, permeability dependent.
Not typically of concern unless the carbonation front intersects the embedded steel.

Leaching & Acid (chemical) attack

Surficial, permeability dependent.
Likely localized to specific service environments.

# Degradation reactions

Freezing-thawing

Damage caused by ~10% volume expansion as water $\rightarrow$ ice.

Requires saturated pores.

Typically limited to horizontal (pavement) surfaces.

# Degradation reactions

Delayed ettringite formation (DEF)

Homogenous paste expansion in mature concrete as a result of an elevated curing temperature.

Alkali-silica reaction (ASR)

~Homogeneous expansion due to silicate gel formation.

# Degradation reactions

Sulfate attack

Formation of ettringite and/or gypsum due in the ingress of sulfates from the service environment.  The zone of damage typically propagates inwards from an evaporative front.

Physical salt attack

Expansive reaction associated with the ingress and crystallization of salts from the service environment.  Typically surficial but can affect embedded steel.

# Degradation reactions

Corrosion of embedded steel

Concrete cracking and debonding due to the increase in specific volumes of local solids as steel corrodes.

ACR (alkali-carbonate reaction)

A relatively rare form of degradation associated with MgO extraction from dolomitic aggregate.

# Degradation reactions common aspects

Freezing-thawing – **locally expansive**

Sulfate attack - **locally expansive**

Physical salt attack - **locally expansive**

Corrosion of embedded metals - **locally expansive**

DEF – **globally expansive**

ACR – **globally expansive**

ASR – **globally expansive**

# VI. Repair Strategies

## What is the objective of the repair?

1. To restore the area of damage.

2. To interfere with the mechanism of damage.

3. To do both.

# Repair methodologies – in situ concrete

Carbonation – R & R of the affected area (1)

Leaching – R & R of the affected area (1)

Acid (chemical) attack – R & R of the affected area (1)

Freezing-thawing – R & R of the affected area (1)

Sulfate attack – R & R of the affected area (1)

Physical salt attack – R & R of the affected area (1)

Corrosion of embedded metals:

- concrete R & R including cleaning the rebar (1)
- ECE (2)
- apply a penetrating corrosion inhibitor (2)

DEF, ACR, ASR - **none**

# ASR

**Mechanism**: silicate aggregate with amorphous or strained microcrystalline material is solubilized by concrete pore soln. $(Ca,Na,K)_xSiO_2.yH_2O$ gel forms. As the ratio of (Na+K)/Ca increases, the gel swells.

**Repair** (practical): There is no generally accepted repair methodology.

**Repair** (theoretical): Repair must involve contriving to create internal conditions within the concrete where ASR is not favorable.

# Some possible repair options

## Deprive concrete of moisture

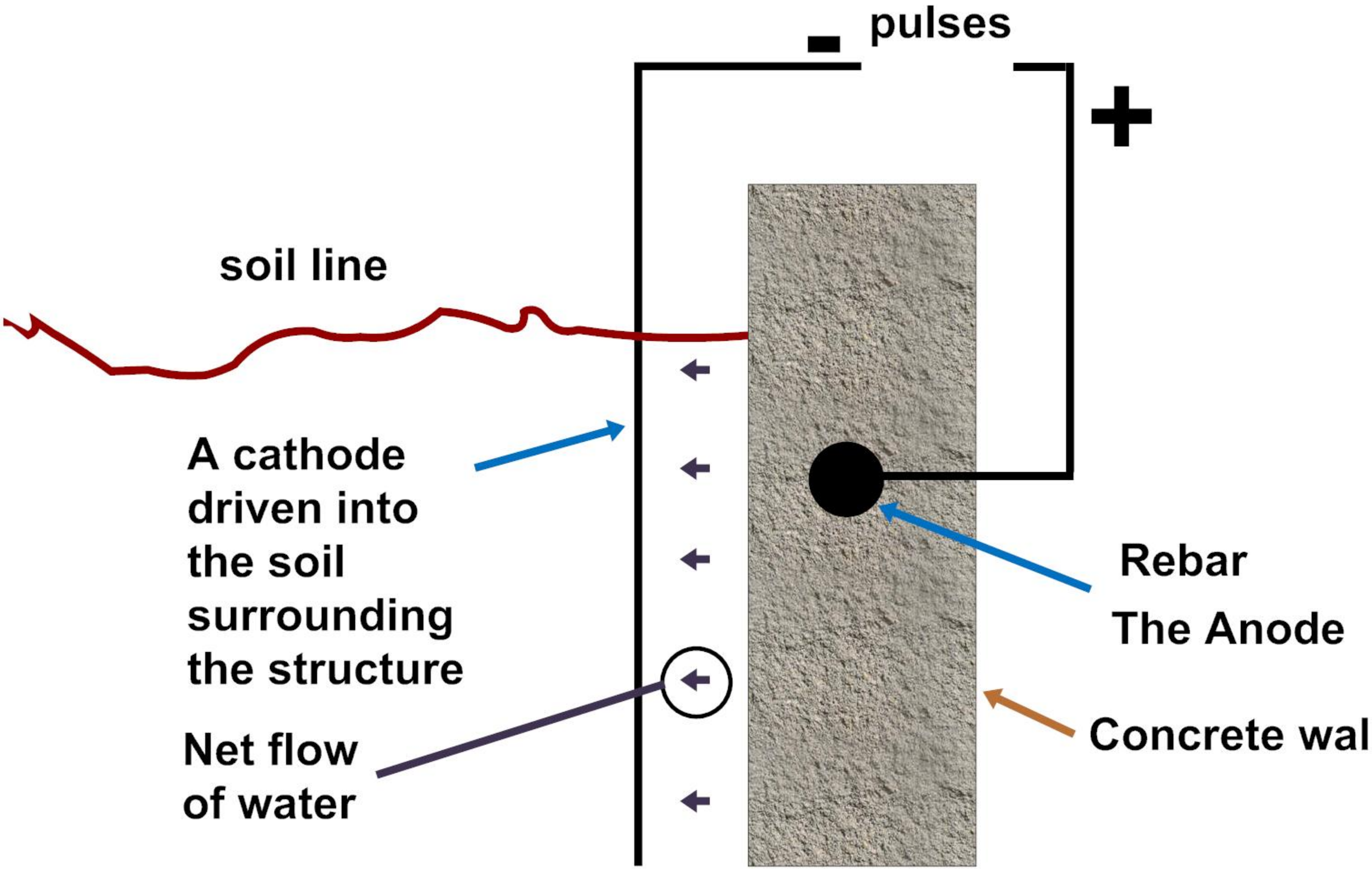
Affect the pore solution chemistry

Introduce Li salts

Reduce the pH of the pore solution

Affect the alkali-to-silica ratios

Deploy a modification of ECE



- pulses
+
soil line
A cathode driven into the soil surrounding the structure
Net flow of water
Rebar
The Anode
Concrete wall

# Some possible repair options

Deprive concrete of moisture

## Affect the pore solution chemistry

### Introduce Li salts

Reduce the pH of the pore solution

Affect the alkali-to-silica ratios

Deploy a modification of ECE

# Some possible repair options

Deprive concrete of moisture

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# Some possible repair options

Deprive concrete of moisture

**Affect the pore solution chemistry**

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# Some possible repair options

Deprive concrete of moisture

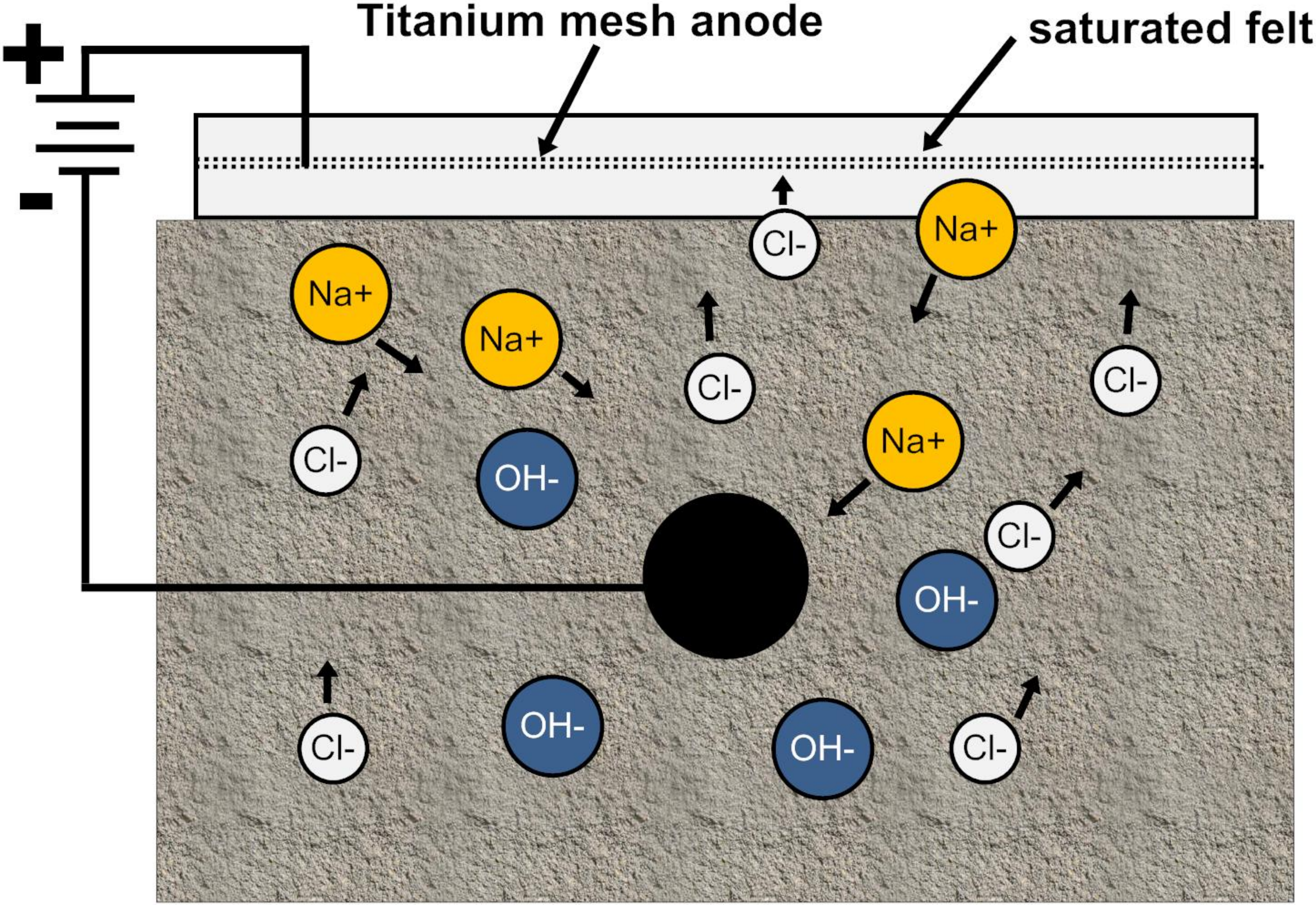
## Affect the pore solution chemistry

Introduce Li salts

Reduce the pH of the pore solution

Affect the alkali-to-silica ratios

## Deploy a modification of ECE

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# VII. Summary

Concrete will always contains flaws.

Concrete will contain cracks, some of which will appear in mature concrete.

The mere detection of cracks does not necessarily mean that the world is coming to an end.

***The absence of macroscopic cracks should not be interpreted as the absence of degradation.**

Strength data can be interpreted in a variety of ways.

While a variety of factors associated with its service environment can degrade a concrete structure, degradative processes are frequently expansive.

With respect to ASR, there is no proven method of remediation.

There are a variety of technologies that may provide a method of remediation an ASR affected structure.

# Methodology for Assessing Long Term Performance of Aging Concrete Structures


Randy James
ANATECH Corp.
San Diego, CA

September 19, 2014
NRC Offices
Rockville, MD

# Background

- Aging can be defined as a change in behavior over time
- Concrete is man-made material of different constituents and begins aging as soon as put into service
- Concrete can exhibit significant changes during maturation from creep, shrinkage, and strength gain
- Concrete is un-symmetric in tension and compression which can significantly affect response to load reversals
- Repetitive cyclic loading can lead to significant degradation due to increasing levels of cracking
- Elevated temperatures (and time at temperature) lead to non-reversible changes in stiffness and strength
- Environment plays a significant role in degradation

# Background

- Many Examples of Aging Concrete in Civil Structures
  - ✓ Navigational locks and dams on inland waterways
  - ✓ Gravity and arch dams for flood control or power generation
  - ✓ Industrial plants, bridges, marine piers
- Fewer Examples of Aging Concrete in Nuclear Plants
  - ✓ Higher standards for concrete design and construction
  - ✓ Relative ages or numbers of nuclear plants
- Aging Management & License Renewals of NPPs
  - ✓ Need assessments when specific issues emerge
  - ✓ Need assessments to help understand possible future issues
  - ✓ Need assessments when modifying older structures
- Assessments for Structural Functionality
  - ✓ Aging is complex issue and simulation is difficult
  - ✓ Concrete structures are generally very resilient to damage
  - ✓ However when limit is reached, failure can be sudden and catastrophic

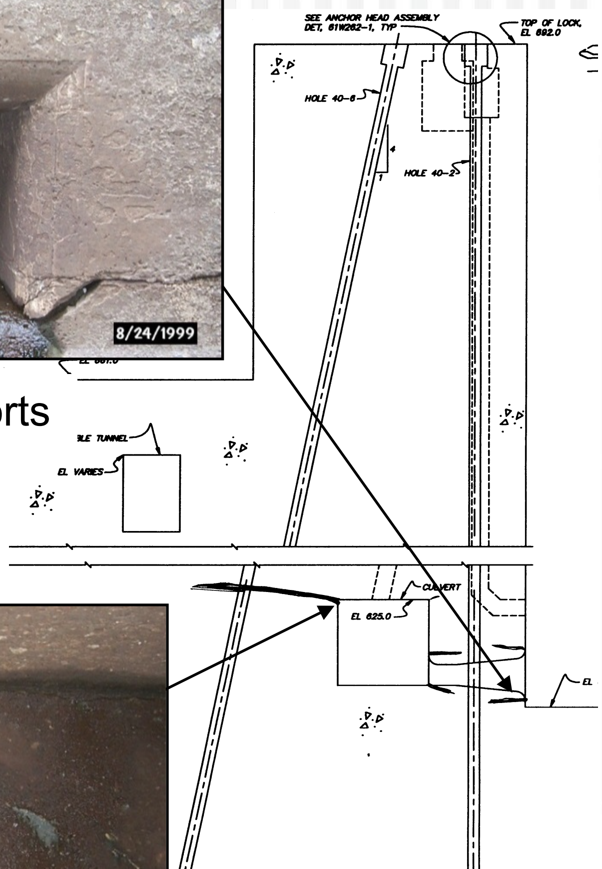
# Assessment Methodology

- Collect in-Situ Data
  - ✓ Material properties, operational history, and structural state
- Employ Adequate Concrete Material Model
  - ✓ Consider spatial and time dependent properties
  - ✓ Include Interaction and progression of cracking effects
- Setup and Benchmark Baseline Model
  - ✓ Incorporate material data from local testing
  - ✓ Perform analysis for structural history, including repairs and operational history, to match current state & field data
- Assessment of Structural Performance
  - ✓ Assess/Demonstrate functionality of current state
  - ✓ Continue analysis to identify potential limit states
  - ✓ Identify possible remediation measures as necessary
- Assessment of Uncertainties
  - ✓ Uncertainties in material property data and future environment
  - ✓ Range of parameters can be estimated
  - ✓ Effects of variations can be established

# Cracking in Lock Monolith with AAR


Cracking at Outlet Ports

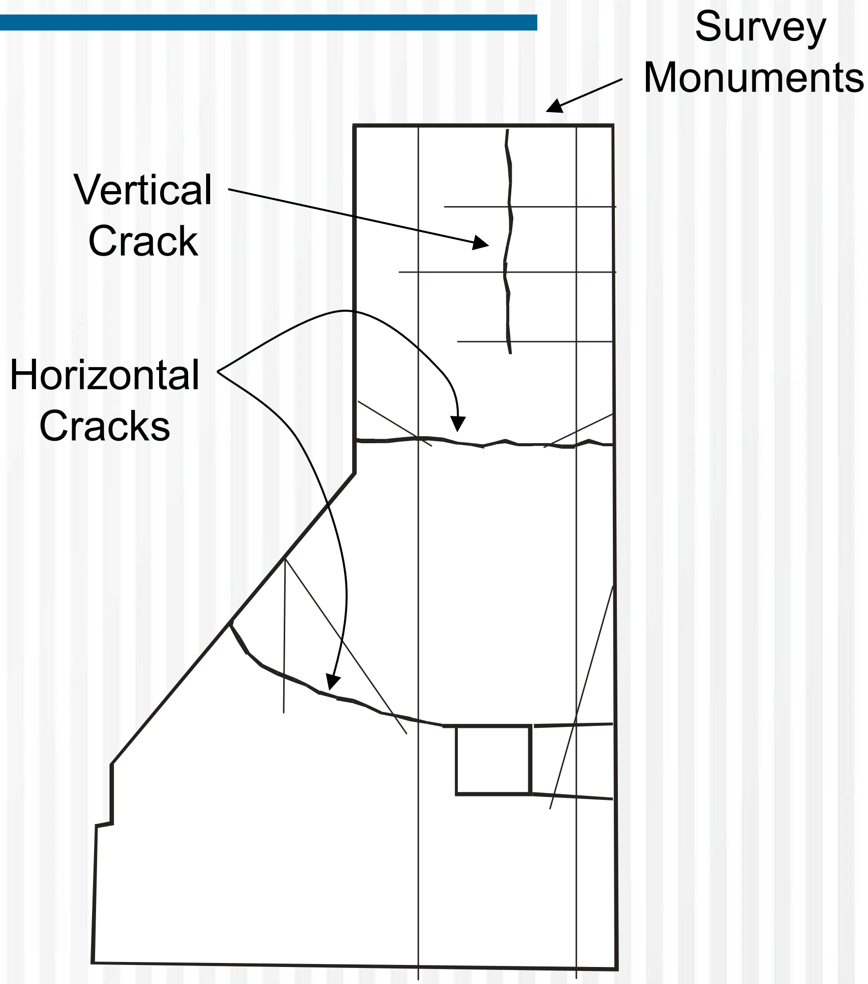
Cracking in Culverts




Chamber Monolith

# Cracking in Lock Monolith with AAR

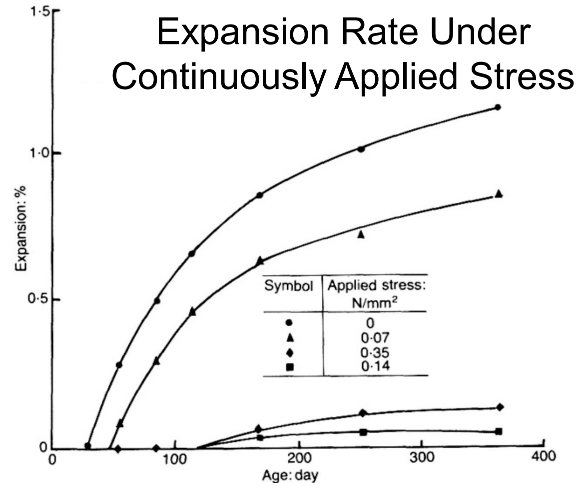
Cracking through Monolith Wall

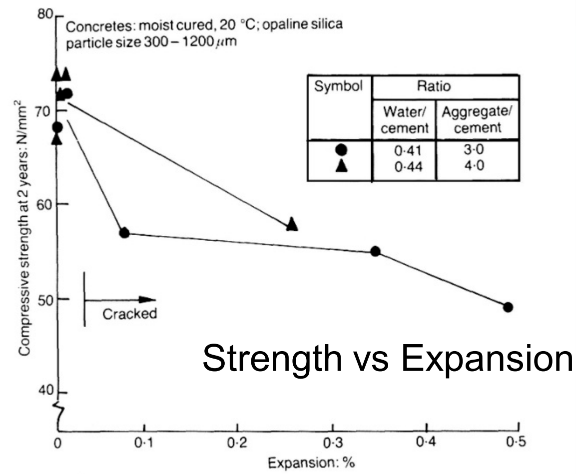




Miter Gate Monolith

# AAR Modeling Difficulties

- (Lack of) Constitutive Relations
  - ✓ Reaction is Function of Temp and Moisture Content
  - ✓ Expansion Rate is Function of Stress and Creep
  - ✓ Properties are Functions of Expansion and Deterioration
  - ✓ Micro-Cracking Can Facilitate an Increase in Reaction Rate
- (Lack of) Material Data for Site
  - ✓ Growth Rate Depends on Batch Placements
  - ✓ Random Concentrations within Batches
  - ✓ Variable Gestation Times

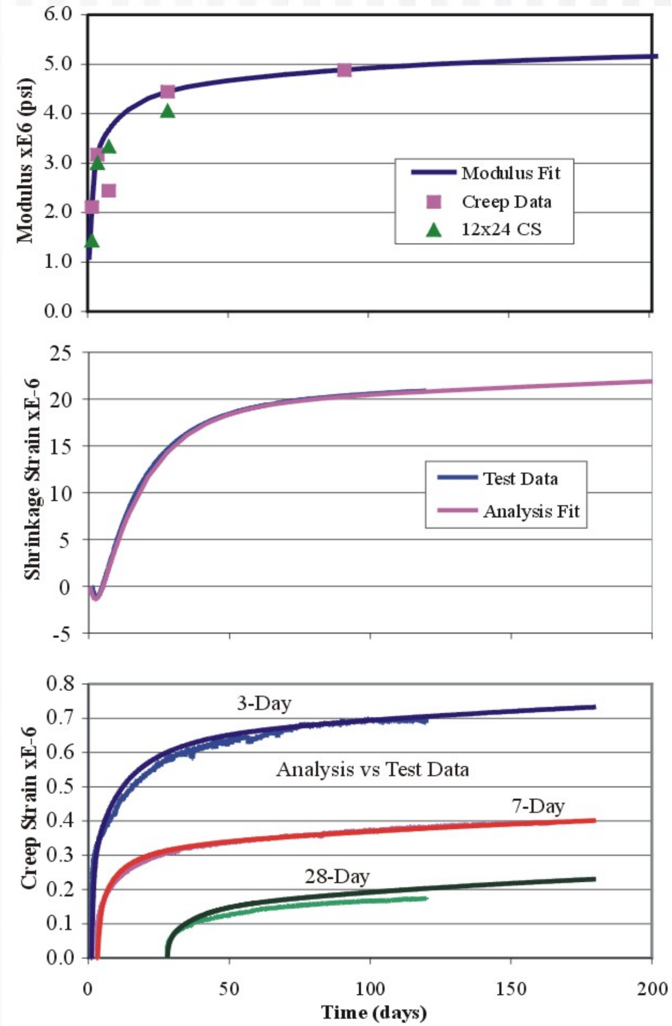



**D. W. Hobbs, Alkali-Silica Reaction in Concrete, Thomas Telford, London, 1988**

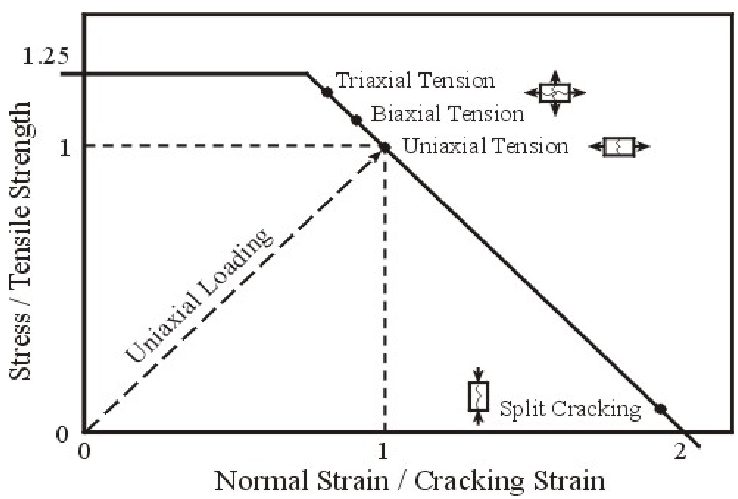
# Concrete Modeling - Time Dependent Properties

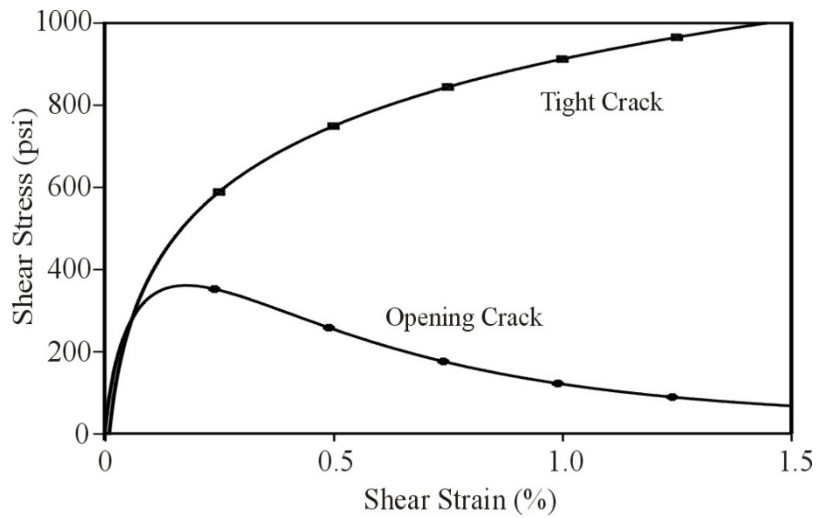
- Aging (Hardening)
  - ✓ Time Dependent Stiffness
  - ✓ Time Dependent Compressive Strength
- Autogenous Shrinkage
  - ✓ Time Dependent Volume Change
- History Dependent Creep Formulation
  - ✓ Viscoelastic Behavior
  - ✓ Age and Loading Dependent
- For AAR Modeling
  - ✓ Reverse the Shrinkage Terms
  - ✓ Modulus and Strength Degradation
  - ✓ Capture Macro Effects



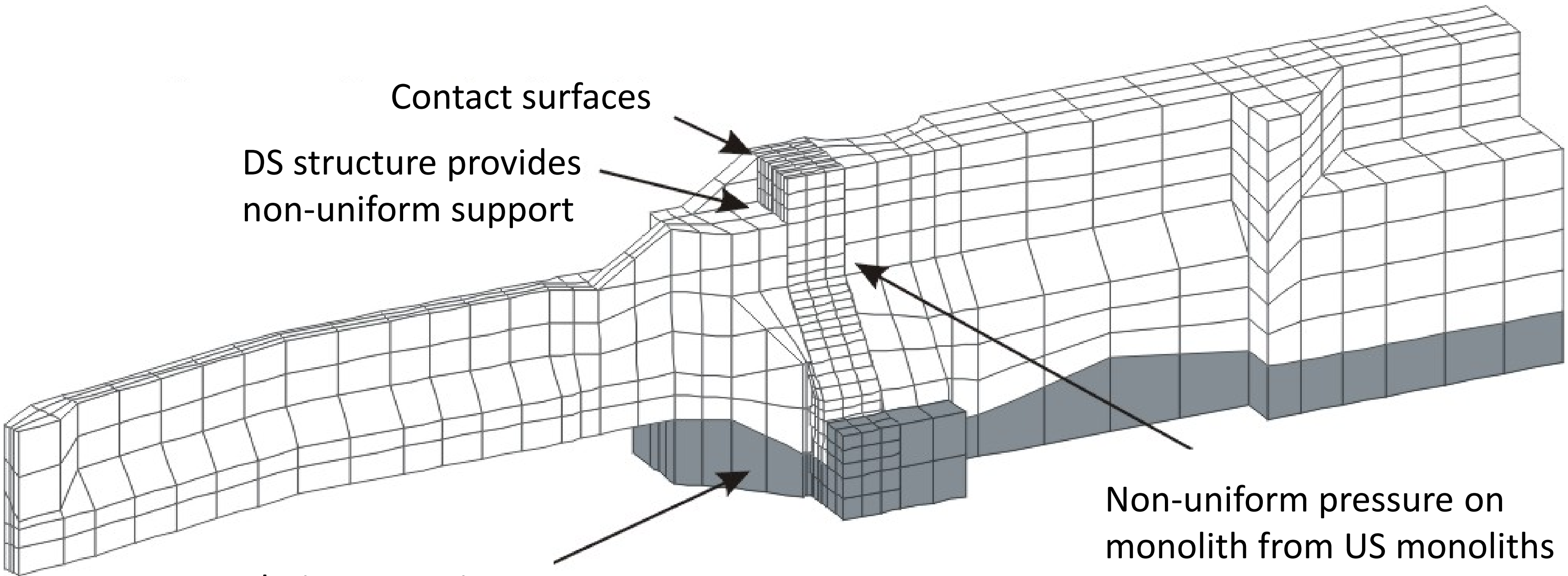
# Concrete Modeling - Cracking Interaction

- Smeared Cracking Formulation Treated at Integration Points
- Crack Criteria is Time Dependent and Treats All Loading States
- Cracks Can Open and Close but Can Never Heal
- Shear Transfer Across Crack Due to Aggregate Interlock
- Reduced Shear Modulus is Function of Crack Opening
- Shear Capacity is Function of Crack Opening Strain



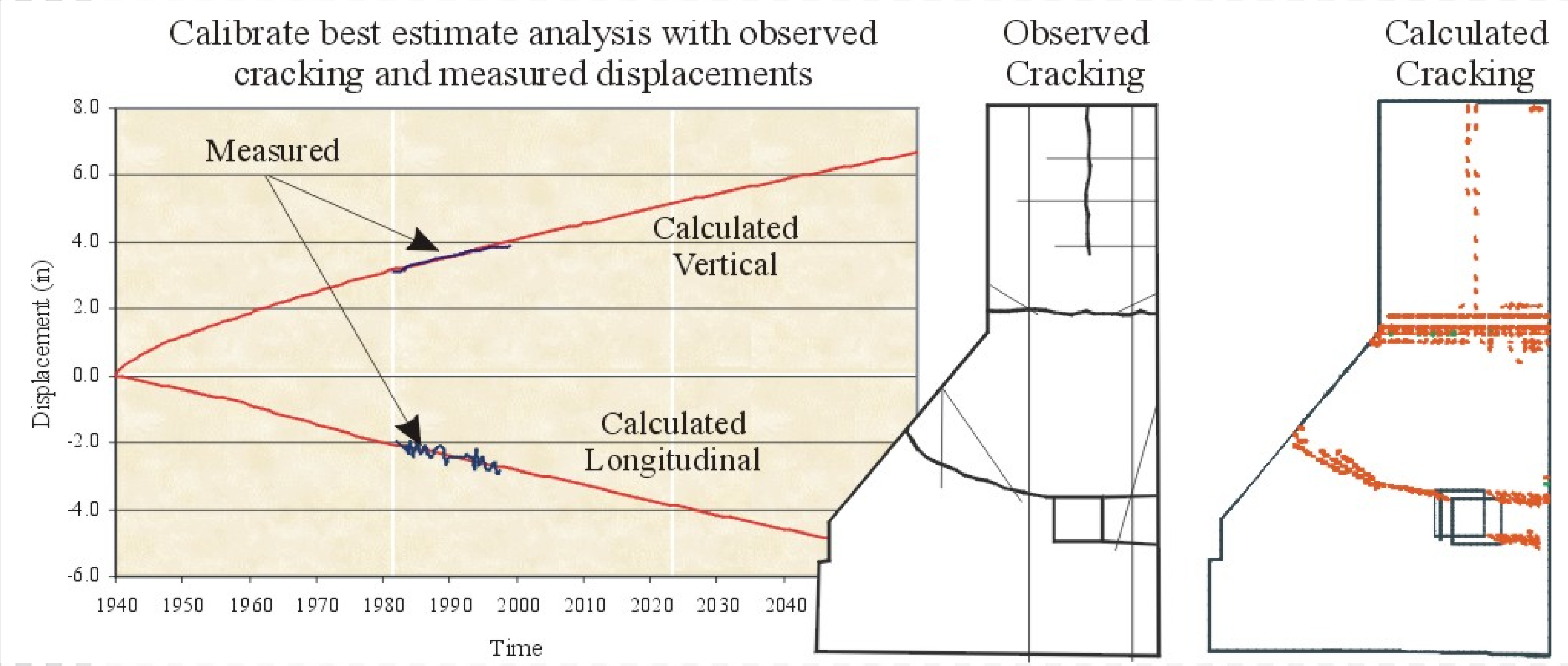



# Global Model of Lock Wall



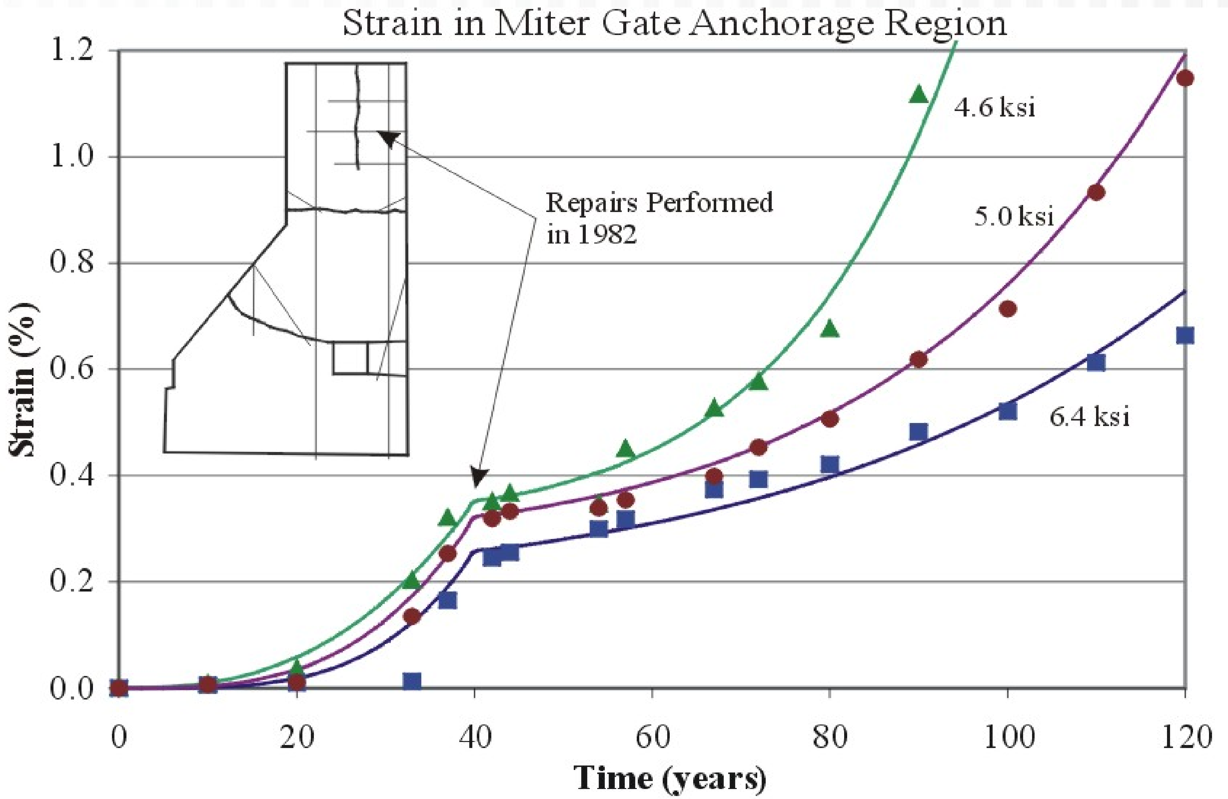

- Calibrate Expansion Rate to Measured Movement
- Provide Stress Distribution from U.S. Wall Growth
- Provide Resistance from D.S. Wall Support

# Benchmark with Field Data



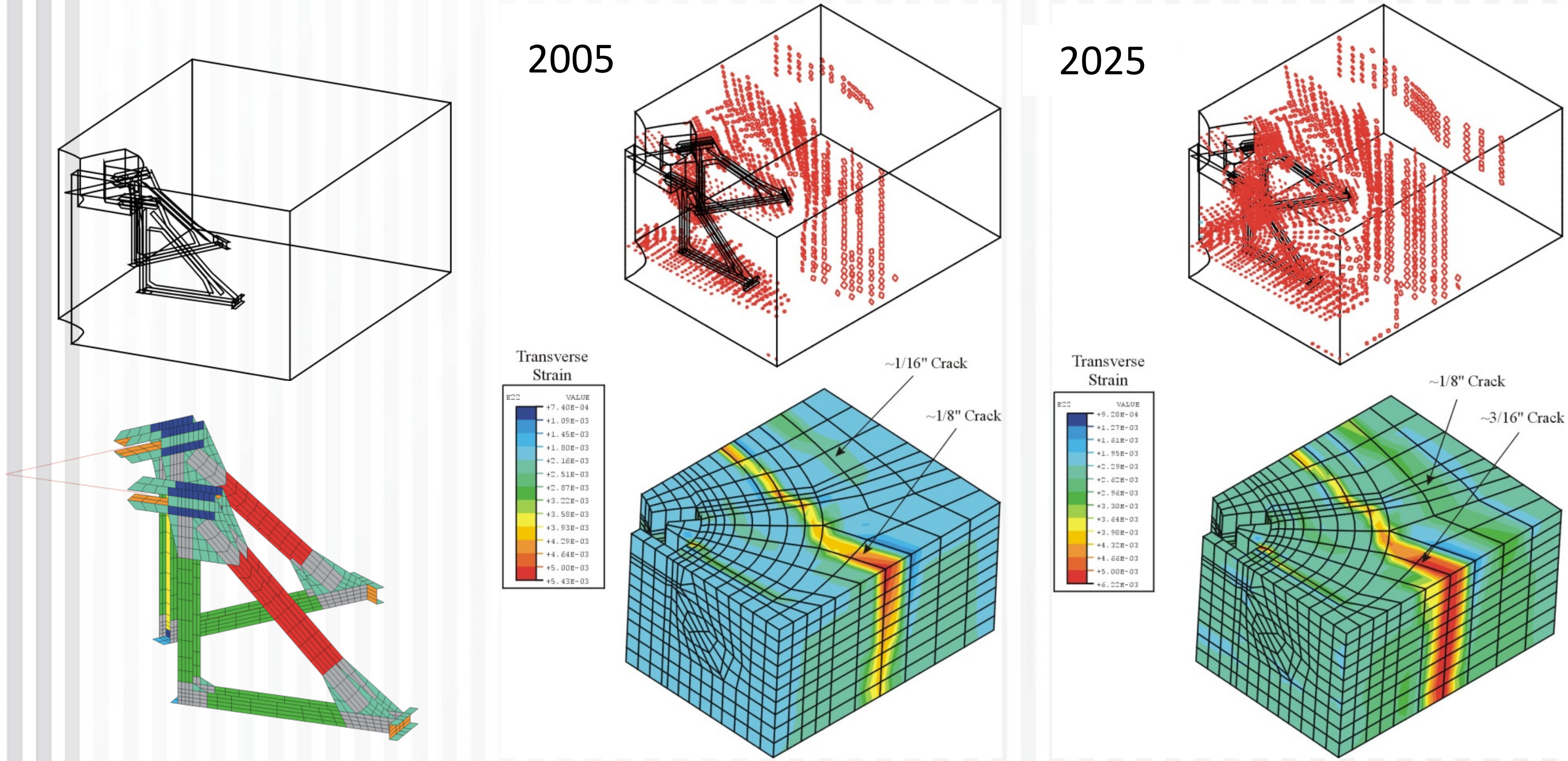

- Benchmark with Measured Global Displacements
- Benchmark with Observed Cracking History
- Cracking History is Signature of Stress Distributions

# Assess Long Term Performance




- Continue analysis to identify potential limit states
- Identify possible remediation measures as necessary

# Assess Limit State

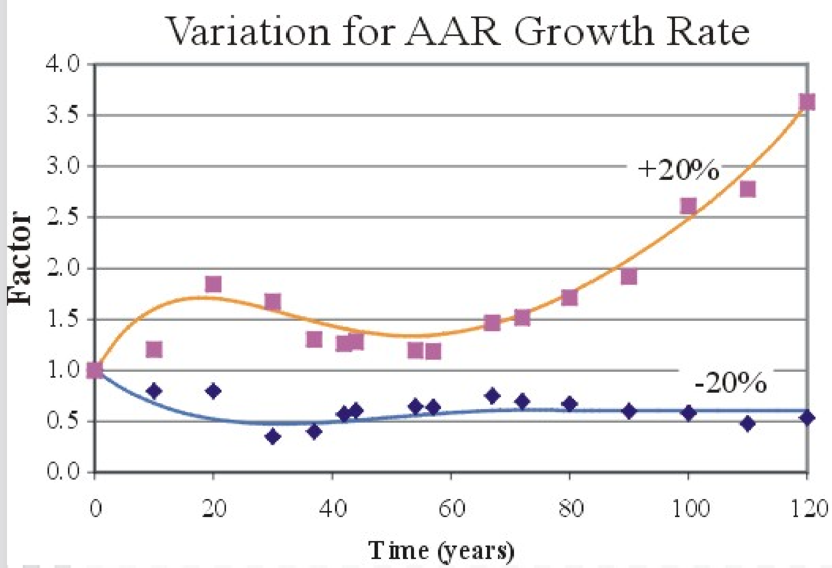


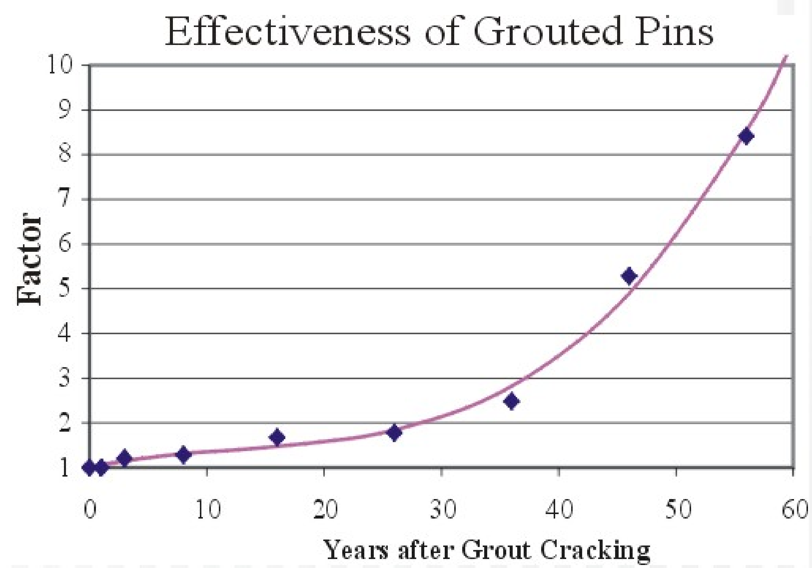

- Detailed local model of A-Fame anchorages
- Boundary conditions from benchmarked global model

# Accounting for Uncertainties

- Identify Range of Key Parameters using Test Data
- Concrete Strength
  - ✓ Core Samples – 3.6 to 6.4 ksi Strength
- AAR Growth Rate
  - ✓ ±20% on Benchmarked Nominal Rate
- DS Support Stiffness due to Cracking
  - ✓ ±20% on Benchmarked Nominal Values
- Effectiveness of Repairs
  - ✓ Stress-Strain Data from Performance Tests
  - ✓ De-bond and Shear Friction from Literature
  - ✓ Corrosion Rate from COE Field Data

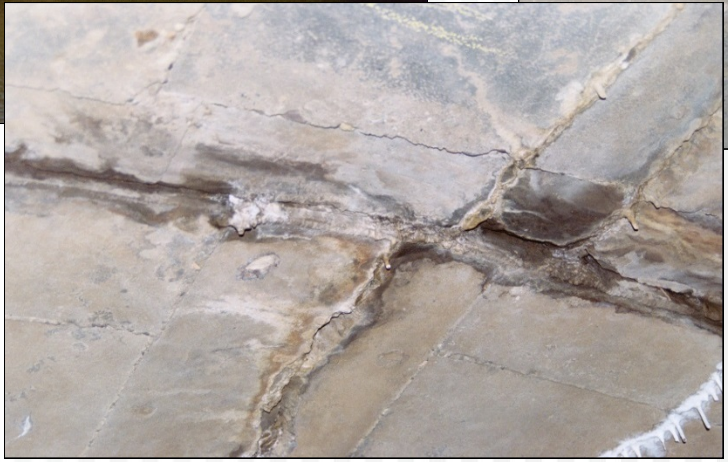
# Assess Effect of Uncertainties




- Example Factors for Growth Rate and Pin Effectiveness
- Performance of Rock Anchors Has Small Effect
- Variation in Downstream Stiffness Has Small Effect

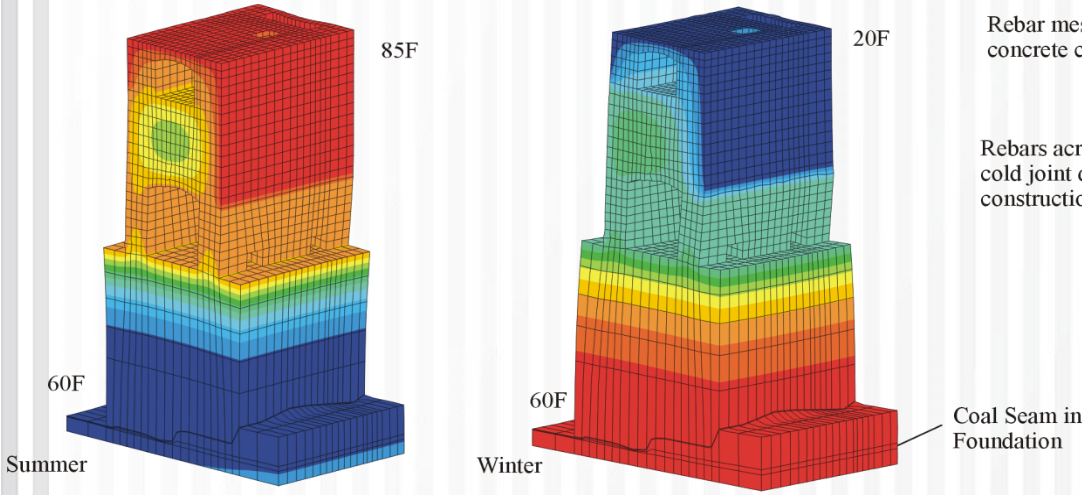
# Thermal Cycling and Freeze Thaw Damage



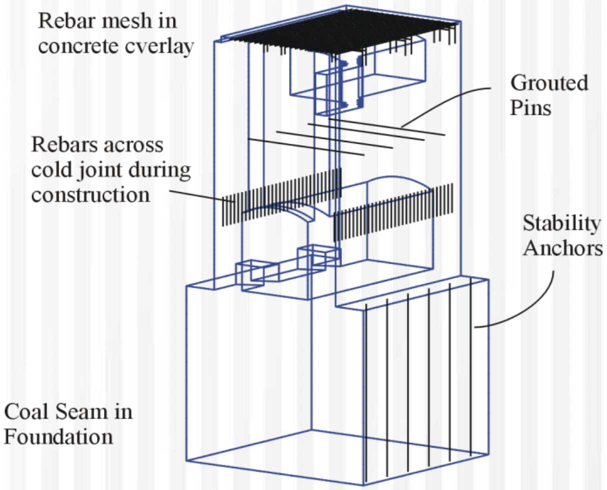
# Freeze Thaw Degradation Modeling

- Mechanical operating loads
  - ✓ not responsible alone for cracking patterns observed
  - ✓ Include effects of mechanical cyclic loading
- Summer to winter thermal cycling
- Time and spatial dependent concrete deterioration
  - ✓ Reduced modulus and tensile capacity
  - ✓ Chamber faces exposed to air, water, or fill and empty
  - ✓ Interior gallery and culvert faces
  - ✓ Exterior faces exposed to air or water
- Include hydraulic pressure for concrete points that reach freezing temperature
- Iterative process to simulate structural history to match current structural state

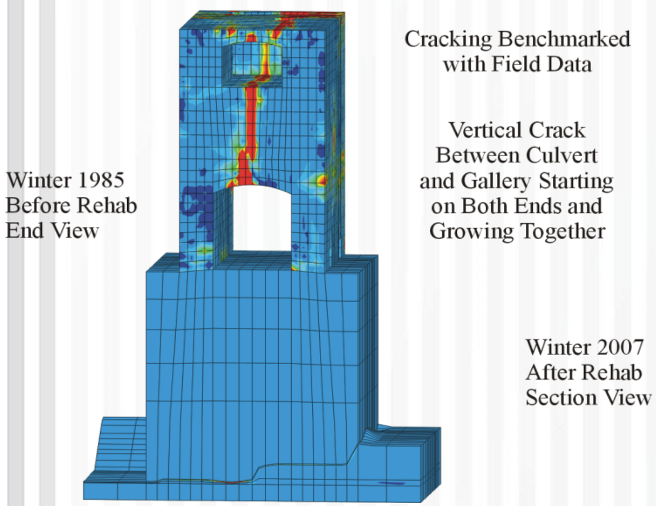
# Thermal Cycling and Freeze Thaw Damage

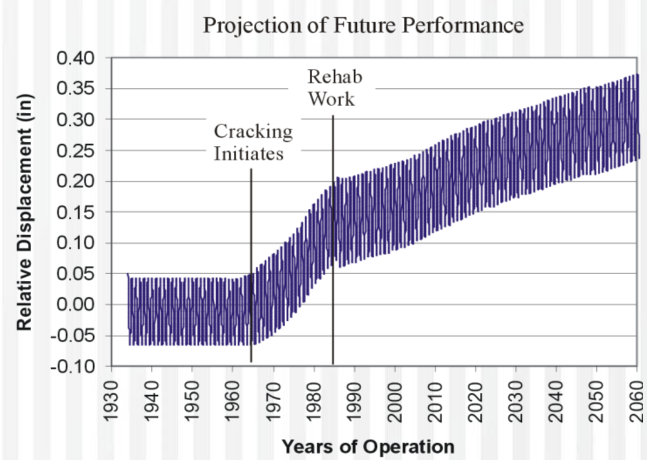



Temperature Distributions for Cyclic Thermal Loading




Modeling of Rehabilitation Work



# Summary

- Collect and Document Data
  - ✓ Visual inspections for general screening and targeted follow ups
  - ✓ Use risk-informed targeting for less accessible areas based on analyses or operating experience
  - ✓ Data collection if abnormal conditions encountered
  - ✓ Document changes in in-situ properties and structural state
- Develop Baseline Analysis Model
  - ✓ Incorporate spatial and time dependent properties and <u>macro</u> aging effects in concrete constitutive model
  - ✓ Perform analysis for structural history, including repairs and operational history to match current state & field data
  - ✓ Assess current functional state
- Assess Future Performance and Uncertainties
  - ✓ Continue analysis to identify potential limit states
  - ✓ Identify possible remediation measures as necessary
  - ✓ Use test and field data to determine range of parameters
  - ✓ Probabilistic based assessment

# Concrete Aging and Degradation in NPPs

# LWRS Activities

**J.T. Busby, D.A. Clayton, K.G. Field,**
**Y. Le Pape, D.J. Naus, I. Remec, T.M. Rosseel**
**Oak Ridge National Laboratory**

**ACRS Meeting on Concrete Degradation**
**September 19, 2014**

Light Water Reactor Sustainability R&D Program

# Outline and Agenda for presentation

- Brief overview of LWRS program and materials research
- EMDA findings and potential knowledge gaps for civil structures and concrete
- LWRS areas of emphasis in concrete degradation
  - Alkali-Silica Reactions
  - Irradiation Effects
  - Non-destructive evaluation techniques

# The DOE-NE Light Water Reactor Sustainability Program is supporting subsequent license extension decisions

***Vision***

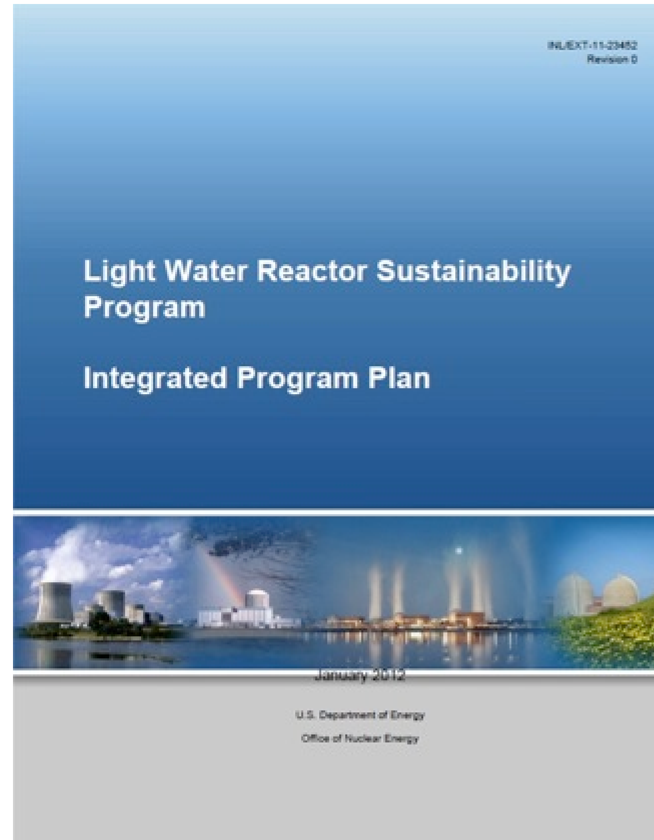
- *Enable existing nuclear power plants to safely provide clean and affordable electricity beyond current license periods (beyond 60 years)*

***Program Goals***

- Develop fundamental scientific basis to understand, predict, and measure changes in materials as they age in reactor environments
- Apply this knowledge to develop methods and technologies that support safe and economical long-term operation of existing plants
- Research new technologies that enhance plant performance, economics, and safety

***Scope***

- Materials Aging and Degradation
- Advanced Instrumentation and Controls
- Risk-Informed Safety Margin Characterization
- Reactor Safety Technology


INL/EXT-11-23452
Revision 0

Light Water Reactor Sustainability Program

Integrated Program Plan

January 2012

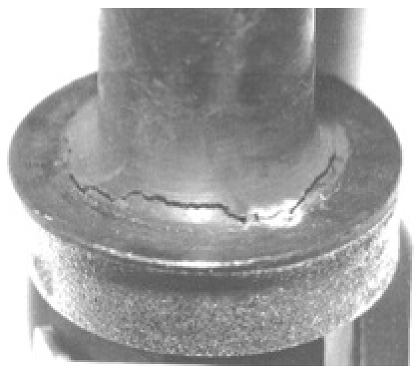
U.S. Department of Energy

Office of Nuclear Energy

LWRS Integrated Program Plan (INL/EXT-11-23452, Rev. 0) Available on www.inl.gov/lwrs

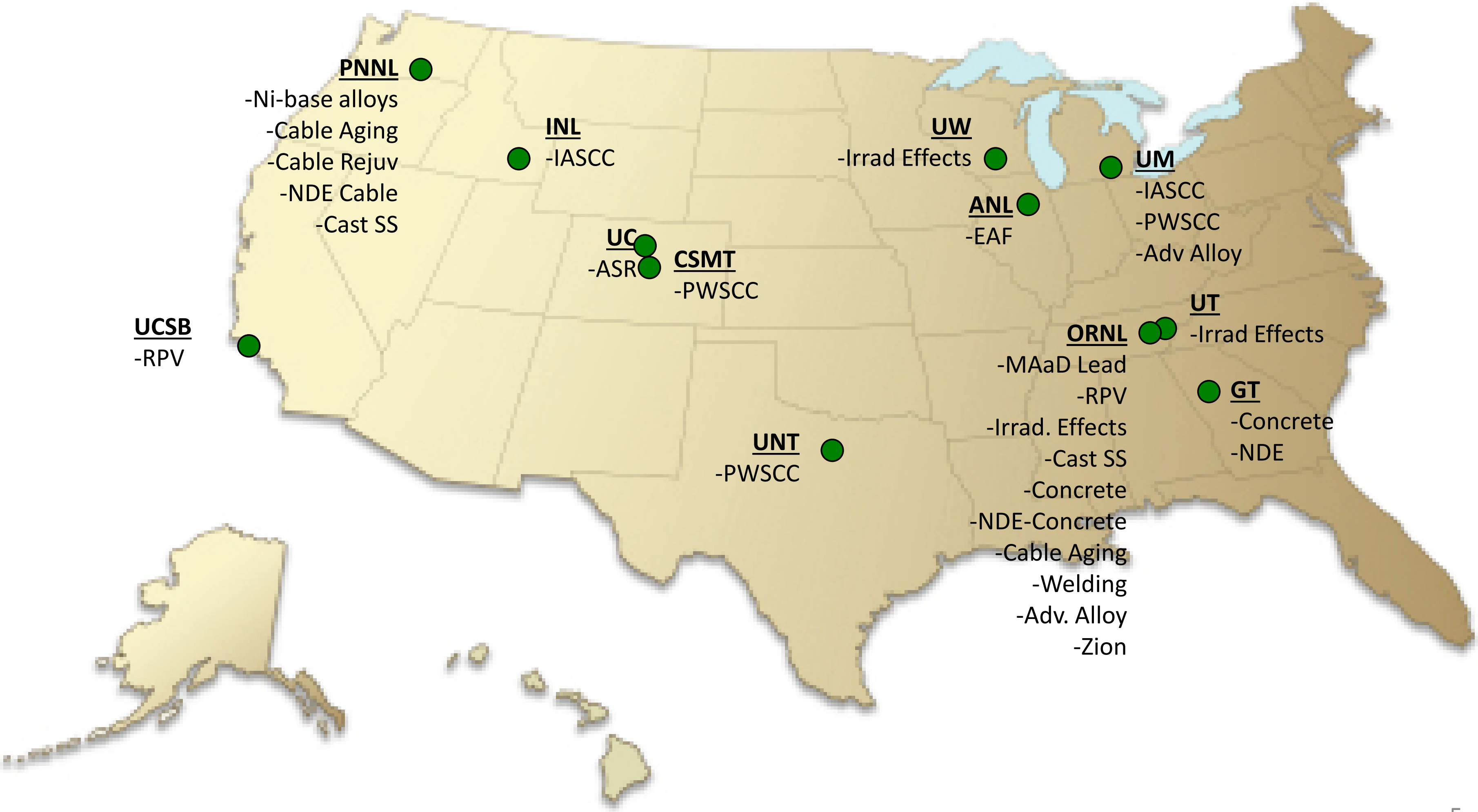
# Materials aging and degradation is a key need for subsequent license renewal

- Increased lifetime leads to increased exposures
  - Time at temperature
  - Stress
  - Coolant
  - Neutrons
- Extending reactor life to 60, 80 years or beyond may increase susceptibility and severity of known forms of degradation
- New mechanisms of materials degradation are possible



- Develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants
- Provide data and methods to assess the performance of systems, structures, and components essential to safe and sustained NPP operations
- Develop means to detect and characterize aging degradation processes
- Develop technologies for mitigation of key forms of degradation

# MAaD includes a diverse materials research effort team



# Materials Aging and Degradation tasks provide results in several ways

- **Measurements of degradation**: High quality data will provide key information for mechanistic studies, but has value to regulators and industry on its own.
- **Mechanisms of degradation:** Basic research to understand the underlying mechanisms of selected degradation modes will lead to better prediction and mitigation.
- **Modeling and simulation:** Improved modeling and simulation efforts have great potential in reducing the experimental burden for life extension studies. These methods can help interpolate and extrapolate data trends for extended life.
- **Monitoring:** While understanding and predicting failures are extremely valuable tools for the management of reactor components, non-destructive monitoring must also be utilized.
- **Mitigation strategies:** While some forms of degradation have been well-researched, there are few options in mitigating their effects. New technologies may overcome limits of degradation in key components and systems.

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# Materials Aging and Degradation Pathway Major Deliverables

**by 2016 – Lead Plant for SLR Selected**

- Expanded Materials Degradation Assessment
- Model for transition temperature shifts in RPV steels
- Modeling for swelling in LWR components
- Model for environmentally-assisted fatigue damage
- Damage parameter for irradiation of concrete

**by 2018 – First SLR License Application Submitted**

- Model for environmentally-assisted fatigue in LWR components
- Model for cable degradation
- Model for cast austenitic stainless steel component aging
- Model of irradiation effects on concrete
- Weld-repair technique transferred to industry

**by 2020 – First SLR License Approved by NRC**

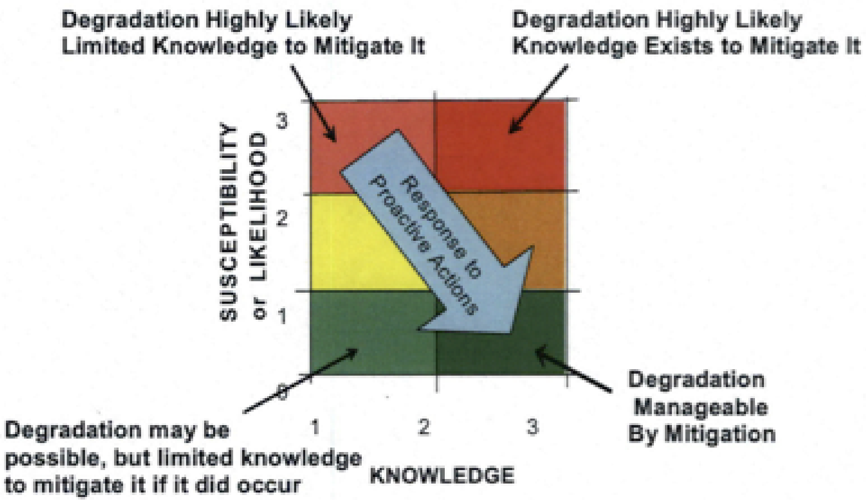
- Predictive capability for end of useful life for cable insulation
- New or improved NDE technologies for concrete and cable
- Model for Ni-base alloy SCC susceptibility

**by 2029 – First License Renewal Expires**

- Complete characterization of demonstration of RPV sections following annealing and reirradiation
- Complete development and testing of new advanced alloy with superior degradation resistance with ARRM partners

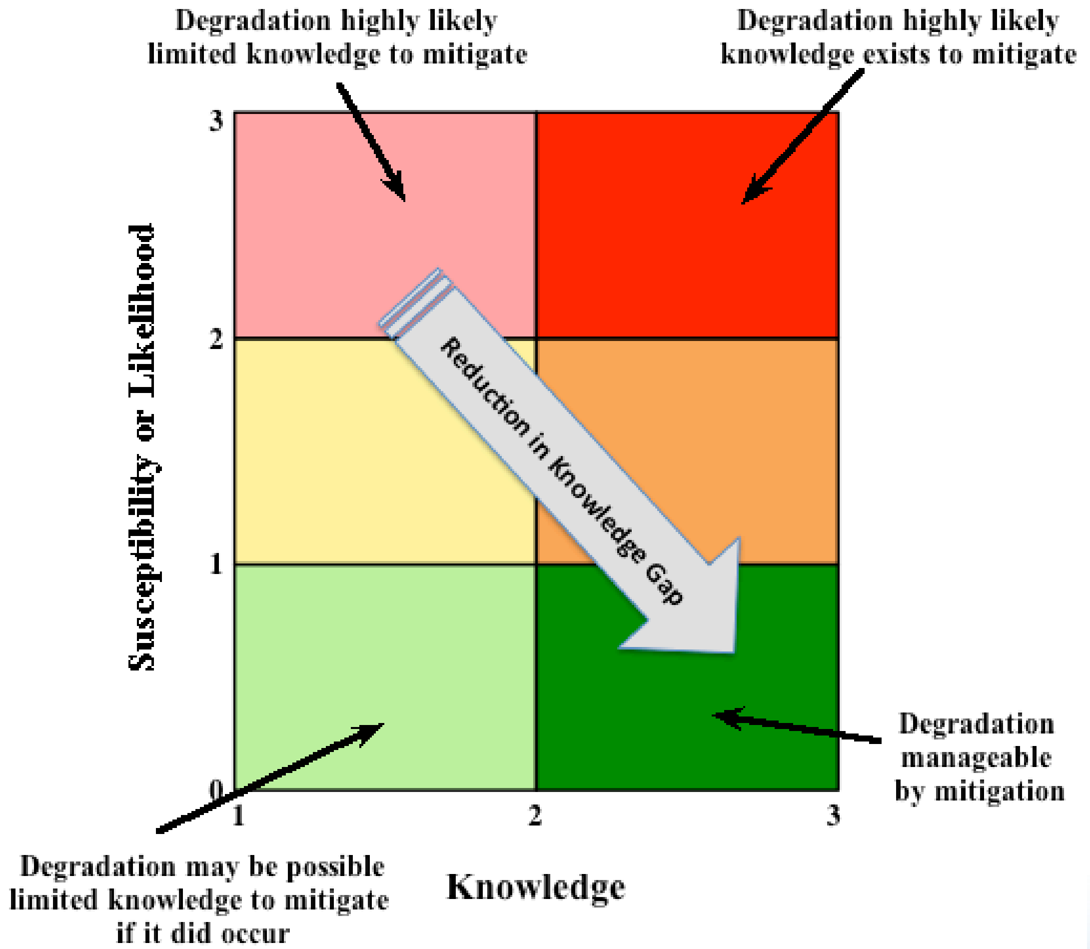
# Given the complexity of the reactor systems and materials degradation, a prioritization tool for research was developed

- "Knowing the unknowns" is a difficult problem that must be addressed.
- This is a particularly difficult issue for such a complex and varied material/environment system.
- An organized approach similar to the US NRC's Proactive Materials Degradation Assessment (PMDA) (*NUREG/CR-6923* was employed .
- Together with the U.S. NRC, the LWRS Program has expanded the initial activity to and longer
  - Core internals and primary piping
  - Pressure Vessel
  - Concrete
  - Cabling

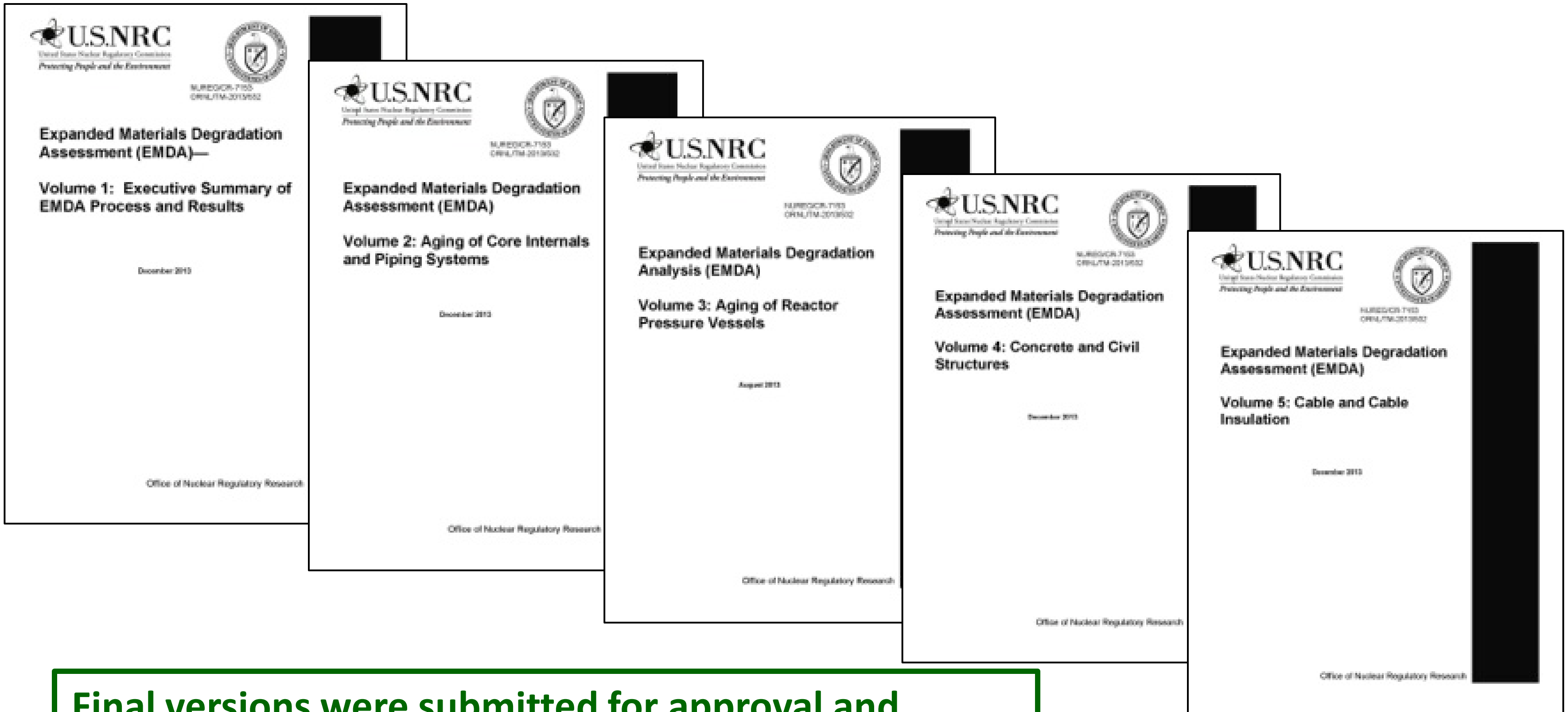



**P**roactive **M**aterials **D**egradation **A**ssessment Matrix

# Schematic illustrating combinations of "Susceptibility" and "Knowledge" and relationship to life-management responses



# NRC and DOE have investigated issues of reactor aging beyond 60 years to identify possible knowledge gaps




**Final versions were submitted for approval and publication in December 2013 and it is in final publication stages.**

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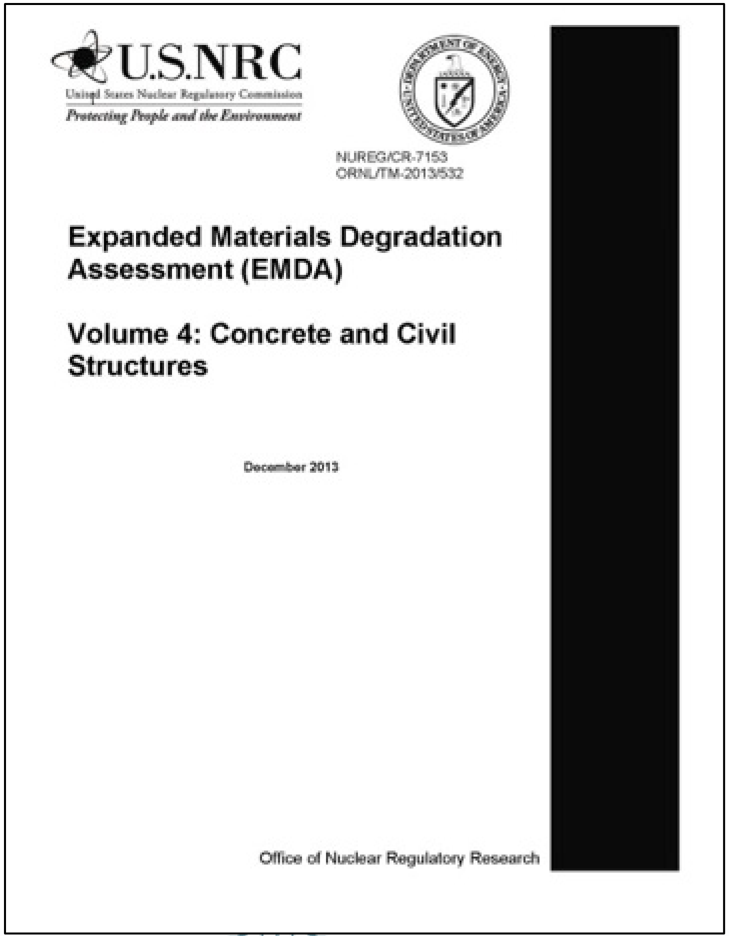
# The concrete expert panel included a diverse background and considerable depth of experience


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

NUREG/CR-7153
ORNL/TM-2013/532

**Expanded Materials Degradation Assessment (EMDA)**

**Volume 4: Concrete and Civil Structures**

December 2013

Office of Nuclear Regulatory Research

**Civil Infrastructure Group**

- **H.L. Graves III**
- **Y. Le Pape**
- **D.J. Naus**
- **J. Rashid**
- **V. Saouma**
- **A. Sheikh**
- **J. Wall**

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

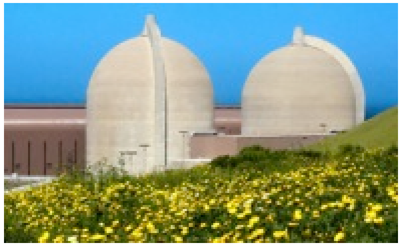
EPRI

ANATECH CORP.
*Linking Theory And Practice*

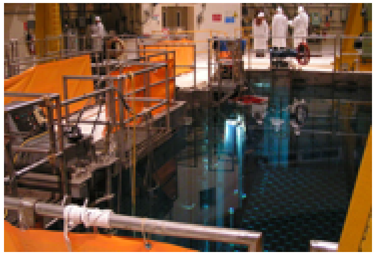
eDF

OAK RIDGE
National Laboratory

# The concrete panel used established PIRT processes to complete their assessment



Concrete Containment



Spent Fuel Pool

Cooling Tower

- List of relevant structures and components prepared and a hierarchical identification of the various degradation modes developed and logged in for each
  - Concrete containments and internal structures – concrete
  - Concrete containments – steel components (mild steel reinforcement, prestressing system, liner, and liner penetrations)
  - Spent fuel pool and transfer canal – concrete and steel components
  - Cooling towers – concrete, steel reinforcement, and prestressing system
  - Cross-cutting issues associated with NPP containment
- Assessment of level of knowledge, susceptibility, confidence, and structural significance for each of degradation modes/mechanisms made by each panel member for each of the classes of structures
- Spreadsheet reflecting assessments prepared and utilized to determine mean, median, and standard deviation for each potential degradation mode/component combination
- EMDA matrix figures constructed

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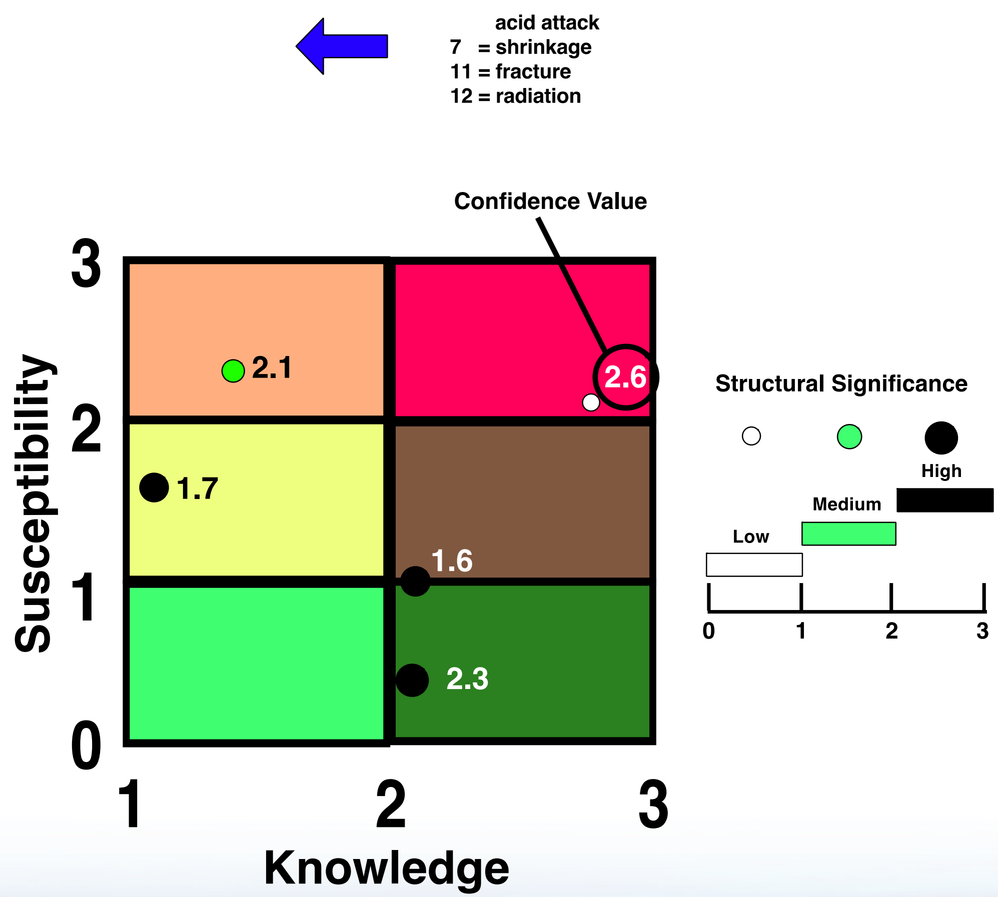
# Concrete civil structures panel added a fourth metric to ranking process to indicate structural significance of degradation to safe operability of the structure or component

## Modified Ranking Process

- **Susceptibility factor – can significant material degradation develop given plausible conditions**
- **Confidence level – personal confidence in the judgment of susceptibility**
- **Knowledge factor – extent to which the relevant dependencies have been quantified**
- **Structural significance level**
  - **"Low": localized mechanism with no significant impact**
  - **"Medium": some impact on serviceability, but can be mitigated**
  - **"High": generic or widely spread mechanism with an impact on structural integrity**



# A number of mechanisms and degradation modes that may be potential knowledge gaps during subsequent operating periods are being considered for the final EMDA report

- Containment/Shield/Bio-Shield/RPV Supports and buildings
  - Radiation
  - Alkali-Aggregate/Silica Reaction
  - Creep/creep-fracture interaction (need to develop to roadmap)
- Containment/Shield/Bio-Shield/RPV Supports and buildings with available remediation/mitigation
  - Liner corrosion (inside/outside)
  - Corrosion of the post-tensioning system
- Spent Fuel Handling Building
  - Boric acid attack (concrete and reinforcement)
- Cooling Towers (non safety related structure)
  - Corrosion
  - Alkali-Aggregate/Silica Reaction

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## Collaborative research is underway to address these potential knowledge gaps

- Research has been underway to support these gaps for several years
  - EPRI/industry projects
  - DOE LWRS programs
  - NRC RES
  - International efforts
- Collaborative efforts have been strong among all research partners
- Frequent meetings are held to coordinate and align ongoing research

# There is considerable research ongoing to support irradiation effects of concrete

Timeline

## Knowledge — Degradation mechanisms

### Mechanisms Understanding

- Prior Existing Knowledge 1960-2012
- γ-ray Irradiation on Cement Paste/Concrete at JAEA 2008-2015
- Effects of Heating and Drying at Nagoya 2013-2016
- Unified Irradiation Parameter 2014-2015
- Evaluate Ion and Neutron Induced Swelling Damage in Aggregates 2013-2015
- Modeling Irradiation Effects on Concrete 2013-2016
- Possibility of IAASR In BSB/RVP support 2013-2015

### Materials Characterization

- Harvesting Irradiated Concrete 2013-2017
- Accelerated Irradiation on Prototypical Concrete at Halden 2013-2016
- Accelerated Irradiation of Minerals and Aggregates 2014 -2015
- Accelerated Irradiation of Prototypical Concrete at HFIR 2015
- PIE at ORNL 2014-2016
- Evaluate and Compare Concrete Results with Aggregate Studies 2016-2017

## Assess and Manage degradation/rate

### NDE/Monitoring

- NLUT Examination of Thermally Damaged Concrete 2012
- Enhanced Instrumentation during Irradiation Test? 2014-2015

### Engineering Validation

## Safety margin assessment — Structural significance

### Structural Significance

- Operation Survey Bounding n fluence $\gamma$ dose 2012-2013
- Radiation Transport Bounding n fluence $\gamma$ dose 2012-2014
- Modeling Irradiation Effect on Bio-Shield Building 2015-2017

### Key

- Prior Research
- DOE Actions
- EPRI Actions
- Third Parties Actions
- R&D gaps

# Alkali-Silica Reaction research is also ongoing

**Knowledge Degradation mechanisms**

**Assess and Manage degradation/rate**

**Safety margin assessment Structural significance**

Timeline

### Mechanisms Understanding

- Prior existing knowledge 1940-2012 Transportation, Hydro-dams. Power Distribution
- Possibility of ASR In SB/RVP support 2013-2014
- Possibility of IAASR In SB/RVP support 2013-2015

### Materials Characterization

- ASR Risk Screening Survey 2014-15
- Characterization of Expansion/Damage of Concrete 2014-2015
- Characterization of Moisture Transport/Thermal Properties of Concrete 2014-2015

### NDE/Monitoring

- NEUP ASR NLUT NDE 2013-2015
- ASR/freeze-thaw mock-ups for NDE 2013-15
- Enhanced/new NDE 2014-2016
- Enhanced Expansion Monitoring 2014-2016

### Engineering Validation

- Beam Shear Testing at U. of Texas 2013-2015
- Block Testing NIST 2014-2016
- Effect of Confinement on ASR Damage and Shear Capacity 2014-2016

### Structural Significance

- Aging Management Toolbox 2013-18
- Computational Simulation of ASR-Affected Structures 2014-2015
- Structural Reliability Analysis 2015-2016

RILEM Technical Committee ISR on Prognosis 2014-2017

### Key

- Prior Research
- DOE Actions
- EPRI Actions
- Third Parties Actions
- R&D gaps

# Creep/fracture interaction research will rely on the extensive database already available.

**Knowledge — Degradation mechanisms**

**Assess and Manage degradation/rate**

**Safety margin assessment — Structural significance**

Timeline

**Mechanisms Understanding**

**Materials Characterization**

**NDE/Monitoring**

**Engineering Validation**

**Structural Significance**

Prior Existing Knowledge
ACI 209 Committee
RILEM/Northwestern
Database

BARCOM !/4th scale mockup (India)
Early 2000's

EDF !/4th scale mockup (France)
2014-2024

+
Several structural test on reinforced/prestressed containments (Sizewell B 1989, Civaux , NRC 1987, CTL/EPRI tests, Sandia 1/4th scale…)

Creep-fracture effect after principal stress rotation

Creep Risk Screening Survey

Acoustic monitoring?

Coupled Creep-Fracture Simulations

**Key**

- Prior Research
- DOE Actions
- EPRI Actions
- Third Parties Actions
- R&D gaps

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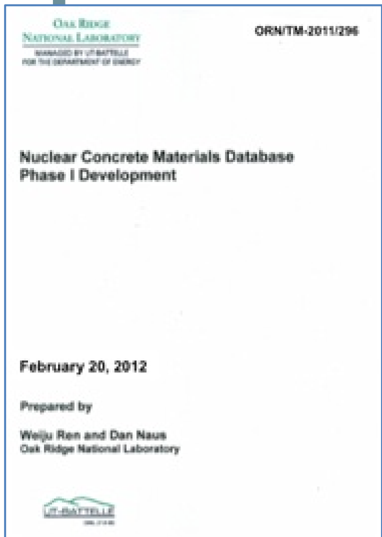
# Concrete structures are of interest for long-term operation and a key area of emphasis under LWRS



Oak Ridge National Laboratory

ORN/TM-2011/296

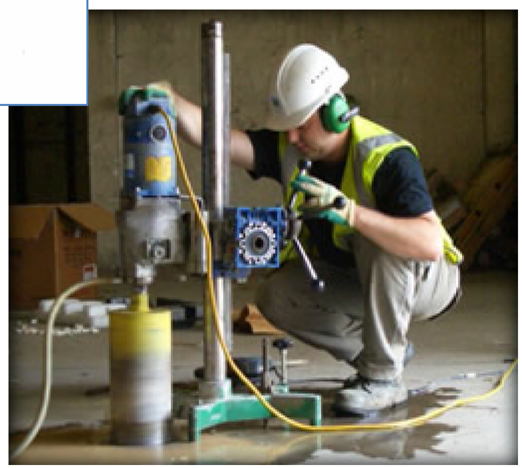
Nuclear Concrete Materials Database
Phase I Development

February 20, 2012

Prepared by

Weiju Ren and Dan Naus
Oak Ridge National Laboratory

ORNL/TM-2011/296



**Concrete coring to obtain samples for evaluating effects of aging and environmental stressors**

- A number of potential environmental effects are important for long-term aging
  - Aging
  - Elevated temperature
  - Irradiation
  - Migration of hostile species (e.g., $Cl^-$, $SO_4$, $CO_2$)
- Phase I of NCMDB has been completed
- Concrete irradiation damage working group formed
  - Development of protocols related to removal and testing of irradiated concrete cores
  - Identification of potential sources of irradiated concrete cores

LWRS
Light Water Reactor Sustainability

# LWRS research has been guided by the EMDA findings

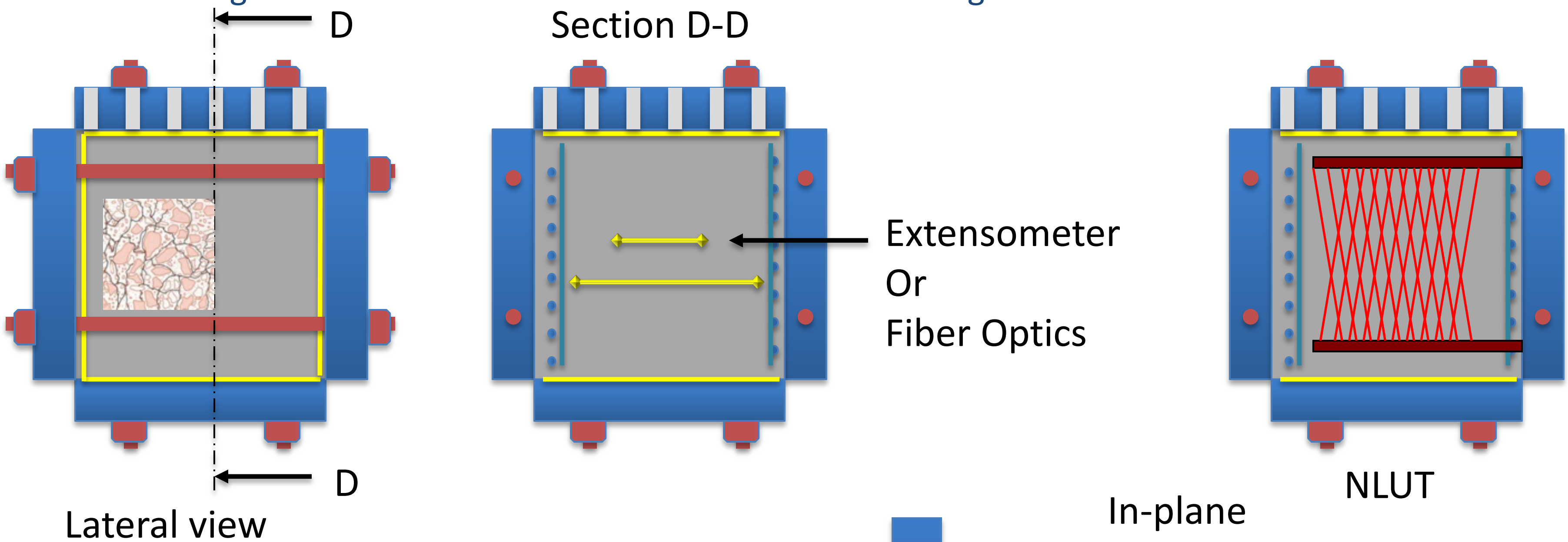
- Containment/Shield/Bio-Shield/RPV Supports Buildings
  - Potential knowledge gaps:
    - Radiation
    - Alkali-Aggregate/Silica Reaction
    - Creep/creep-fracture interaction (need to develop to roadmap)
  - Mode with available remediation/mitigation
    - Liner corrosion (inside/outside)
    - Corrosion of the post-tensioning system
- Spent Fuel Handling Building
  - Potential knowledge gaps:
  - Boric acid attack (concrete and reinforcement)
- Cooling towers (non safety related structure)
  - Corrosion
  - Alkali-Aggregate/Silica Reaction

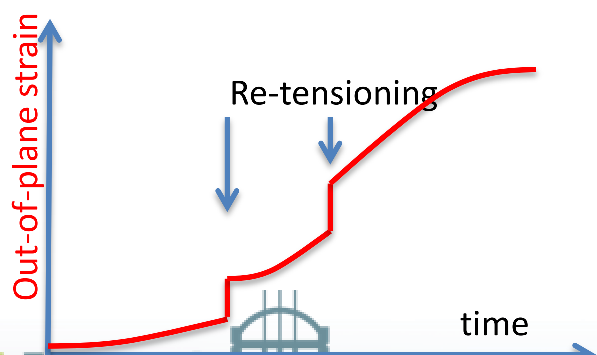
## Summary of LWRS On-going ASR Program

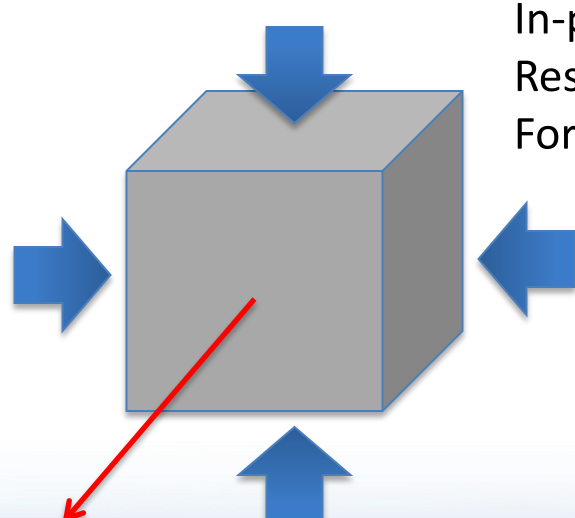
- Investigate the residual shear capacity of massive concrete structures using numerical simulation
- Design/fabrication of a large test ASR mock-up
- Confinement system (replication of actual condition in service)
- Monitoring
- Study of the damage evolution (including coring in different directions)
- Investigate the possibility of a coupling mechanism with irradiation induced expansion
- Organization of a Workshop on ASR simulation

# A conceptual design for an ASR test system has been completed

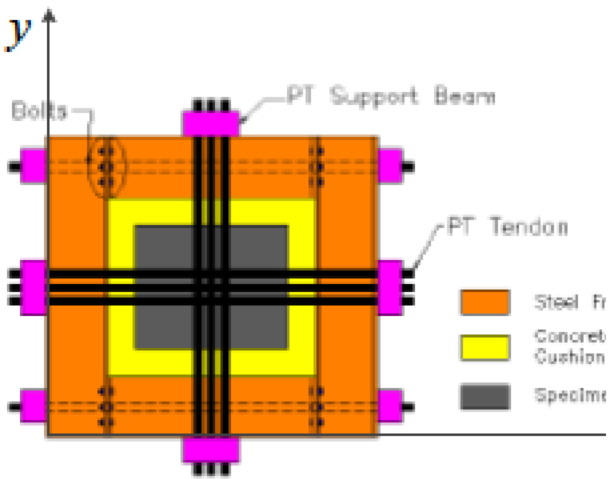
Monitoring the 'Out-of-Plane' Deformation and the Cracking Index

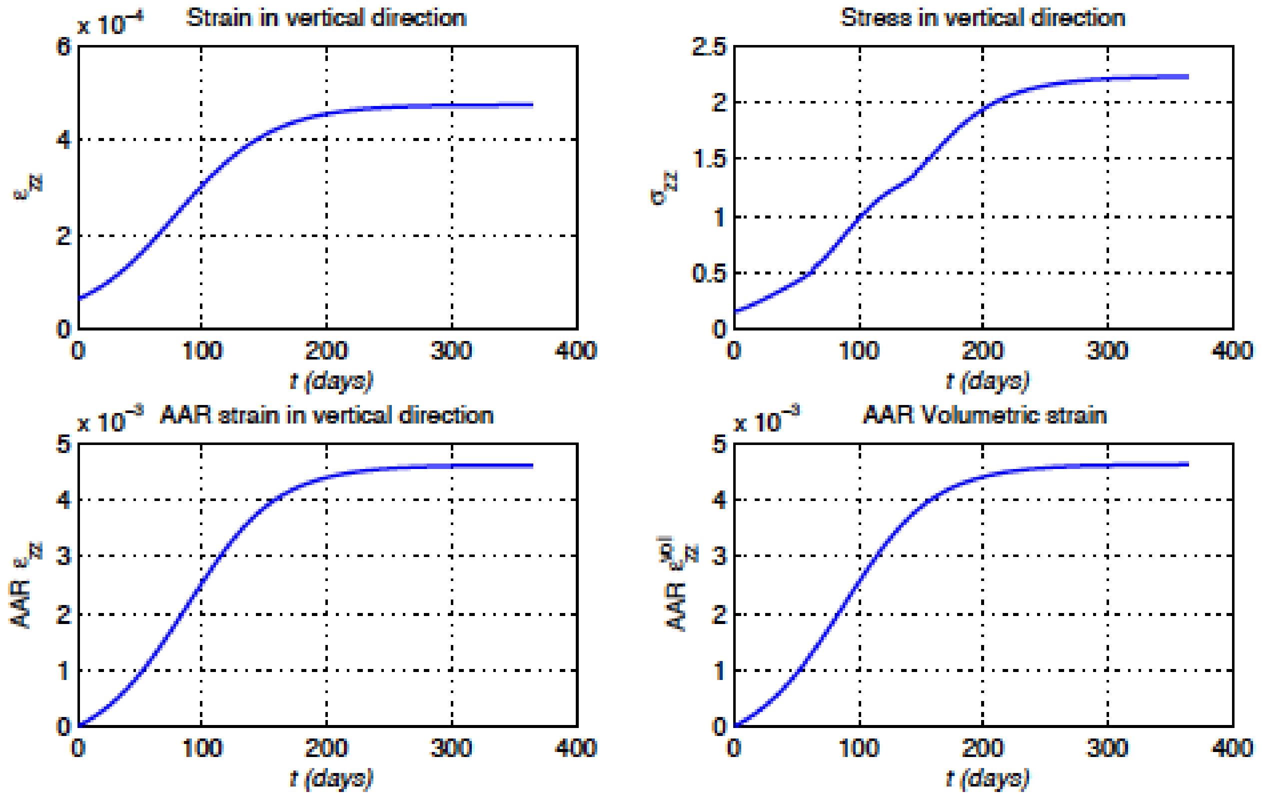


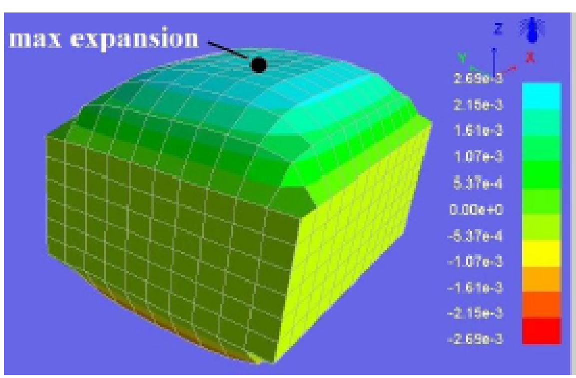



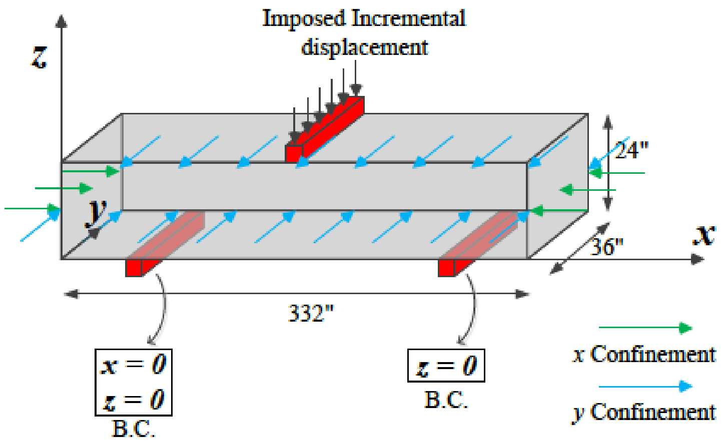
# Simulation of the Structural Restraining Effects on ASR Swelling are ongoing

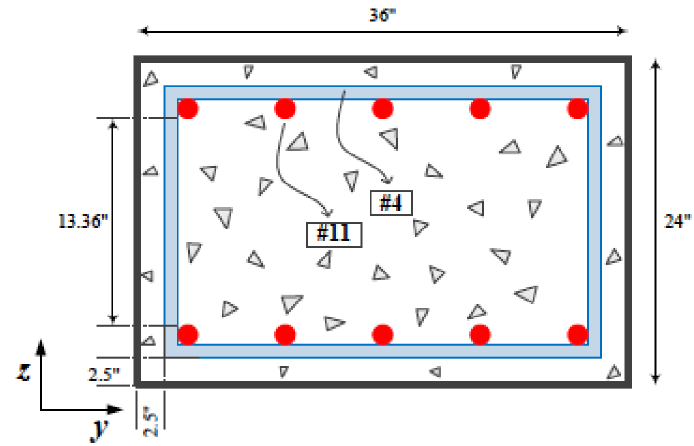


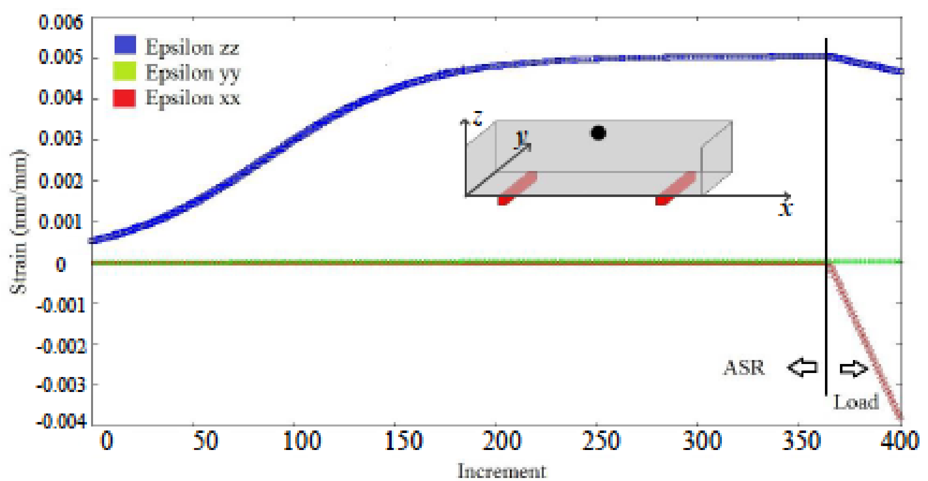



# Simulation capabilities of the structural restraining effects on ASR swelling are being developed



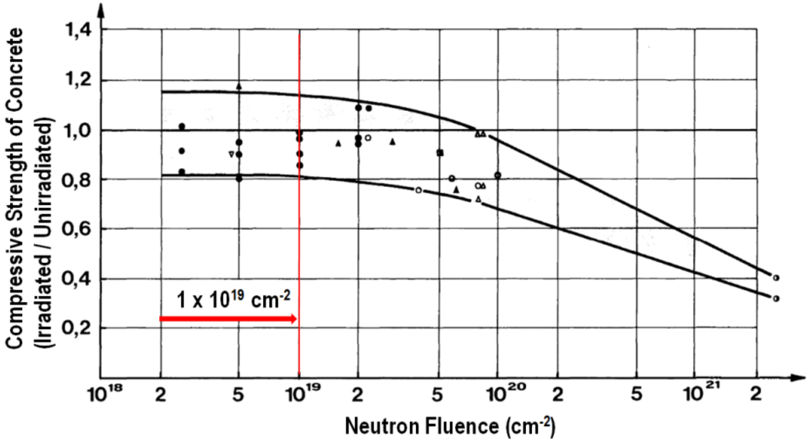



# A new joint OECD-RILEM committee was formed with a focus on ASR

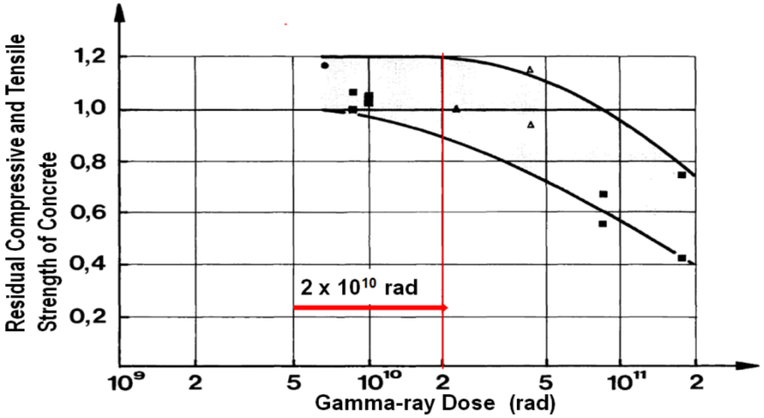
- Kick-off meeting Washington DC at EPRI office, June 30th 2014
- Organized by Neb Orbovic (CSNS), Victor Saouma (U. of Colorado), Yann Le Pape (ORNL) and hosted by EPRI.
- 37 participants from Canada, France, Japan, Spain, Sweden, Switzerland, The Netherlands, USA
- Universities, Canadian Nuclear Safety Commission, Hydro-Quebec, EMPA, EPRI, USACE, IAEA, VTT, Vattenfall, SIMCO, US NRC, NIST, ORNL, SRNL, Torroja Institute
- Interest Group of about 60 persons including also participants from Austria, Australia, Brazil, China, Finland and Norway

# Irradiation induced degradation of concrete was identified by EMDA panel as a potential gap and is one of the largest components in the LWRS program

Current understanding of radiation effects on concrete is largely based on the 'Hilsdorf curve,' dating back to 1978. Onset at ~$1 \times 10^{19}$ n/cm$^2$




Gaps in information: the neutron fluence cutoff energy, the composition of concrete, the irradiation temperature, gamma-ray dose, etc.



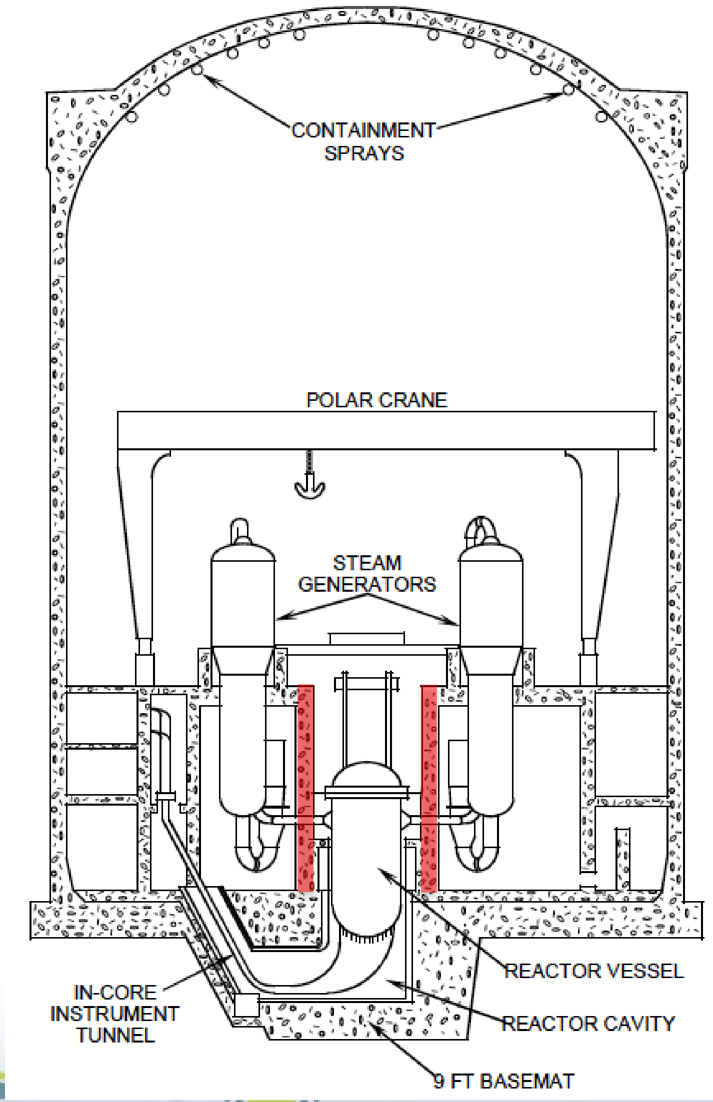

Because the applicability to NPP concrete is uncertain, more data is needed.

LWRS Light Water Reactor Sustainability

# LWRS has developed a strategy for investigating irradiation effects in concrete

- Characterize radiation fields in concrete structures in NPPs and determine the bounding values of neutron fluence and gamma-ray dose in the biological shield concrete at 80 years of operation and beyond.
- Obtain more data on the effects of neutron and gamma irradiation as well as extended time at elevated temperature on concrete.
  - Irradiate mineral analogues of aggregates and aggregates to evaluate swelling
  - Irradiate prototypical concrete to levels equal to or greater than expected in extended service (accelerated irradiation studies) and evaluate possible degradation.
  - Harvest and test irradiated concrete from decommissioned plants (US and international).
- Develop a more robust fundamental understanding of the effects of radiation on concrete.
- Establish a collaborative research effort with international partners.

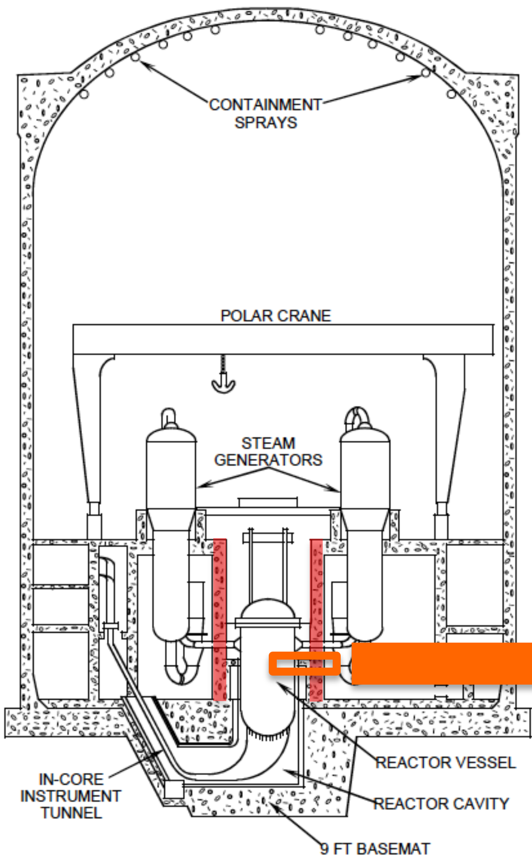
# Primary (Biological) Shield Exposure up to 80 years of operation is being estimated

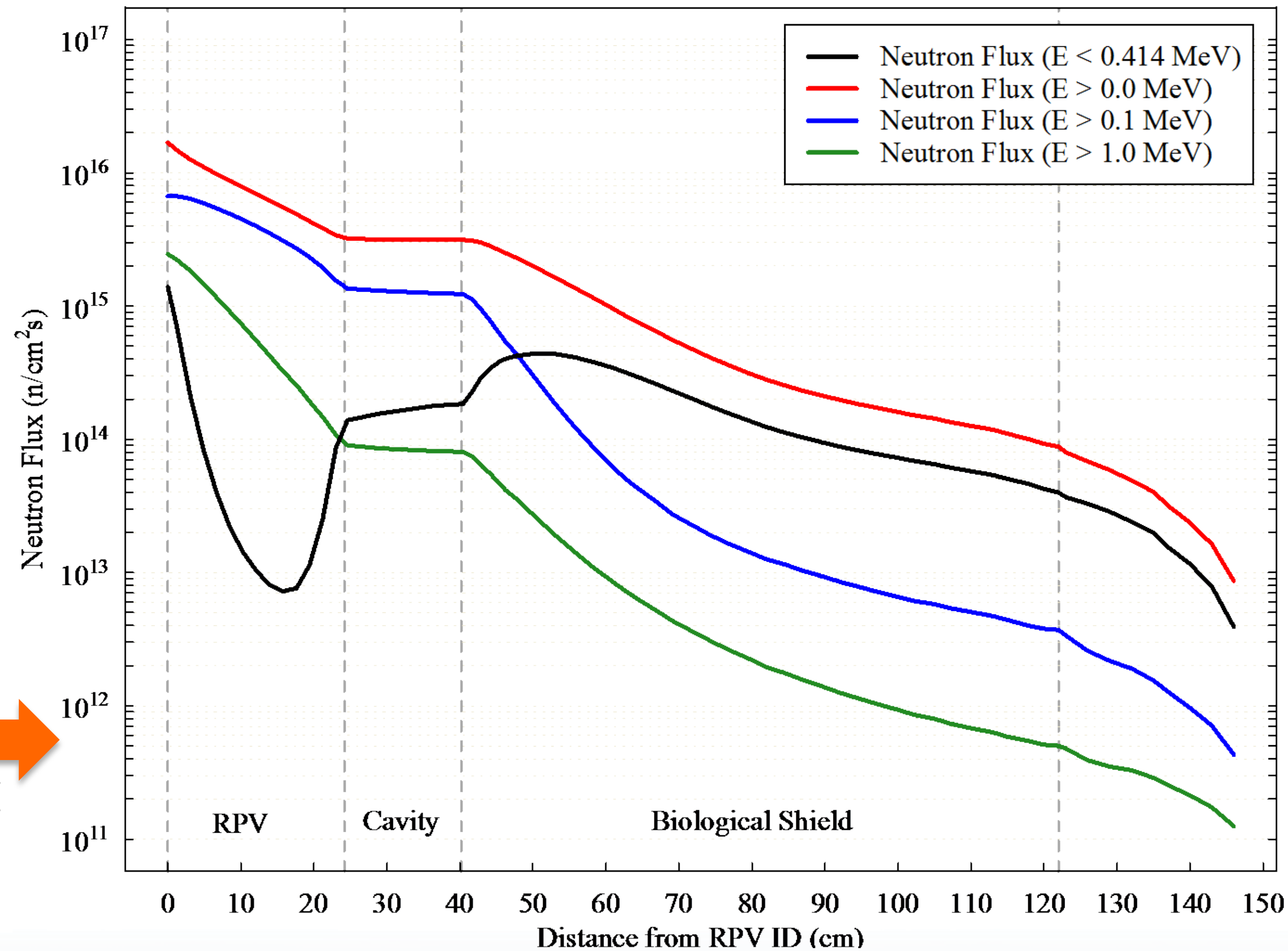



- Biological shield anticipated to receive the highest neutron fluence
  - Safety related structure and provides essential radiation protection
- Typically consists of Type II Portland cement, fine aggregates (e.g. sand), water, admixtures, and normal weight or heavyweight coarse aggregates
- Bounded by design at 65 °C with peak values not exceeding 93 °C
- The total expected neutron fluence and expected energy spectrum of the neutron flux can be inferred from modeling and RPV dosimetery reports

Light Water Reactor Sustainability

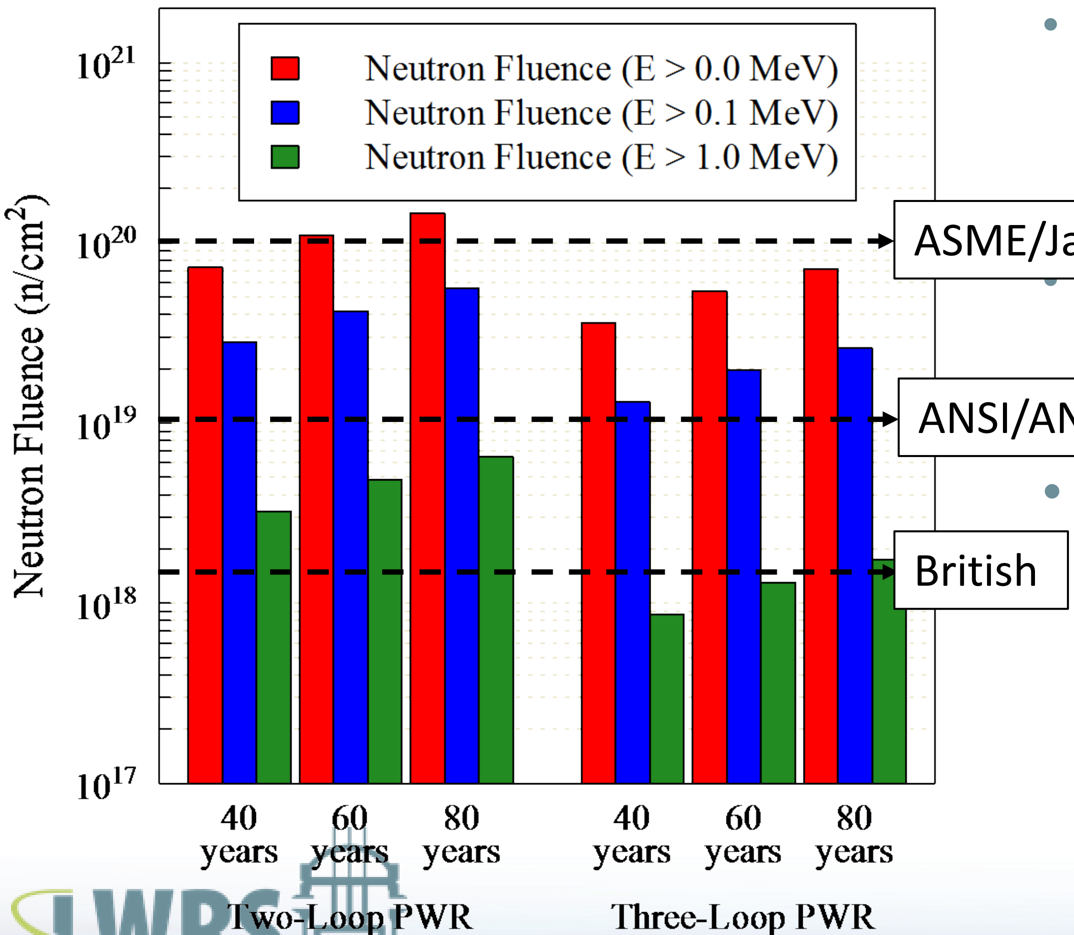
# Neutron flux profile radially from the reactor core has been calculated



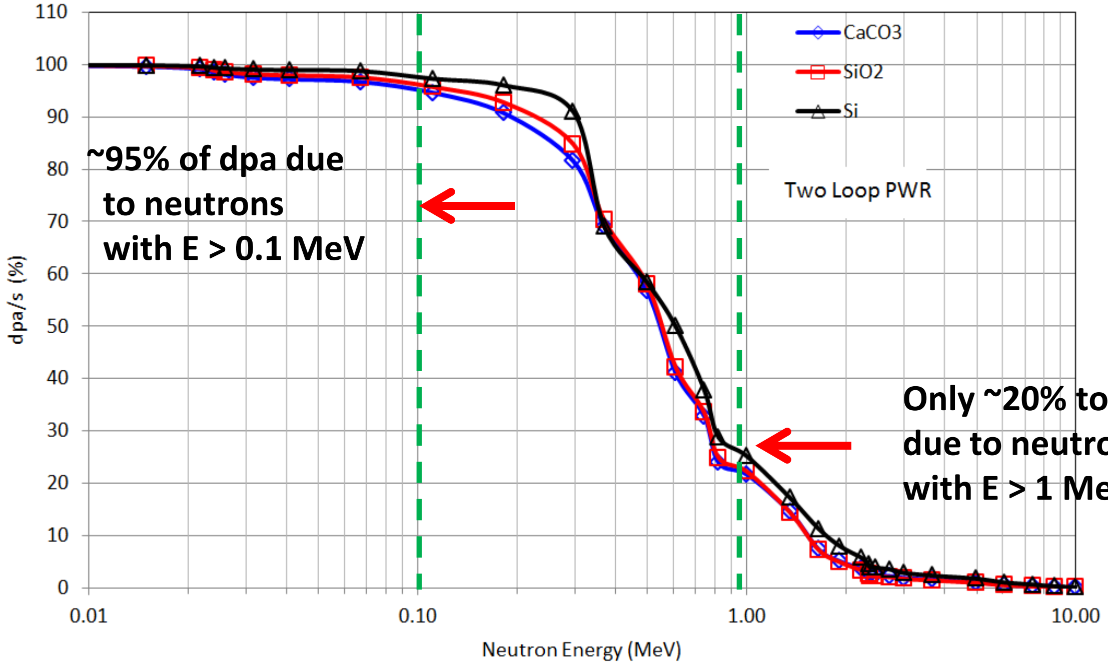

Distribution of neutron flux for given neutron energy cut-offs in a three-loop PWR in the radial direction from the core.

# The variance of expected peak neutron fluences in the biological shield for different cut-off energies can be determined

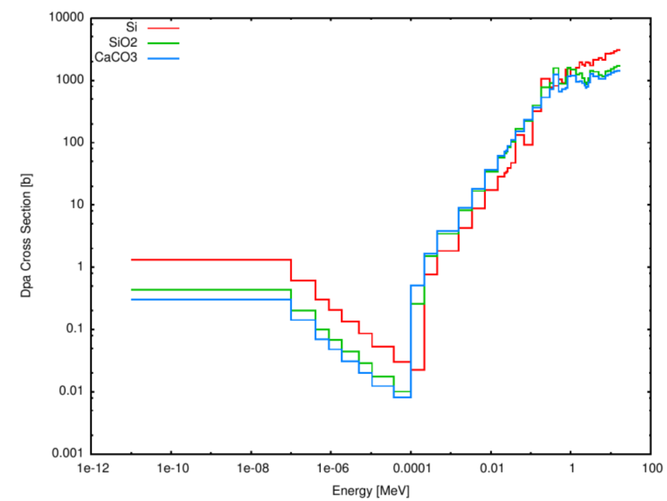



- Values reported here only to serve as a guide, fluence will change depending on plant configuration, fuel loading scheme, capacity [illegible]r, etc.
- Peak neutron fluence can change over an order of magnitude depending on selected neutron energy cut-off
- **Determining which energy cutoff, if any, is correct for the fluence determination is crucial for the assessment of the concrete degradation, in particular for the operation during extended plant life**

# A unified parameter for radiation-induced degradation of concrete has been determined




**Dpa/s versus neutron energy for the neutron spectrum in the cavity of a two-loop PWR, for Si, $SiO_2$, and $CaCO_3$**




**dpa cross section versus neutron energy for Si, $SiO_2$, and $CaCO_3$**

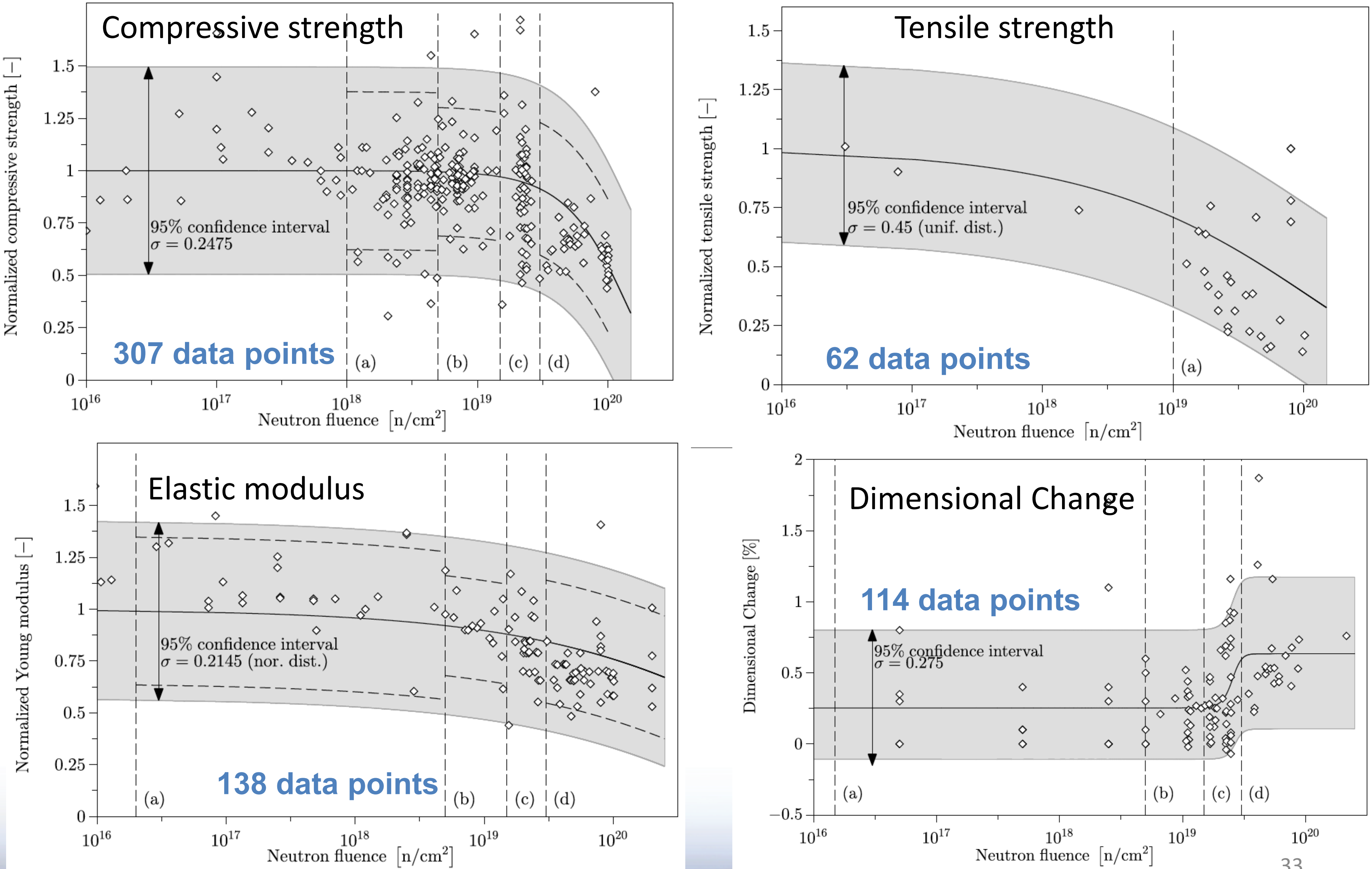
- About 90% of the atom displacements in Si, $SiO_2$, and $CaCO_3$ are caused by neutrons with energies between 0.1 MeV and 2 MeV
- Neutron fluence with E > 0.1 MeV appears to be much more relevant correlation parameter than the fluence with E > 1MeV
- Gamma-ray induced displacement rate was not addressed so far but it is expected to be much smaller than neutron induced dpa rate.
- These results are preliminary

# A database of irradiation data has been expanded well beyond Hilsdorf!

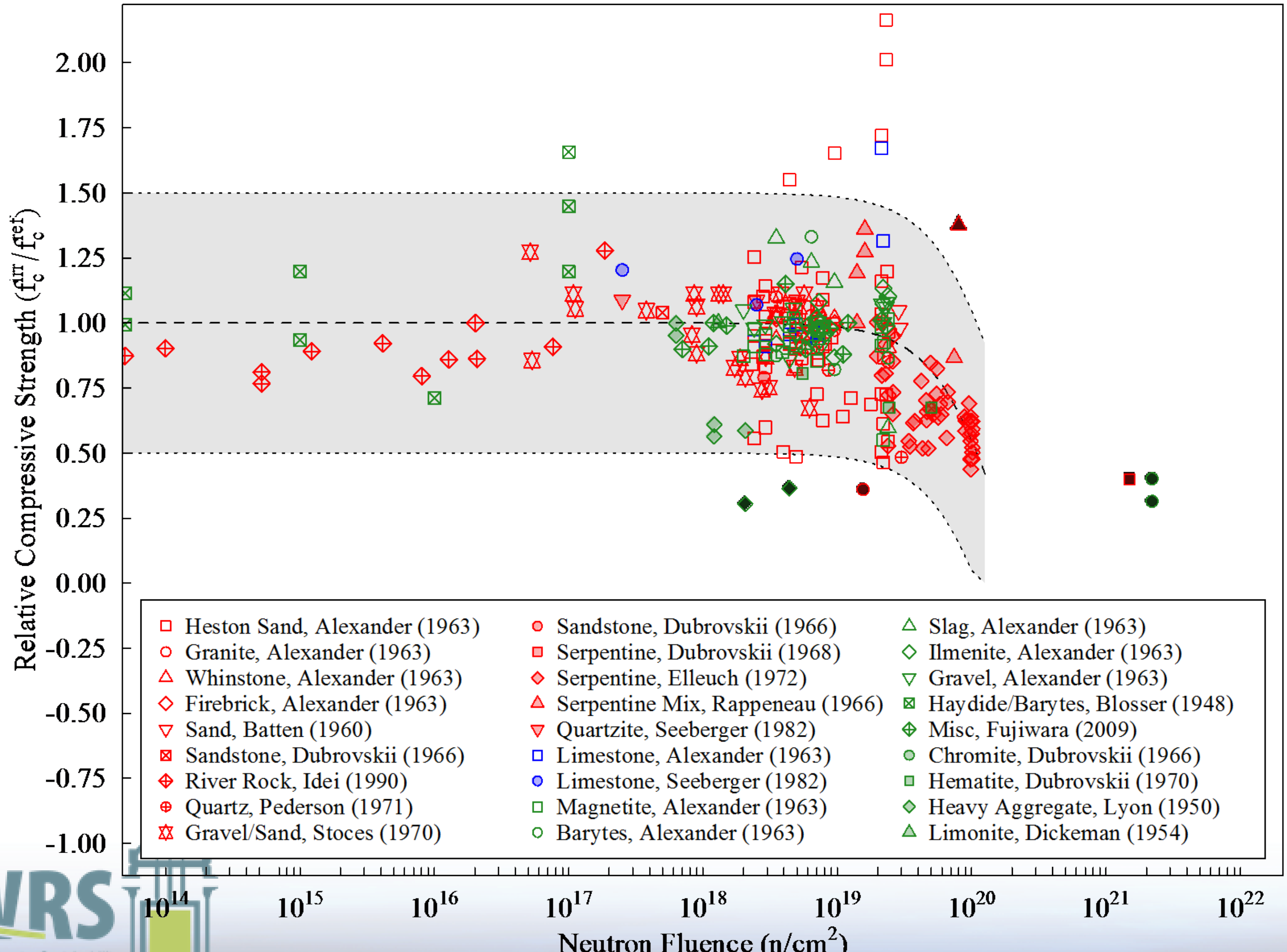
| Ref. | Neutron Fluence | Energy Cut-off | Temp. Range (°C) | Aggregates | Cement Type | A/C Ratio | W/C Ratio | Specimen Geometry | Reported Properties* |
|---|---|---|---|---|---|---|---|---|---|
| Alexander (1963) | $0.25 \times 10^{19}$ - $2.00 \times 10^{19}$ | slow & fast | 20-100 | gravel, limestone, magnetite, ilemnite, granite, baryte, slag, whinestone, firebrick | ordinary Portland cement (OPC), high alumina cement, low-heat-slag cement, super sulphate cement, OPC with fuel ash | 3:1, 6:1 | - | 0.50" cube, 2" cube, 0.50" cylinder, 2" x 1.75" x 8" beams | W, fc, E |
| Batten (1960); Price et al. (1957) | $0.43 \times 10^{19}$ - $7.50 \times 10^{19}$ | thermal | 50 | river sand | Portland cement, Cement Fondu | 3:1, 8:1 | 0.45, 0.50 | 2"x2"x8" beams | W, $f_c$, $f_t$ |
| Blosser et al. (1958); Rockwell (1948) | $1.00 \times 10^{8}$ - $1.00 \times 10^{17}$ | thermal | Oct-37 | rock, sand or baryte, haydite | Portland cement | 4.5:1 | 0.61 | - | fc |
| Christiani et al. [No year]; Granata and Montagnini (1971) | $2.50 \times 10^{18}$ - $3.80 \times 10^{19}$ | fast | 100-125 | limestone, baryte | Portland cement | 3:01 | 0.5 | 4 cm x 4 cm x 16 cm beams | D, ρ, $f_t$, E |
| Crispino et al. (1971) | $1.00 \times 10^{19}$ - $1.00 \times 10^{20}$ | thermal | 130-280 | limestone, baryte | Portland cement | - | - | 4 cm x 4 cm x 16 cm beams | D, ρ, |
| **Dickeman (1951)[1]** | | | | | | | | | **D, $f_c$** |
| Dubrovskii et al. (19 | | | | | | | | | D, W, $f_c$, E |
| **Dubrovskii et al. (19** | | | | | | | | | **D, ρ, W, $f_c$, E** |
| **Dubrovskii et al. (1968)[1]** | **$1.30 \times 10^{21}$ - $1.70 \times 10^{21}$** | **Integrated** | **350** | **serpentine** | **-** | **-** | **-** | **-** | **D, $f_c$, E** |
| **Dubrovskii et al. (1970)[1]** | **$0.40 \times 10^{19}$ - $5.50 \times 10^{19}$** | **E 0.8 MeV** | **100-400** | **hematite** | **Portland cement** | **8:01** | **1.01** | **15 mm x 15 mm OD** | **D, W, $f_c$, E** |
| Elleuch et al. (1971); Elleuch et al. (1972) | $1.20 \times 10^{19}$ - $1.11 \times 10^{20}$ | E > 1.0 MeV | 150-240 | serpentine | Lafarge aluminous cement | 3.85:1 | 0.38 | 2.5 cm x 2.5 cm x 5/10 cm | D, W, $f_c$, $f_t$, E |
| **Fujiwara et al. (2009)[1]** | **$0.70 \times 10^{18}$ - $1.20 \times 10^{19}$** | **E > 0.1 MeV** | **50 - 56** | **-** | **-** | **~6:1** | **0.55** | **100 mm x 50 mm OD** | **D, W, $f_c$, E** |
| Gray (1971); Kelly et al. (1969) | $1.20 \times 10^{18}$ - $4.33 \times 10^{19}$ | fast[2] | 55 | flint, limestone | Portland cement | 2.70:1 | 0.36 | .25" x 0.50" OD | D, ρ, W, $f_t$, E |
| Halliday (1956)[1] | $3.16 \times 10^{19}$ | - | - | - | - | - | - | - | - |
| Houben (1969); Van de Schaaf (1967); Van de Schaaf (1969) | $3.00 \times 10^{19}$ - $8.00 \times 10^{19}$ | fast | 150 - 200 | baryte, magnetite, hollith | Portland cement, HOC | ~5:1 | 0.14-0.16 | 8 mm x 8 mm x 70 mm beams | $f_t$, E |
| Idei et al. (1990) | $2.07 \times 10^{11}$ - $1.86 \times 10^{17}$ | E > 0.1 MeV | 100 | river rock | Portland cement | 6.5:1 | 0.48 | - | $f_c$, $f_t$, E |
| **Lyon (1951)[1]** | **$2.06 \times 10^{18}$ - $4.40 \times 10^{18}$** | **Integrated** | **-** | **heavy Aggregate** | **MgO cement** | **22:01** | **1.62** | **-** | **$f_c$** |
| Pederson (1971) | $8.50 \times 10^{18}$ - $3.00 \times 10^{19}$ | fast | 80 | quartz | Portland cement | 3:01 | 0.4 | 11.3 mm x 11.3 mm OD | D, W, $f_c$, E |
| **Rappeneau et al. (1966)[1]** | **$1.40 \times 10^{19}$ - $1.10 \times 10^{20}$** | **fast** | **130- 260** | **serpentine, corundum, rare earths** | **Lafarge aluminous cement** | **4.1:1** | **0.38** | **4 cm x 4 cm x 16 cm, 2.5 cm x 2.5 cm x 10 cm beams** | **D, W, $f_c$, $f_t$, E** |
| **Rockwell (1956)[1]** | **$3.00 \times 10^{18}$** | **thermal** | **-** | **-** | **-** | **-** | **-** | **-** | **-** |
| **Seeberger and Hilsdorf (1982)[1]** | **$2.5 \times 10^{17}$ - $5.00 \times 10^{18}$** | **fast** | **150** | **limestone, quartzite** | **Portland cement** | **3:01** | **0.5** | **32 mm x 16 mm OD** | **$f_c$, E** |
| Stoces et al. (1970) | $3.00 \times 10^{16}$ - $4.20 \times 10^{18}$ | E > 0.1 MeV[2] | 20-80 | gravel, sand | Portland cement | 3.6:1 | 0.35 | cylinder | D, W, $f_c$, E |

300+ Unique data points!

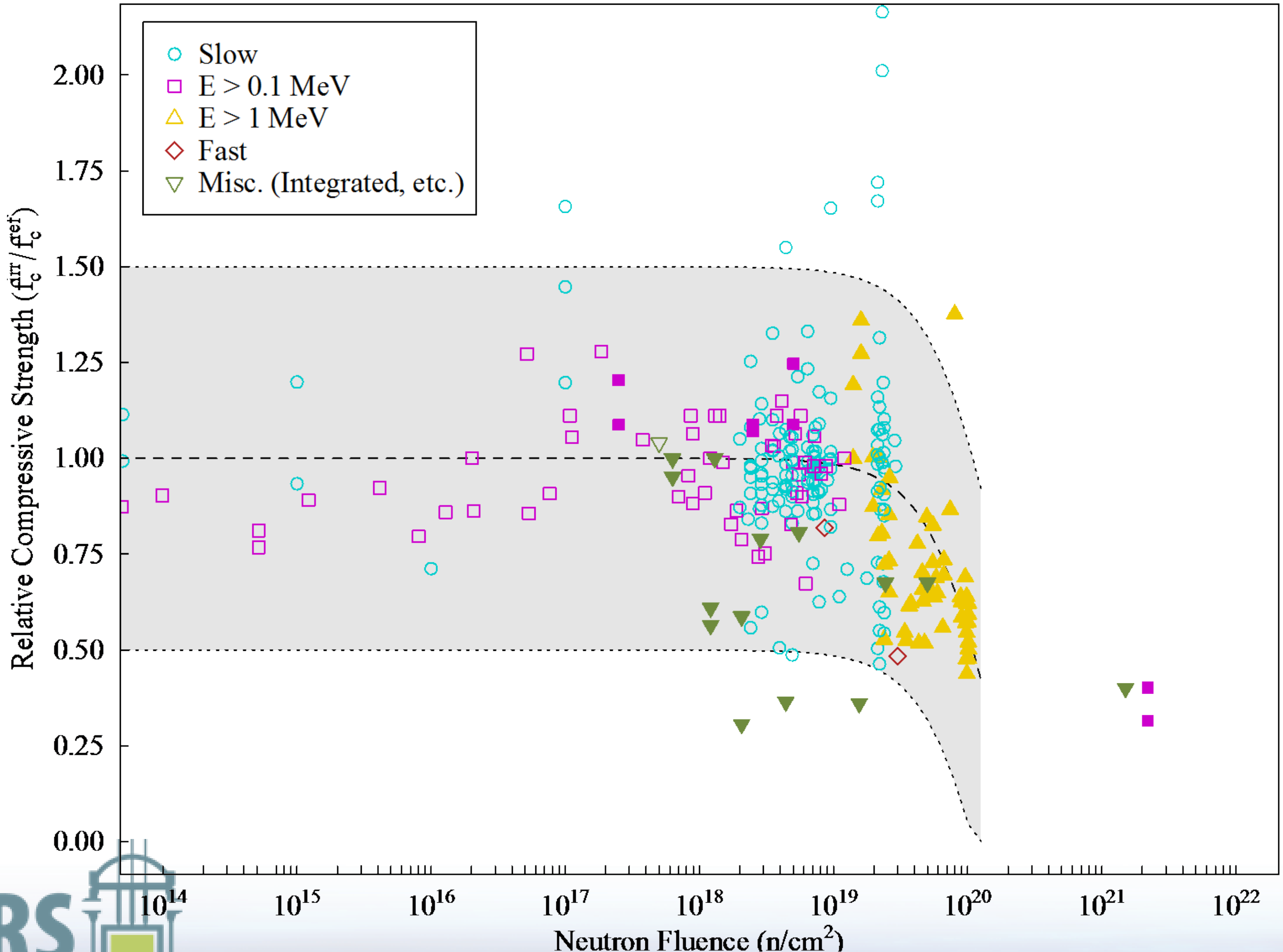
# Updated Irradiated Concrete Database



# This improved database also allows for examination of complicated variables



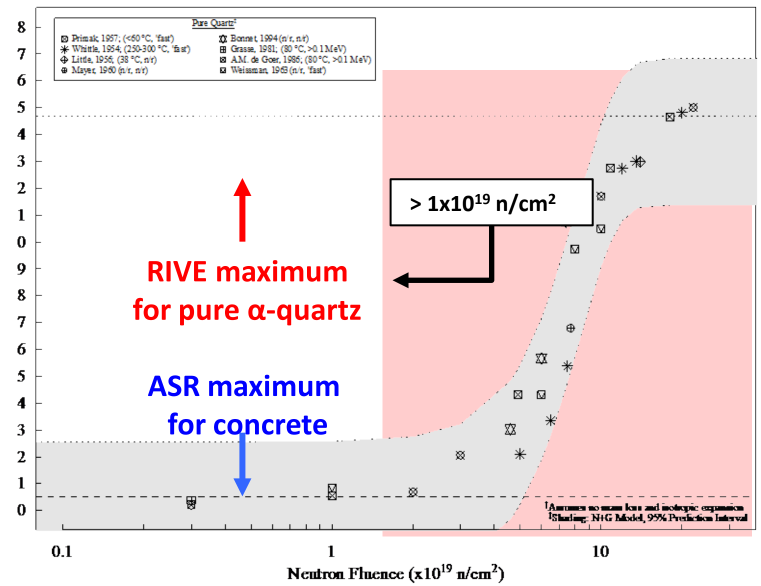
# Factors which could shift data points if normalized to a ‘standard value’




LWRS Light Water Reactor Sustainability

# An assessment of RIVE in concrete structures is being performed

- Literature review suggests that a significant loss of concrete mechanical properties is due to radiation induced swelling of aggregates.
- Radiation induced volumetric expansion (RIVE) of aggregates, primarily due to amorphization (loss of long-range order) leads to differential strains between the cement paste and aggregate and causes microcracking in the paste.
- The onset is estimated to occur near $1 \times 10^{19}$ n/cm$^2$ (E > 0.1 MeV) based on the swelling/amorphization curve of α-quartz, (common mineral in aggregates used in NPPs).
- Based on the calculations for estimated peak neutron fluence in biological shield components at 80 years of operation, a risk assessment requiring detailed knowledge of the concrete mix design, operating environment, and neutron environment may need to be considered.



# A research plan for Radiation Induced Volumetric Expansion (Swelling) of minerals, aggregates, and concrete has been developed

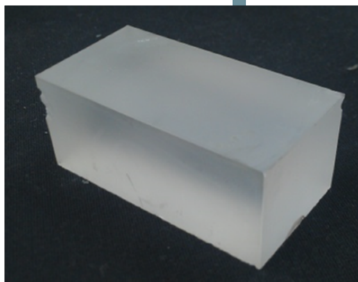
2014-2015

- Evaluate swelling on 5 minerals as a function of dose and temperature
  - Quartz, calcite, dolomite, muscovite and pure hcp
  - 7 fluences 0.5 - 40 x $10^{19}$ n/cm$^2$ (E > 0.1 MeV) - below swelling onset to saturation
  - Temperatures: 50 °C and 200 °C (biosheld temperature – literature studies)
  - Determine dimensional, weight, hardness, mechanical properties (3 pt. bend: stress, strain, elastic modulus), and microstructural changes

2015-2016

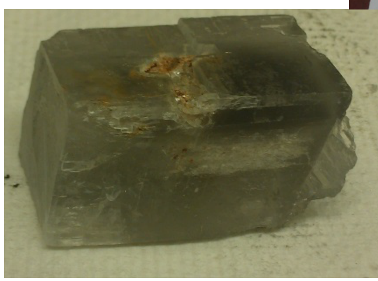
- Evaluate swelling of aggregates as a function of dose and temperature
  - 7 fluences 0.5 - 40 x $10^{19}$ n/cm$^2$ (E > 0.1 MeV) - below swelling onset to saturation
  - Temperatures: 50 °C and 200 °C (biosheld temperature – literature studies)
  - Determine dimensional, weight, hardness, mechanical properties (3 pt. bend: stress, strain, elastic modulus), and microstructural changes
- Evaluate swelling of concrete as a function of dose and temperature

# Preliminary mineral and hardened cement paste HFIR irradiations have now been completed

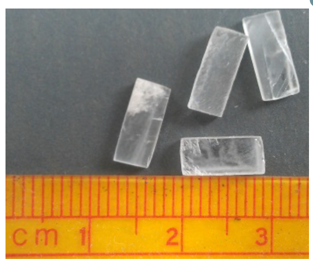


Quartz

Calcite

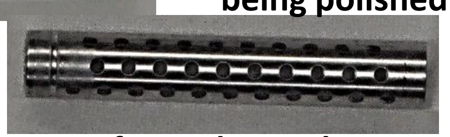


Dolomite



Calcite specimens being polished

Sealed capsule

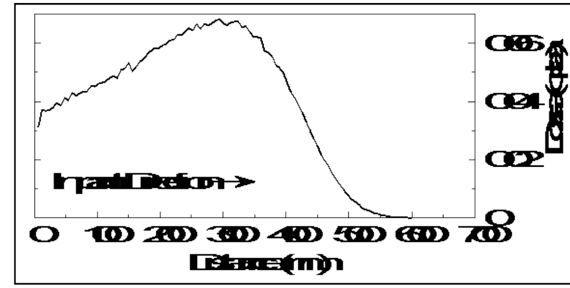


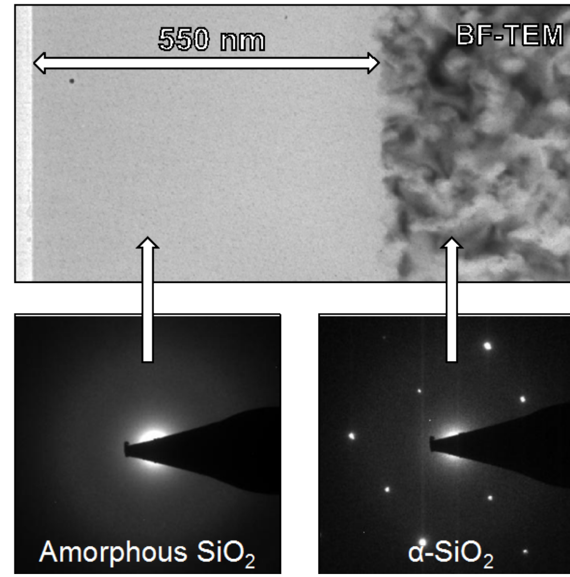
Perforated capsule

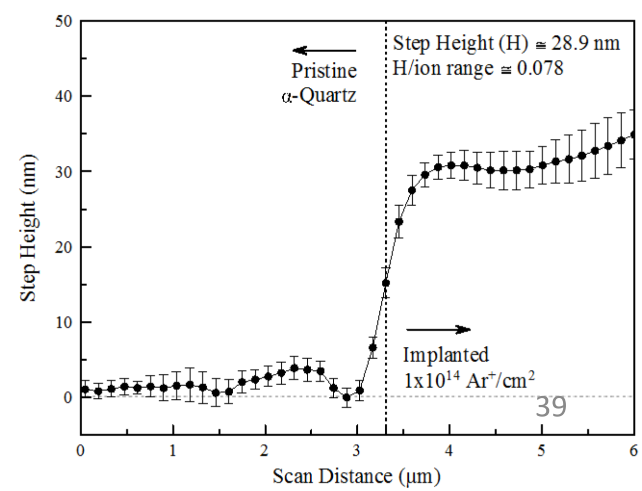
- Irradiation of hardened cement paste and single crystals representative of the most common aggregate mineral components
  - Quartz $SiO_2$
  - Calcite $CaCO_3$
  - Dolomite $CaMg(CO_3)_2$
- Two different irradiation capsule designs to test irradiation temperature control
  - Sealed
  - Perforated to allow best heat transfer with the core coolant
- Fast neutron fluences
  - $0.5 \times 10^{19}$ n/cm$^2$ (E > 0.1 MeV)
  - $4 \times 10^{19}$ n/cm$^2$ (E > 0.1 MeV)
  - $20 \times 10^{19}$ n/cm$^2$ (E > 0.1 MeV
- Irradiation complete 30 August 2014

# Application of ion beams for accelerated testing of irradiated concrete and neutron irradiated PIE techniques are being validated

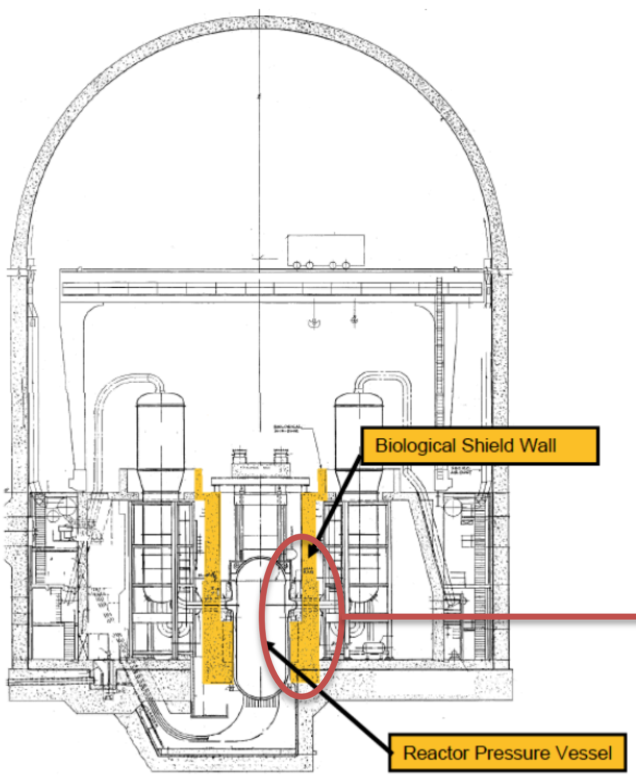
- Recent literature review indicates radiation induced aggregate swelling leads to degradation of concrete properties
- Neutron based irradiation campaigns are time consuming and costly, can techniques learned from decades of ion beam research be applied to irradiated concrete research?
- Initial work has been completed to implant α-Quartz using $Ar^+$ to induce full amorphization in a thin layer
  - Cross-sectional FIB lift-outs were conducted for TEM investigation
  - Surface layer shows full amorphization up to 550 nm from the surface and out of plane expansion of roughly ~30 nm
- **Techniques applicable to irradiated concrete and neutron irradiated concrete PIE**

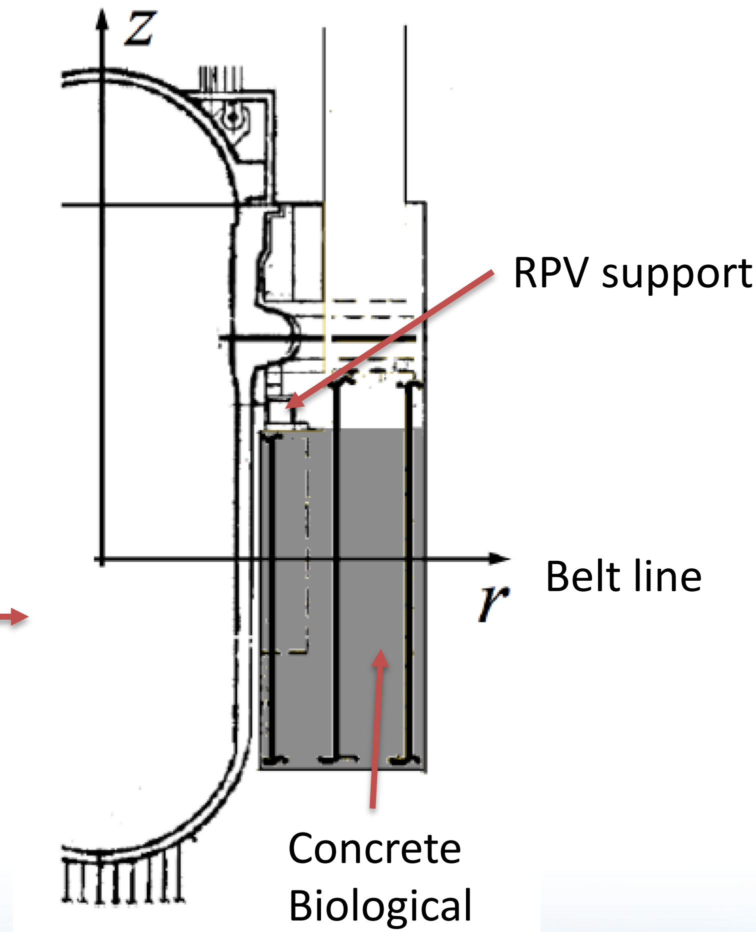




# Irradiation effects are also being examined at the structure level: PWRs Typical Concrete Biological Shield

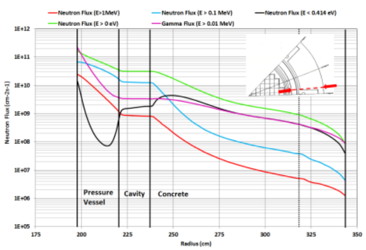


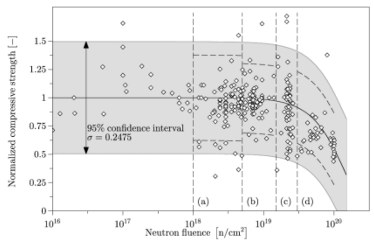



# An evaluation of the structural integrity is being performed

- Use fluence profiles and irradiated concrete properties to obtain the strength and elastic properties radial profile

$$\Phi(r) * f_c(\Phi), f_t(\Phi), E(\Phi) = f_c(r), f_t(r), E(r)$$




- Use fluence profiles and irradiated induced swelling to obtain free swelling radial profile

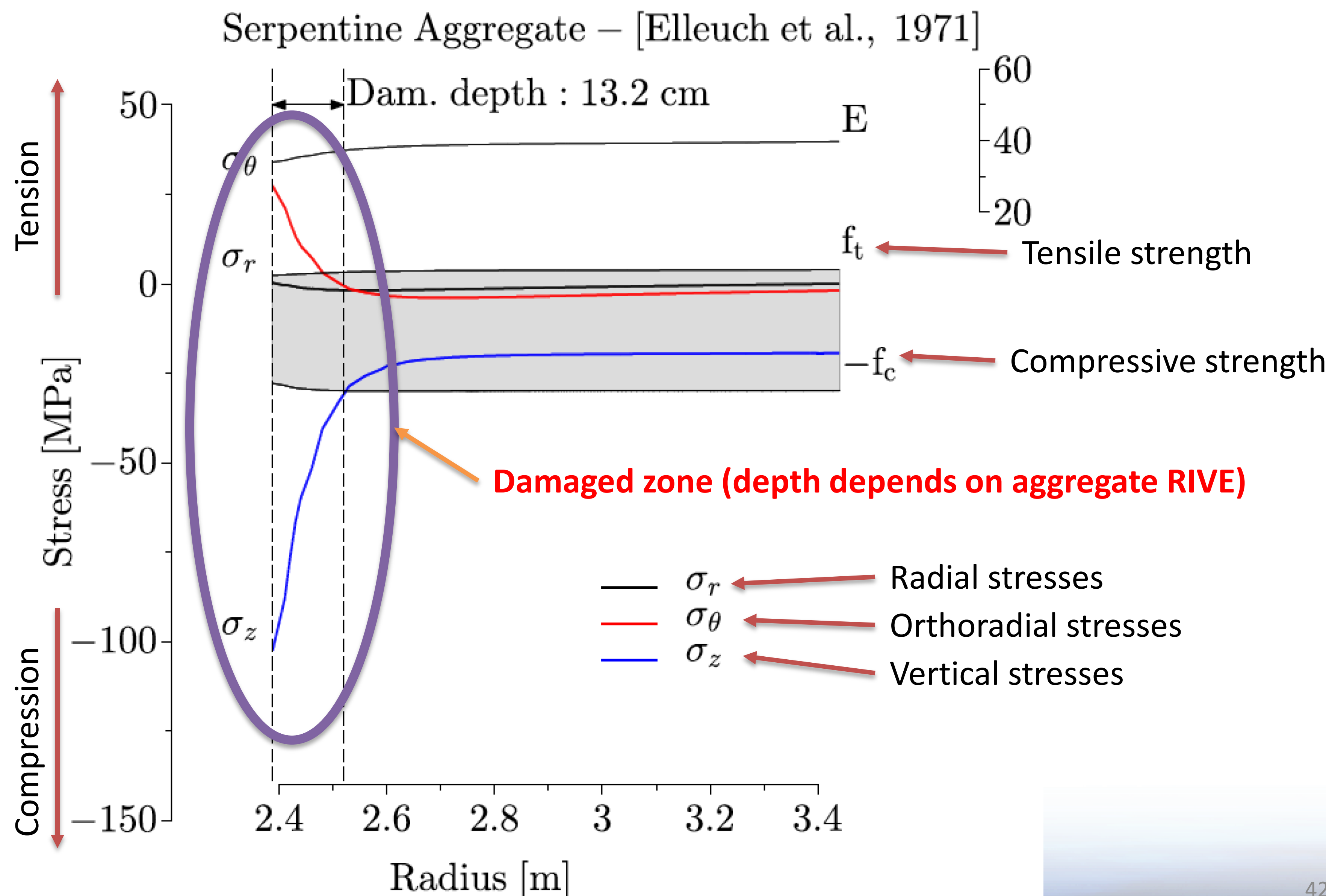
$$\Phi(r) * \varepsilon_0(\Phi) = \varepsilon_0(r)$$

- Solve the structural problem (Finite element, finite difference…)

$$\mathrm{div}[\sigma(r)] = 0$$

- Evaluate potentially damaged zone

# Example of Stress Profiles in the CBS

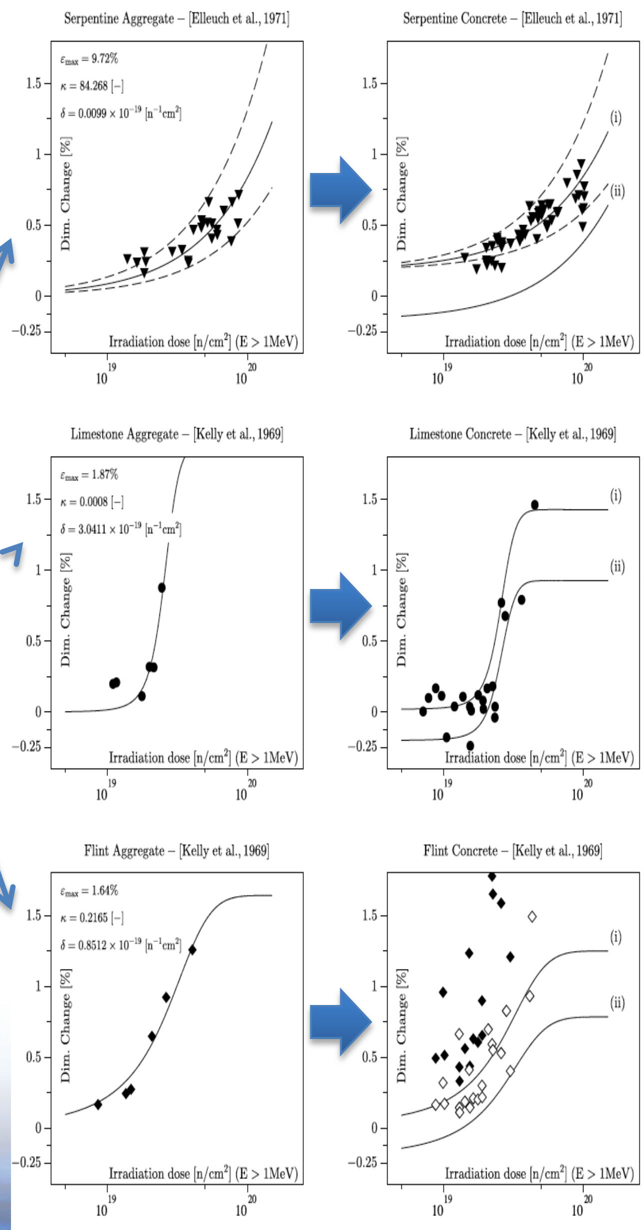


# Advanced modelling may be required to deconvolute different effects

Deconvolution of temperature, shrinkage and irradiation effects

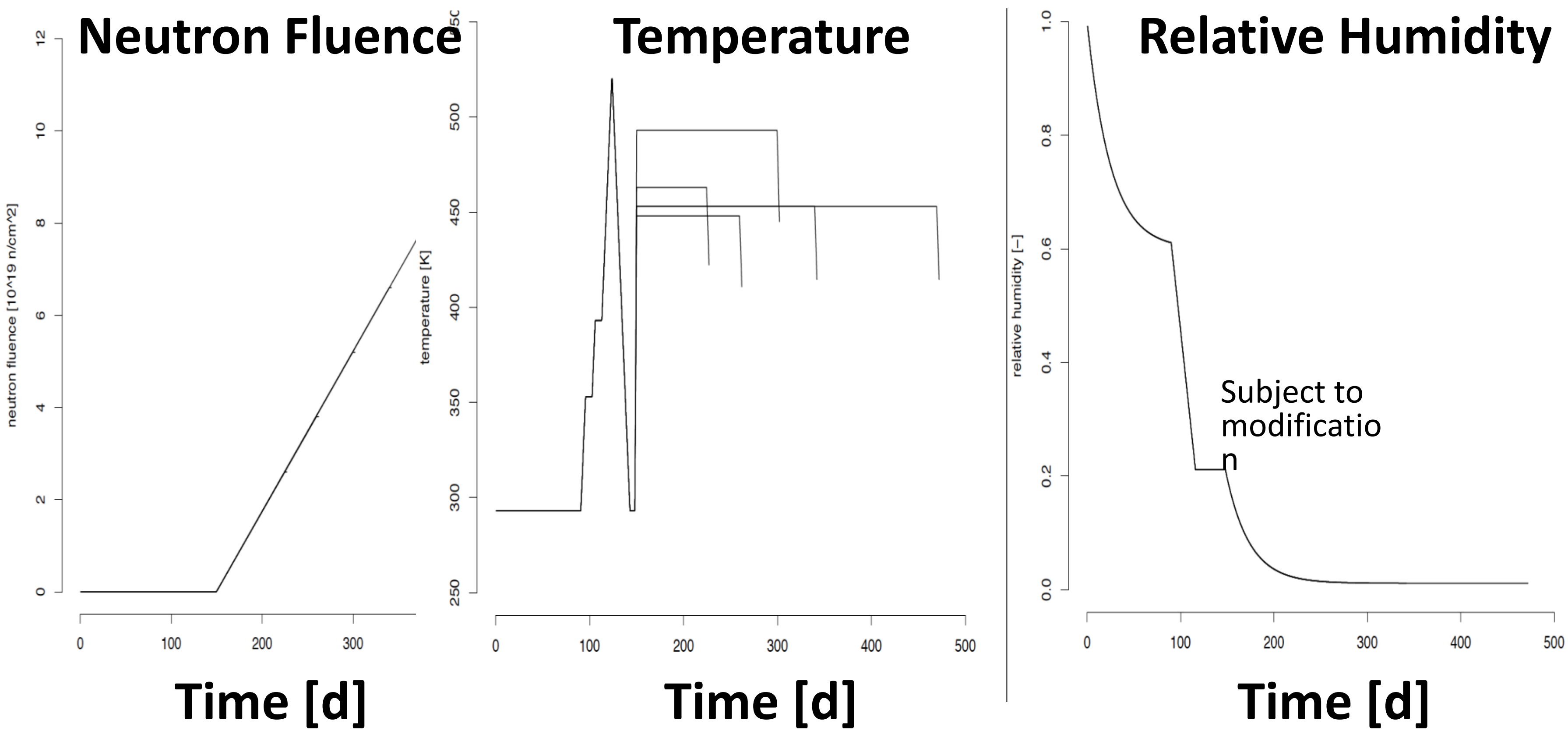
$$\varepsilon^*(T,\omega,\Phi)$$

Aggregate




Concrete

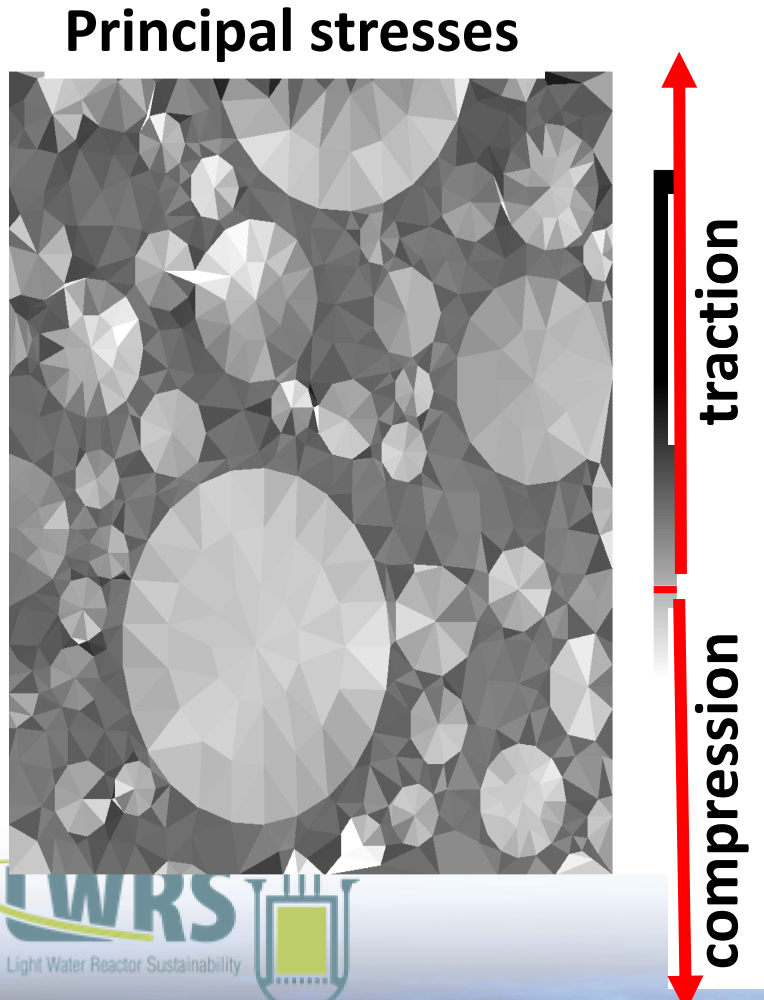
# Advanced modeling may help understand complicated thermo-hygro-radiation histories

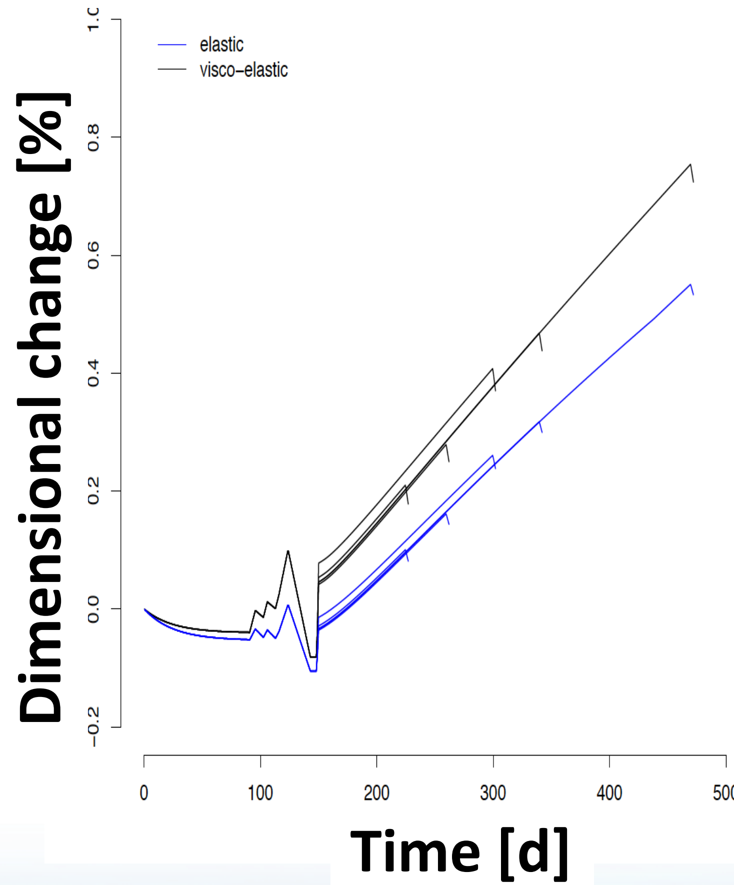



Actual histories of Elleuch et al.'s experiment (1971)

# Complicated coupled behaviors must also be understood

Creep, shrinkage, irradiation induced expansion, damage etc. interact




Simulation of Elleuch's experiment.
Preliminary work... to be continued.

# Irradiated Concrete Structural Significance: Preliminary Conclusions

- The loss of tensile and compressive strengths has limited impact on the structural integrity.
- Structurally restrained radiation-induced volumetric expansion (RIVE) may cause important induced stresses (elastic analysis)
- Further research needed:
  - Risk of RIVE: on-going testing of mineral analogues and ricks at HFIR
  - Refined structural simulations including creep and damage

LWRS
Light Water Reactor Sustainability

## Evaluate Irradiated Concrete from Retired NPP: Zion and Barseback

- On-going discussions with Scanscot (Lund, Sweden) to obtain concrete cores from Barseback reactor
- On-going discussions with Energy Solutions to obtain concrete cores from Zion NPPs
- Objectives:
- Evaluate possible degradation (corrosion, temperature, radiation) modes. Compare aged unirradiated and irradiated cores. Gradient effects
- Evaluate NDE techniques for degradation characterization
- Evaluate options to irradiate NPP concrete.
- Make decision to proceed with harvesting cores by the end of CY 14.

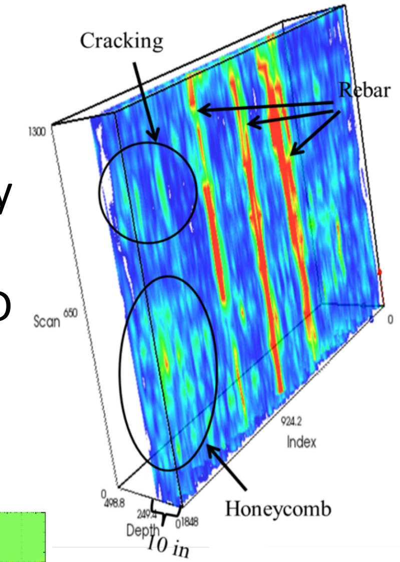
# International Irradiated Concrete Information Exchange Framework Meeting Helsinki, Finland 8 -10 October 2014 (I)

- Organizing Second International Committee on Irradiated Concrete (ICIC) Information Exchange.
  - Provided a forum for discussing cutting edge issues that advance the state of knowledge of the effects of irradiation on structural concrete used in nuclear reactor facilities including storage sites..
- As chair and organizer, the goals are to facilitate the exchange of technical information on the effects of radiation on concrete,
- Establish Technical Tasks Groups to expedite research progress,
- Select Technical Area Coordinators (TAC) to lead Task Groups
- Finalize ICIC Charter
- Elect officers
- Local host: Fortum, Oyj (Tapani Eurajoki and Ritva Korhonan)

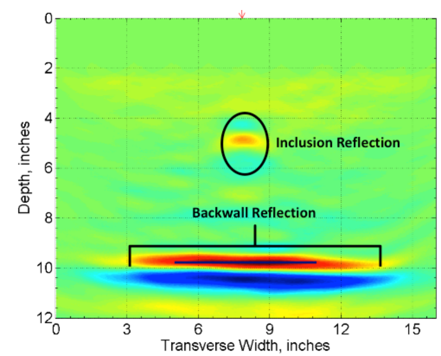
# NDE development provides other tools for component management

- To create synergies and efficiencies, NDE development is integrated with materials degradation research
- NDE Roadmaps were developed in FY12
  - Concrete
  - Cables
  - Fatigue damage
  - Reactor pressure vessel
- Roadmaps were assembled based on a variety of sources
  - Assessed key degradation modes
  - Interacted with materials experts
  - Assembled an expert panel and hosted a workshop
- Roadmaps are available on the LWRS website

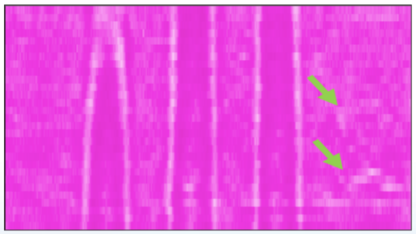
Ultrasonic array without post processing – 3D




Ultrasonic array with post processing – 2D



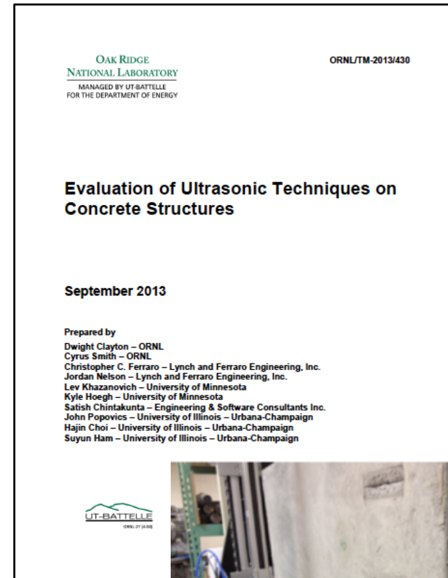

Ground Penetrating Radar



Light Water Reactor Sustainability

# Several concrete NDE techniques are being explored

- ORNL, the University of Minnesota, and Engineering & Software Consultants tested ultrasonic nondestructive examination techniques to perform volumetric imaging on thick reinforced concrete sections.
- Seven ultrasonic techniques were tested on specimens fabricated by the University of Florida for the Florida Department of Transportation's nondestructive examination validation facility at their State Materials Office in Gainesville, Florida.
  - Specimens included a rebar detection block and a void and flaw detection block
  - Generally, all techniques performed well on the two selected test specimens though each method has some limitations and shortcomings
  - Each technique has situations where it performs very well and other situations where it is somewhat lacking in performance, providing a baseline performance indication of each technique
- The ultimate solution to volumetric imaging of a thick concrete section might be a fusion of data from various technologies


OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/TM-2013/430

Evaluation of Ultrasonic Techniques on Concrete Structures

September 2013

Prepared by

Dwight Clayton – ORNL
Cyrus Smith – ORNL
Christopher C. Ferraro – Lynch and Ferraro Engineering, Inc.
Jordan Nelson – Lynch and Ferraro Engineering, Inc.
Lev Khazanovich – University of Minnesota
Kyle Hoegh – University of Minnesota
Satish Chintakunta – Engineering & Software Consultants Inc.
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Hajin Choi – University of Illinois – Urbana-Champaign
Suyun Ham – University of Illinois – Urbana-Champaign

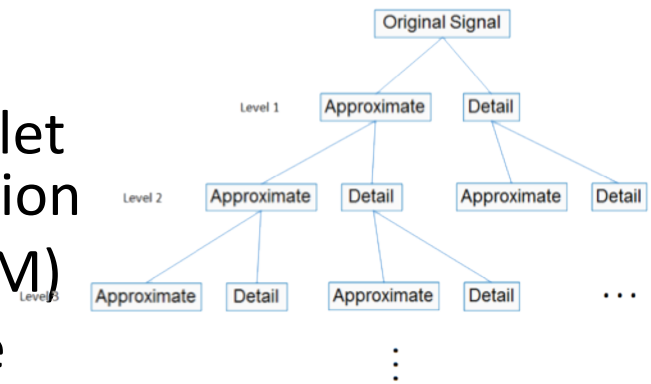
UT-BATTELLE

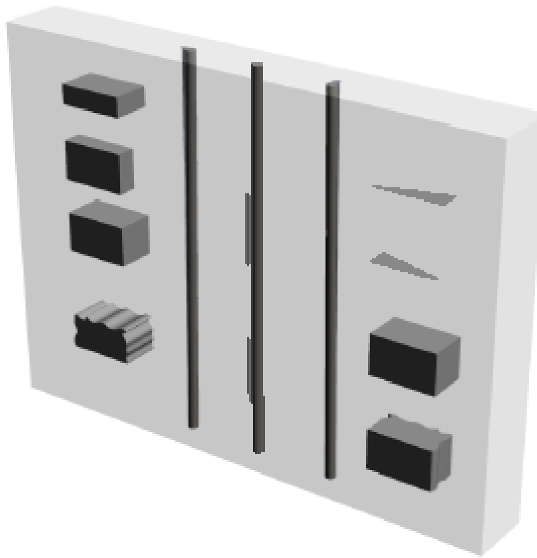
Ground Penetrating Radar Scans and Ultrasonic Scans of Concrete Samples Were Performed at the University of Florida

LWRS Light Water Reactor Sustainability

# Concrete NDE efforts have been focused on signal processing in recent months

- Investigated two advanced signal processing techniques
  - Frequency band extraction using wavelet packet decomposition and reconstruction
  - Modified Total Focusing Method (mTFM)
  - Used a simple test specimen (12” cube with a single dowel installed in the middle)
  - Used “Rebar” and “Void and Flaw” test specimens – note these specimens are only 10” thick
- These two signal processing techniques can be used together



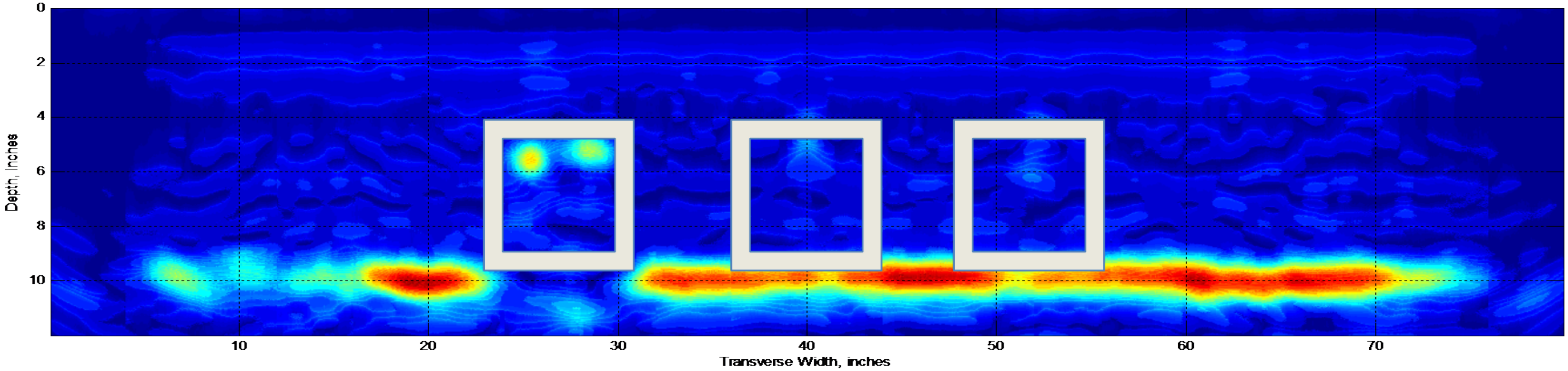
Light Water Reactor Sustainability

# Frequency Band Extraction Using Wavelet Packet Decomposition and Reconstruction

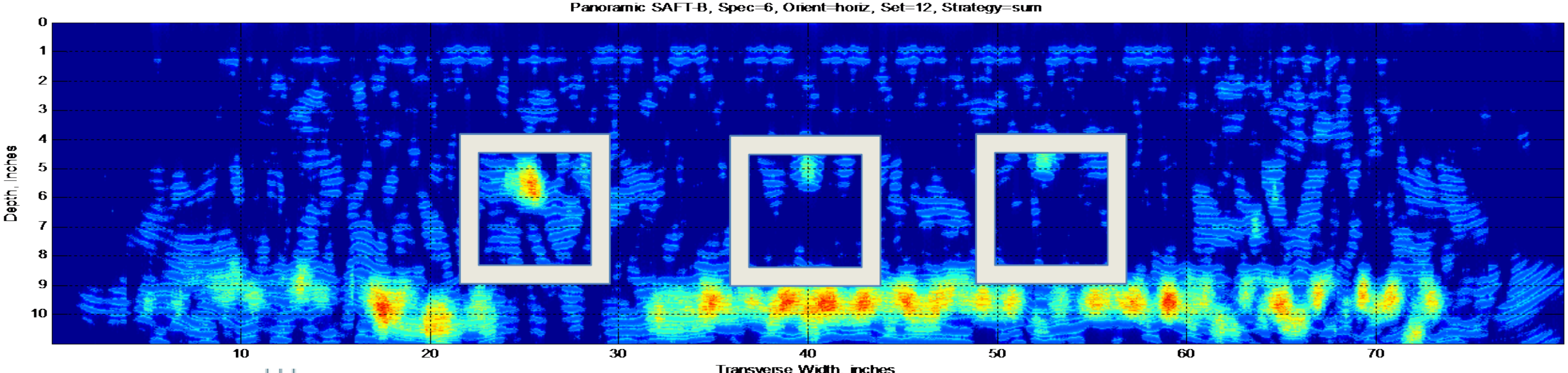
- Ultrasound uses reflected energy to “image” specimens
  - Synthetic Aperture Focusing Technique (SAFT)
    - Delay received signals to account for the spacing between transducers
    - Sum amplitudes of the delay corrected signals
  - Larger amplitude = more reflected energy
  - The amplitude is the net “strength” of the entire 500 kHz bandwidth
- But it doesn’t have to be the entire bandwidth
  - Narrowing the frequency band allows us to focus on defects/flaws and improve the signal to noise ratio (SNR)
    - Think of it as ignoring all the background conversations at a party and listening to just one person
    - Retain the ability to switch to any band, i.e. any person

LWRS
Light Water Reactor Sustainability

# Frequency Banding improves the ability to identify defects, structural elements, etc.




Using Frequency Banded Dataset – second harmonic

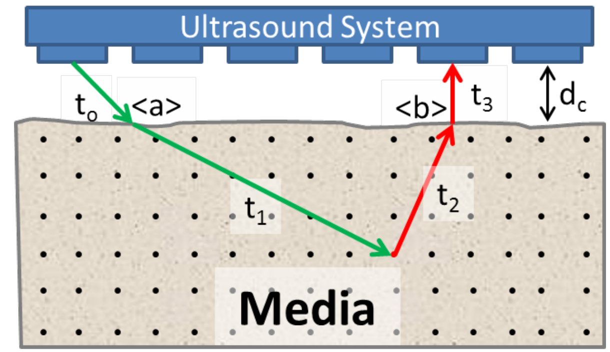



**Note: The second harmonic is used almost exclusively in medical ultrasound applications.**

LWRS Light Water Reactor Sustainability

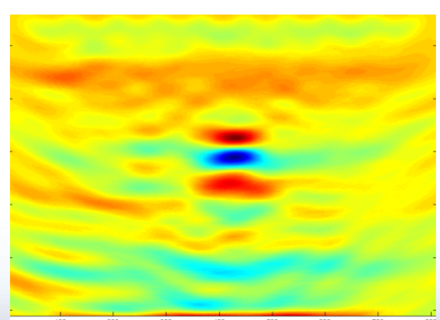
# Implementation of the modified Total Focusing Method (mTFM) is complete.

- Modified TFM removes the assumption of constant acoustic velocity
  - Benefits
    - More compact point spread
    - Slight SNR improvement
    - Object shapes are more accurate (rebar more circular, not elliptical as SAFT)

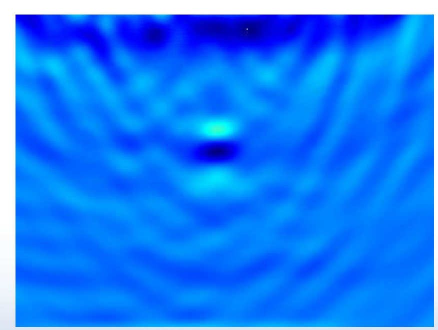



- Correction for sound attenuation improved the Signal-to-noise ratio (SNR)

SAFT-B



TFM



# Summary

- The EMDA process identified several potential knowledge gaps for concrete and civil structures in the subsequent operating period.
  - Irradiation effects
  - Alkali silica/aggregate reactions
  - Creep/fracture mechanisms
- Joint research is underway in these key areas with a focus on irradiation, ASR, and NDE development
- Collaborations and coordination is strong and growing

LWRS Light Water Reactor Sustainability

# Discussion?

LWRS

Light Water Reactor Sustainability

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# Concrete Research at EPRI

**John Lindberg**

**Program Manager, NDE Innovation**

**ACRS Meeting on Concrete Degradation**

September 19, 2014

# Agenda

- **Background**
- Structures of Interest
- Irradiation damage in concrete (reactor cavities and biological shielding)
- Boric acid attack of concrete (spent fuel pools)
- Concrete Creep
- Alkali Silica Reaction
- Inspections - NDE

# Nuclear Power Plants

STRUCTURES

Containments

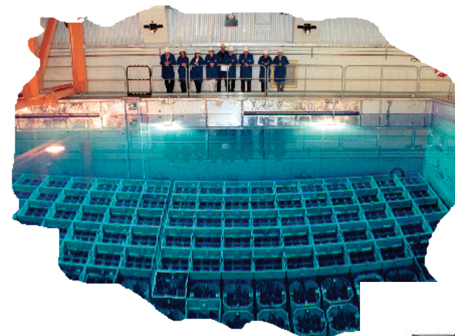
Spent fuel pools

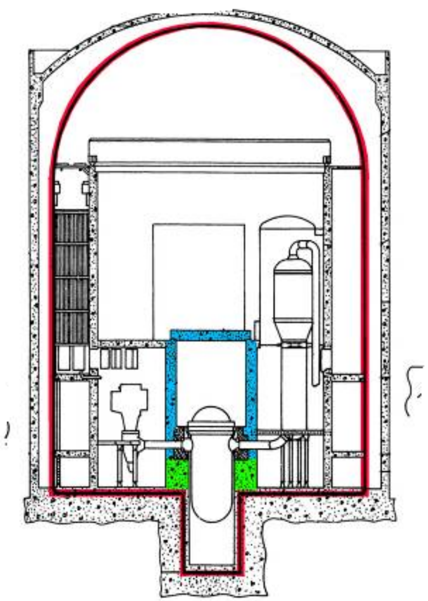
Concrete pipes (PCCP)

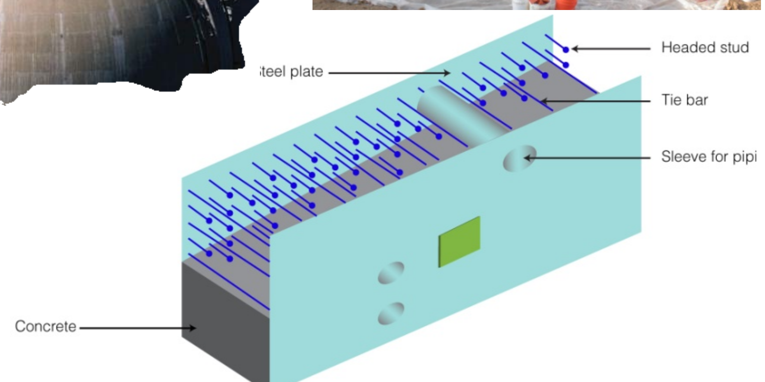
RPV pedestals

Torus – suppression pool

Dry cask storage









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# EPRI Projects – Concrete Degradation and Management

| 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|

**Degradation matrix**

**Aging analysis of individual structures**

*Cooling towers – Spent Fuel Pools – Containments – RPV support structure*

**Concrete NDE reliability lab**

*Commercially available inspection techniques*

**Assess and develop NDE inspection tools**

*Non traditional NDE tests – Deployment - New infrastructure*

**Asset Management Platform for concrete structures**

*Toolbox*

**Repair and Mitigation**

*Durability – Quality control - Inspection*





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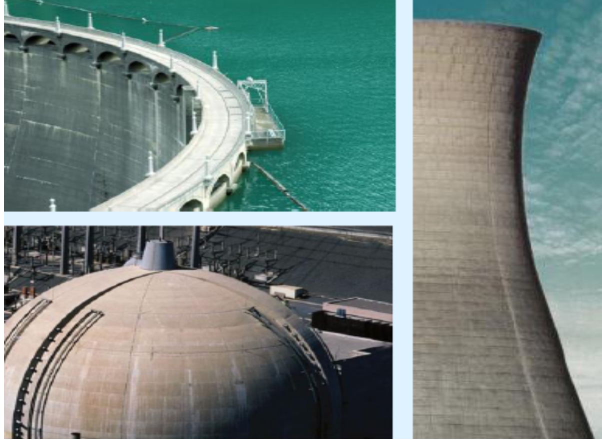
# Concrete Technical Advisory Committee



- Concrete Technical Advisory Committee
  - Started January 2013 - 5 meetings, 4 webcasts

- Vision
  - Provide tools for long term, safe and reliable operation of concrete infrastructure
- Mission
  - Identify industry needs and emerging issues pertaining to concrete
  - Provide guidance for construction, inspection, evaluation and repair of concrete structures
  - Coordinate work with other industry groups to provide comprehensive solutions
  - **Exchange operating experience**

# Agenda

- Background
- **Structures of Interest**
- Irradiation damage in concrete (reactor cavities and biological shielding)
- Boric acid attack of concrete (spent fuel pools)
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- Inspections - NDE

# Structures of Interest for Concrete LTO

2 Unit Nuclear Plant (Pressurized Water Reactor [PWR])


1 – Cooling Towers

2 – Containments (including internal structures such as RPV biological shield and supports)

3 – Spent Fuel Pools/ Dry Cask Storage

4 – Buried Pre-tensioned Concrete Pipe

5 – Intake Structure





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# EPRI Concrete Aging Structures Reference Manual

- In 2011 EPRI published a Nuclear Concrete Structures Aging Reference Manual (TR 1023035)
  - Define possible degradation mechanisms
  - Discuss operational experience
  - Degradation Structures Index – a chart to cross-reference incidences of degradation with SSCs

| | | Research Gap Analysis | | |
|---|---|---|---|---|
| **Issue** | **Ranking** | **Materials** | **Inspection** | **Prediction** |
| Chloride diffusion into concrete | High | | X | X |
| **Boric acid effects on concrete** | High | X | O | X |
| Corrosion of reinforcing steel embedded in concrete | High | | X | X |
| **Radiation damage of reactor cavity concrete** | High | X | ? | ? |
| Containment liner corrosion - accessible and inaccessible areas | High | | X | |
| Posttensioning tendon relaxation | High | | X | |
| Leaching of minerals from the cement paste | High | | | X |
| Bulging of the containment liner | High | | | X |
| Freeze-thaw damage | High | X | X | X |
| Spent fuel pool liner stress corrosion cracking (welds) | High | | X | |
| Pre and posttensioning tendon corrosion / SCC | High | | X | X |
| Concrete carbonation and effects on steel reinforcement | Medium | | X | |
| **Swelling due to alkali-aggregate reaction or delayed ettrengite formation** | Medium | X | X | X |
| **Concrete creep - microcracking** | Medium | X | X | X |
| Concrete dissolution effects on spent fuel pool liners | Medium | | X | X |
| **Boric acid attack of steel reinforcement** | Medium | X | ? | ? |
| Water treatment chemical attack of concrete | Medium | X | ? | ? |
| Aggressive groundwater / external sulphate attack | Low | | X | X |
| Thermal cycling / cooling towers (operational temperatures) | Low | | | X |
| Containment pressurization / depressurization (ILRT) | Low | | X | X |
| Hydrogen embrittlement of posttensioning tendons | Low | | O | X |
| Thermal fatigue at penetrations | Low | X | | X |
| Differential settlement of structures | Low | | | X |
| **Spent fuel pool channel corrosion** | Low | | X | |

**A prioritization of research needs and gaps**

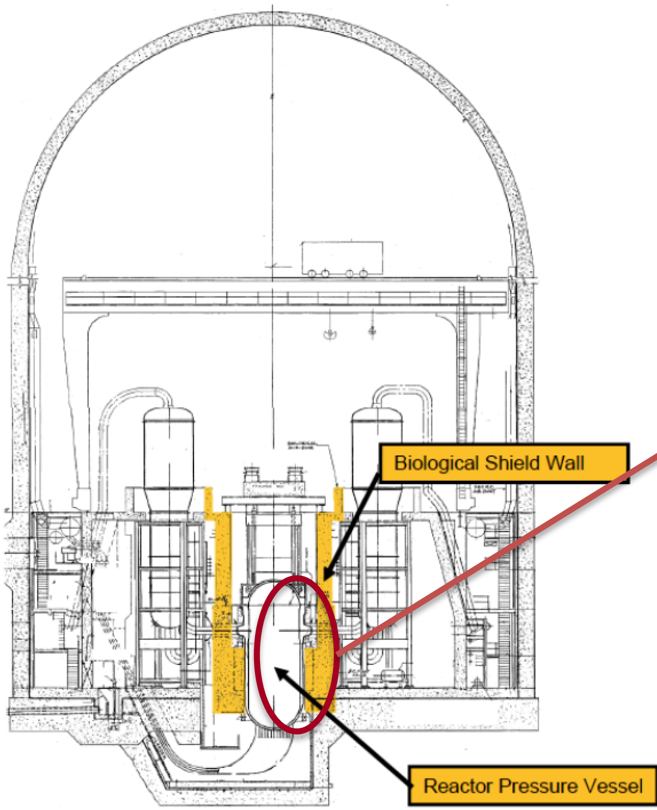
# Agenda

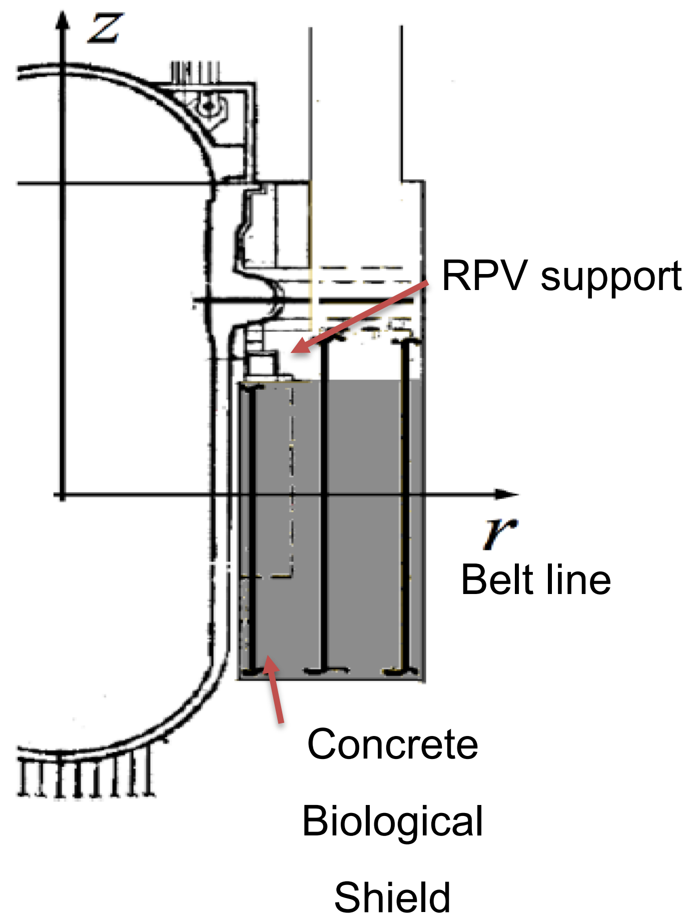
- Background
- Structures of Interest
- **Irradiation damage in concrete (reactor cavities and biological shield)**
- Boric acid attack of concrete (spent fuel pools)
- Concrete Creep
- Alkali Silica Reaction
- Inspections - NDE

# Irradiation Damage in Concrete

- Scope of the project – structures exposed to chronic irradiation due to reactor operation:

  RPV cavity (Bio Shield and Supports)





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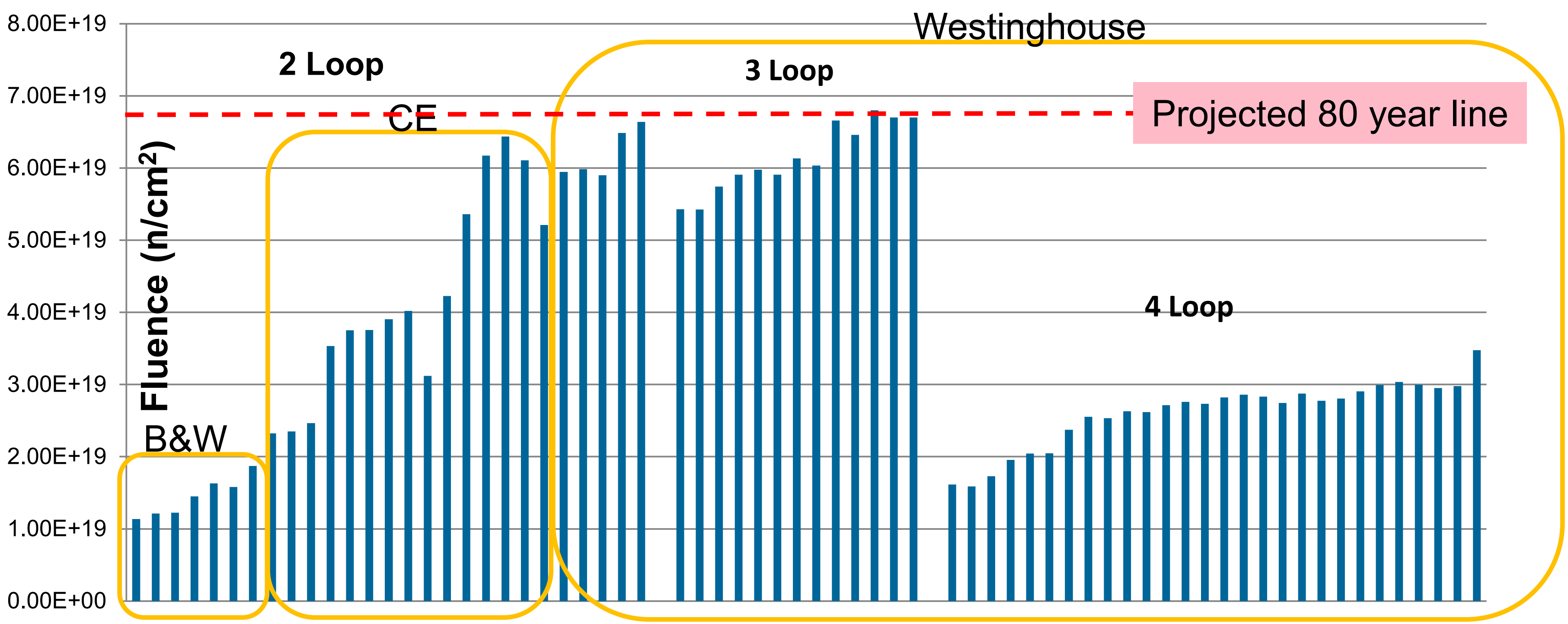
# PWR 1T Fluence Values for 80 yr Operation




Extrapolated from reported RPV 1T data from ADAMS. Converted to energy > 0.1 MeV.





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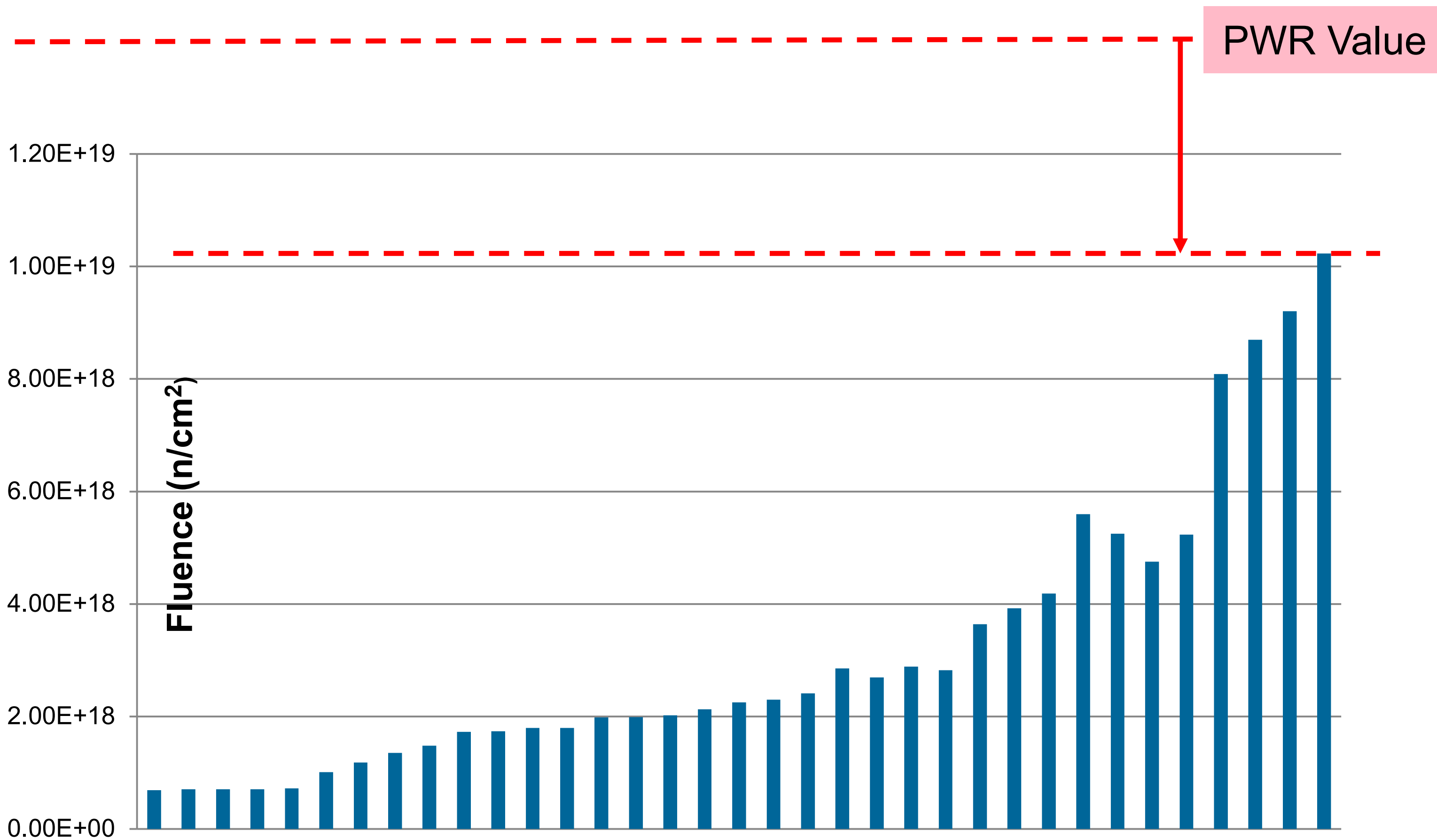
# BWR 1T Fluence Values for 80 yr Operation




Extrapolated from RPV 1T data from ADAMS and converted to energy > 0.1 MeV.

BWR's are not bounding





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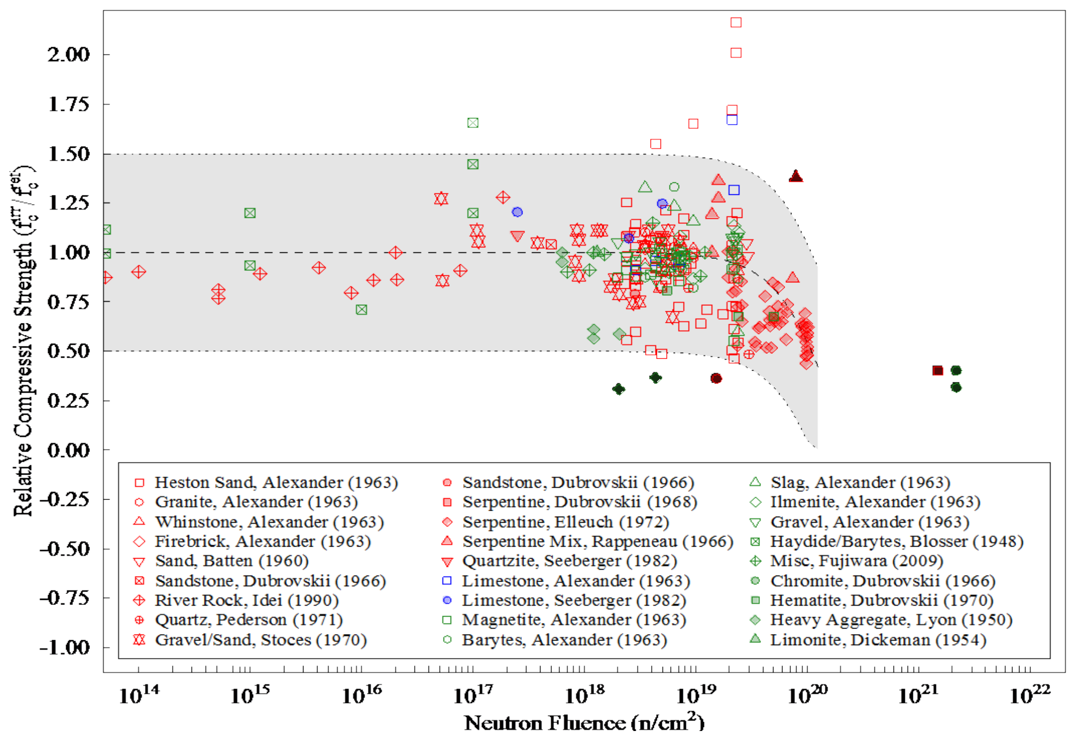
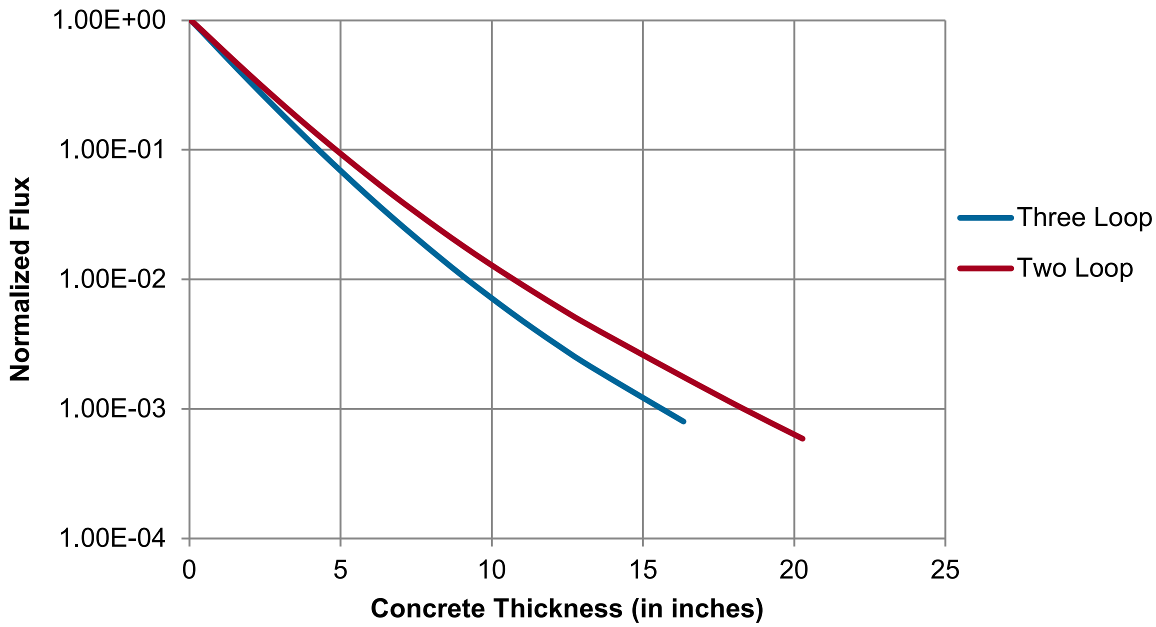
# Irradiation Damage In Concrete – Previous Work

- Data previously summarized by Hilsdorf and others have neutrons of different energies and many data points with temperatures greater than 100°C.
- More extensive data is now being evaluated and classified



# RADIATION ATTENUATION IN CONCRETE

- Simplified models for 2-loop and 3-loop PWRs were developed using the Monte Carlo N-Particle Code (MCNP5) with the cavity concrete constructed with Portland concrete.




Neutron fluence drops by an order of magnitude in the first several inches of the concrete





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# Bounding Fluence

- 6.8 E19 n/cm2 estimates to bound the US fleet for neutron damage in concrete to 80 years operation for energy > 0.1 MeV.
- At a concrete depth of 3 inches, the bounding neutron fluence will drop to 1.4 E19 n/cm2.
- Existing data for E > 0.1 MeV shows no loss of compressive strength up to 2.3 E19 n/cm2.
- Appears that margin is adequate for 80 years of operation.
  - *Loss of compressive strength a near-surface effect*
- Additional work is planned to further quantify margin.

# Irradiation Damage in Concrete - Conclusions

- Data that is available indicates adequate margin.
- Additional work is being performed.
  - LWRS Tasks
    - Fundamentals of radiation damage
    - Neutron and ion irradiation of mineral analogues to characterize swelling
    - Structural significance of radiation damage due to near surface swelling (done in concert with EPRI)
  - EPRI Tasks
    - Structural significance of radiation damage due to near surface swelling (done in concert with DOE - LWRS)

# Agenda

- Background
- Structures of Interest
- Irradiation damage in concrete (reactor cavities and biological shielding)
- **Boric acid attack of concrete (spent fuel pools)**
- Concrete Creep
- Alkali Silica Reaction
- Inspections - NDE

# Boric Acid Attack – Introduction

- PWR spent fuel pools contain boric acid in the water to absorb neutrons emitted from the fuel.
- Spent fuel pools are susceptible to leakage due to cracking in the seam and plug welds in the liner.
- Boric acid is known to react with cement paste and some aggregates, causing degradation of mechanical properties


1 in. = 25.4 mm




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# Boric Acid Attack – Introduction

- Leakage is collected in channels beneath the seam welds.
- Collection channels can be obstructed by re-precipitated minerals leached from the cement paste in the concrete.
  - This can result in pooling of water beneath the liner.

# Boric Acid Degradation

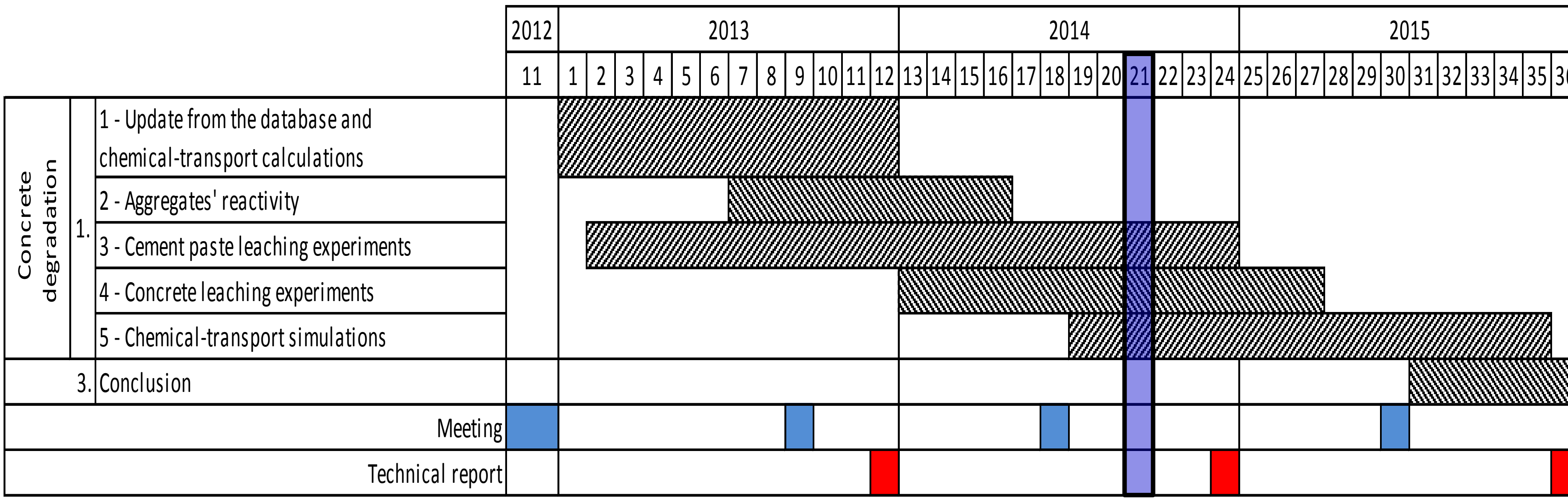
- EPRI project to study the effects of boric acid on concrete degradation in spent fuel pools

- Builds on previous work
  - Reactivity of different types of aggregate
  - Computational modeling of the reaction process
  - Characterization of the reaction products
  - More accurate determination of the reaction front

- Collaborative project with the Material Aging Institute and CEA (France)

# Boric Acid Degradation

- SFP leakage project timeline and current status




The results will be used to determine the rate of degradation and, if appropriate, be used to develop a toolbox to perform generic structural assessment of boric acid leakage leading to degradation for a typical spent fuel pool geometry

# Agenda

- Background
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- Alkali Silica Reaction
- Inspections - NDE

# Concrete Creep

- Concrete deforms slowly and nonlinearly with time when subjected to loading (post-tensioned containments, static loading)
  - Dimension change
  - Lost of post stressing
  - Cracking
  - Liner deformation
- EPRI is evaluating creep deformation of concrete structures to determine if and where it may be an issue
- Assessing feasibility of new NDE techniques for characterizing concrete creep

# Agenda

- Background
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- Concrete Creep
- **Alkali Silica Reaction**
- Inspections - NDE

# Alkali Silica Reaction (ASR)

- Caused by a reaction between the alkali cement and amorphous silica in aggregates.
  - Causes formation of an expansive gel that causes the concrete to swell and crack
  - Causes mechanical properties to degrade
  - Reaction between the cement and aggregates requires water
  - Depends on aggregate mineralogy



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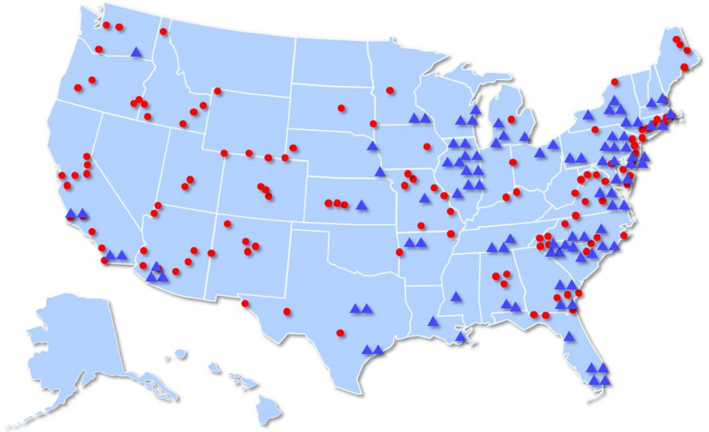
# Risk screening for ASR

Provide utilities with tools to evaluate the risk of having alkali-silica reaction

www.nrc-cnrc.gc.ca

- Concrete used during construction of the existing fleet was considered as non-reactive

- Those aggregates may be classified differently today due to improved testing methods that have been developed to detect the potential of ASR.



www.fhwa.gov





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# ASR Research Plan summary

- Develop map of geographic distribution of reactive aggregates
- Evaluate and compare reactivity of aggregates based on current testing procedures
- Testing various NDE methods on large ASR mockups
  - Nonlinear ultrasonic testing R & D for ASR damage

**Comprehensive tools to assess risks and manage, as appropriate, ASR**

# Agenda

- Background
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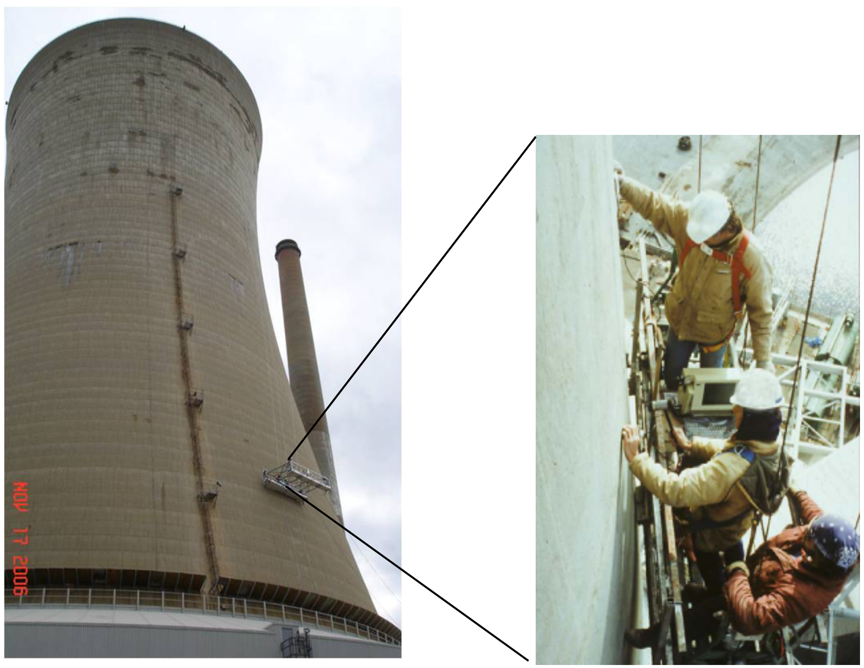
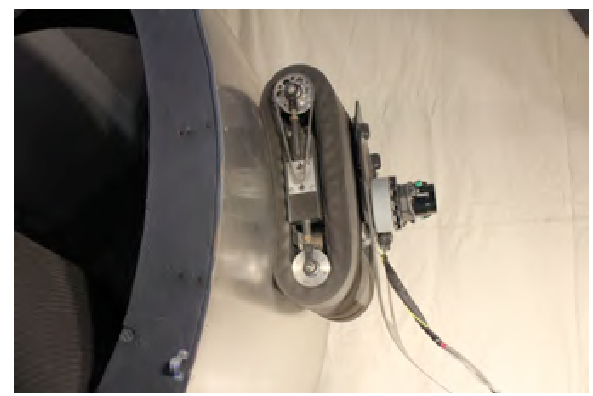
- Irradiation damage in concrete (reactor cavities and biological shielding)
- Boric acid attack of concrete (spent fuel pools)
- Concrete Creep
- Alkali Silica Reaction
- **Inspections - NDE**

# Automation of concrete inspection

The availability of automated concrete inspections will translate into faster and less costly inspections of large structures.

- This will allow for easier and more frequent inspections of the aging nuclear fleet.







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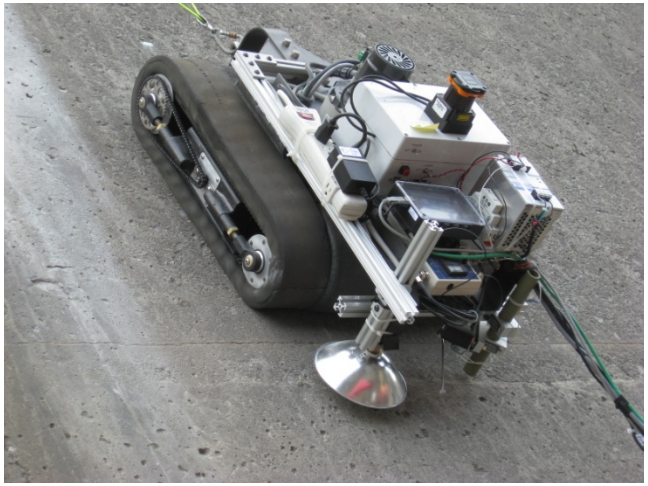
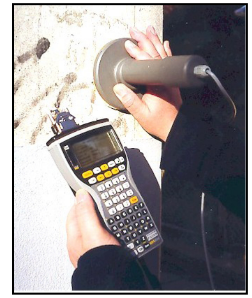
# Concrete Crawler

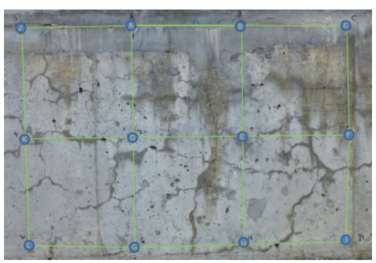
Download EPRI White Paper # 1026732



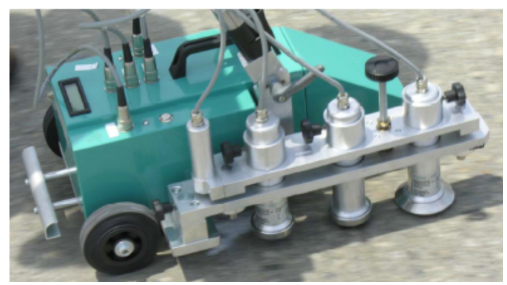


*corrosion?*

*Crack mapping?*



*moisture?*



Key advantage of this technology is its **flexibility** to accommodate different inspection devices





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# Early Demonstrations

Niagara, July 2013

Crystal River, Fall 2014

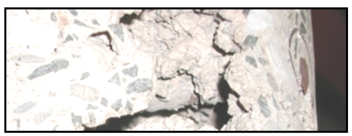
Claytor Dam, July 2014

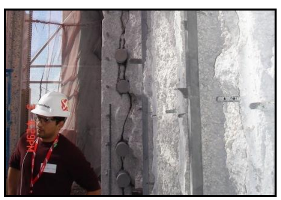
# NDE capabilities for concrete

## Corrosion

Corrosion of embedded steel

## Single defect





Delamination

Voids

Vertical cracks

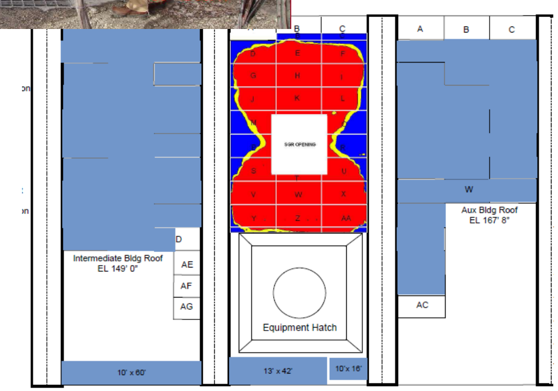
## Pattern cracking

ASR

Freeze - thaw

High temperature

Independent resource for concrete NDE technical capability assessment and development





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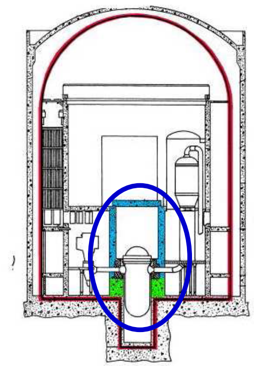
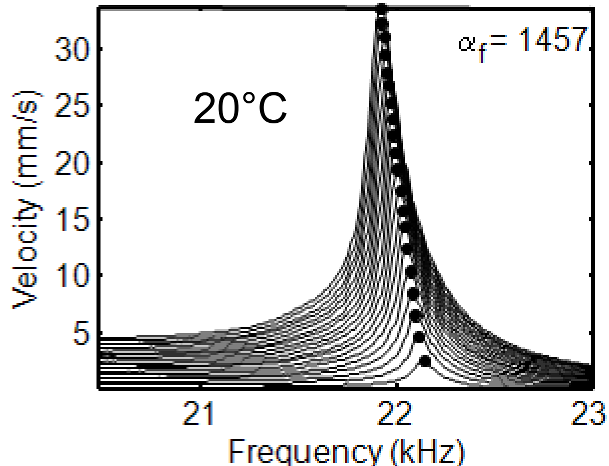
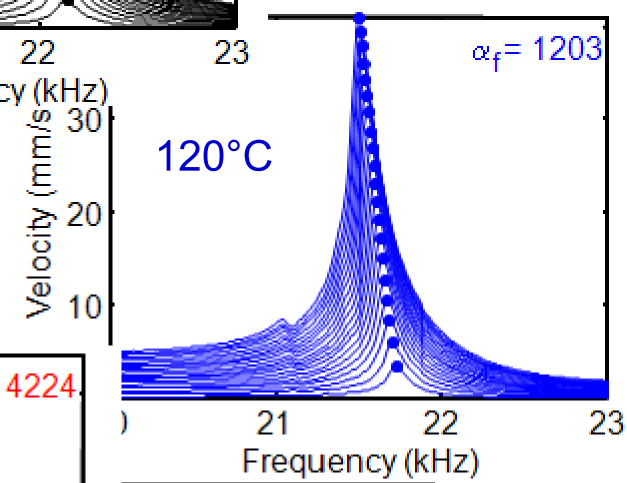
# Expanding inspection techniques

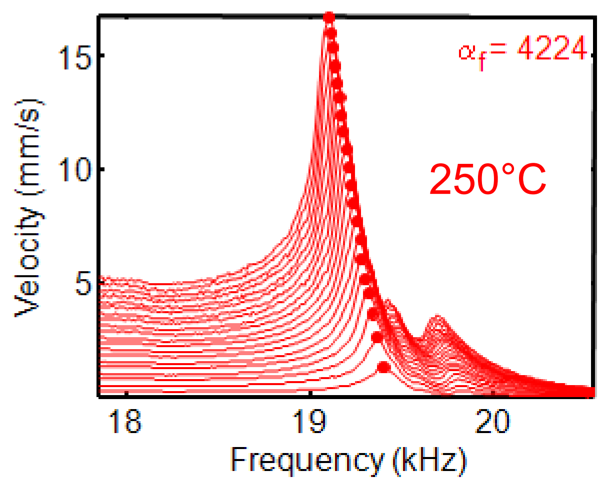


Non-linear UT can give information on degree of damage with depth for concrete subjected to:

- Radiation
- Carbonation
- Alkali-silica reaction
- Temperature damage



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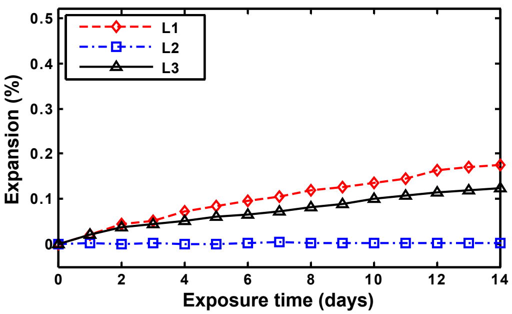
# Nonlinear wave mixing technique to measure the ANLP in concrete

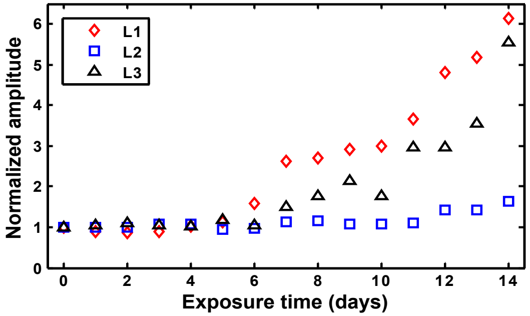
A co-linear wave mixing technique is under development on concrete bar-samples for measuring the acoustic nonlinearity parameter (ANLP).

Good correlations were observed between the ANLP measurements and the expansion of the bar-samples due to ASR damage.


$\beta$ vs. ASR damage parameters

$$\beta = \beta_0 + \beta_{gel}(\delta_{gel}) + \beta_{stress}(P_{\text{int}}) + \beta_{crk}(N_0^{crk})$$





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# Inspection: Mock-up Testing

- New inspection techniques are normally developed in small laboratory sized specimens.
  - Real structures are larger and behave differently.
- EPRI has developed large specimens with various degradation and damage mechanisms, for testing and validation of existing and new NDE techniques
  - The samples are being used and tested by 3 different Universities and a National Lab




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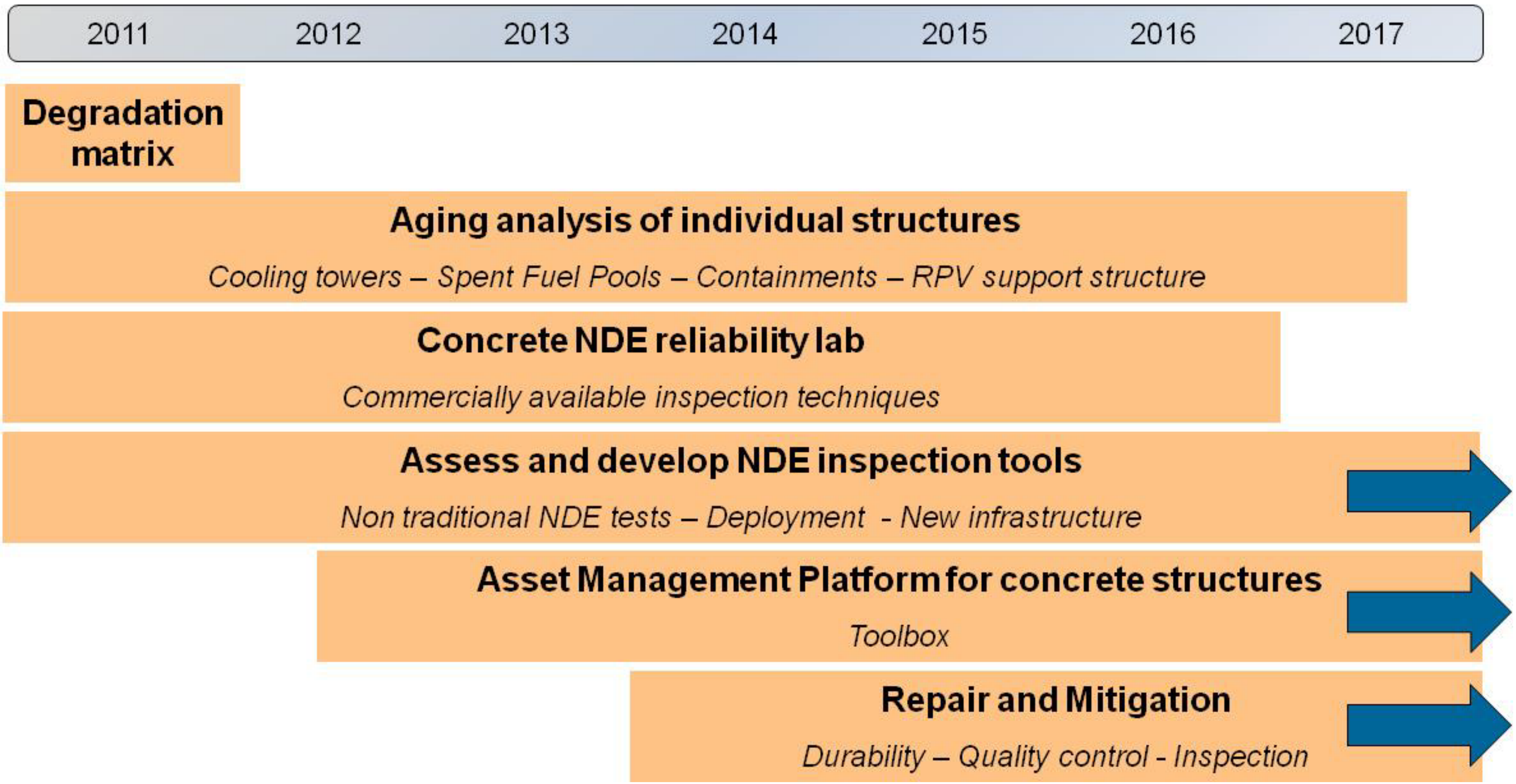
# Summary

- Concrete research at EPRI is in progress with a Nuclear and LTO focus to support utility decision making





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