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

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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

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WEDNESDAY,

JULY 9, 2025

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The meeting was convened at Two White Flint North, 11545 Rockville Pike, Rockville, Maryland, and via videoconference, at 8:30 a.m. EDT, Walter L. Kirchner, Chair, presiding.

PRESENT:

WALT KIRCHNER, Chair, ACRS

GREG HALNON, Vice Chair, ACRS

DAVE PETTI, Member-at-Large, ACRS

RON BALLINGER, Member, ACRS

VICKI BIER, Member, ACRS

VESNA DIMITRIJEVIC, Member, ACRS *

CRAIG HARRINGTON, Member, ACRS

ROBERT MARTIN, Member, ACRS

SCOTT PALMTAG, Member, ACRS

TOM ROBERTS, Member, ACRS

MATT SUNSERI, Member, ACRS

DESIGNATED FEDERAL OFFICIAL:

DEREK WIDMAYER

NRC STAFF PRESENT:

THOMAS DASHIELL, PMDA, ACRS

TIM DRZEWIECKI, NRR, DANU, UTB2

DENISE McGOVERN, NRR, DANU, UAL2

TRAVIS TATE, NRR, DANU, UTB1

ALSO PRESENT:

BRIAN FROESE, X-energy

MILAN HANUS, X-energy

DREW NIGH, X-energy

MATT THOMAS, X-energy

JAMES TOMPKINS, X-energy

*Present via Teams

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

8:30 a.m.

CHAIR KIRCHNER: Good morning. The meeting will now come to order. This is the first day of the 727th meeting of the Advisory Committee on Reactor Safeguards, ACRS.

I'm Walt Kirchner, Chairman of the ACRS. ACRS members in attendance in-person are Ron Ballinger, Vicki Bier, Greg Halnon, Craig Harrington, Robert Martin, Scott Palmtag, Dave Petti, Thomas Roberts, and Matt Sunseri. ACRS Member Vesna Dimitrijevic is participating virtually via Teams.

If I've missed anyone, either ACRS members or consultants, please speak up now.

Derek Widmayer of the ACRS staff is the Designated Federal Officer for this morning's full Committee meeting.

No member conflicts of interest were identified. And I note that we have a quorum.

The ACRS was established by statute and is governed by the Federal Advisory Committee Act, or FACA. The NRC implements FACA in accordance with our regulations.

Additionally, in accordance with Sections 29 and 182(b) of the Atomic Energy Act, the Advisory

Committee on Reactor Safeguards shall advise the Commission with regard to hazards of proposed or existing facilities and the adequacy of proposed safety standards.

In addition, the ACRS is implementing Executive Order 14300, ordering the reform of the Nuclear Regulatory Commission, dated May 23, 2025. Section 4(b) of the Executive Order states, in part, that the "functions of the Advisory Committee on Reactor Safeguards shall be reduced to the minimum necessary to fulfill ACRS's statutory obligations," and that review by ACRS shall focus on issues that are unique, novel, and noteworthy.

Reviewing/reporting on new reactor facilities and proposed safety standards are the minimum statutory functions of the ACRS under Sections 29 and 182(b) of the Atomic Energy Act. The Commission may refer additional duties to the ACRS in accordance with the Act.

Per these regulations and the Committee's bylaws, the ACRS speaks only through its published Letter Reports. All member comments, therefore, should be regarded as only the individual opinion of that member and not a Committee position.

All relevant information related to ACRS activities, such as letters, rules for meeting participation, and transcripts, are located on the NRC public website and can be easily found by typing "About Us ACRS" in the search field on the NRC's home page.

The ACRS, consistent with the agency's value of public transparency and regulation of nuclear facilities, provides opportunity for public input and comment during our proceedings. For this full committee meeting, we have received no written statements. However, written statements may be forwarded to today's Designated Federal Officer. We have also set aside time at the end of this meeting for public comments.

A transcript of the meeting is being kept and will be posted on our website. When addressing the Committee, the participants should first identify themselves and speak with sufficient clarity and volume, so that they may be readily heard. If you are not speaking, please mute your computer on Teams. If you are participating by phone, press star-6 to mute your phone and star-5 to raise your hand on Teams.

The Teams chat feature will not be available for use during the meeting.

For everyone in the room, please put your electronic devices in silent mode and mute your laptop microphone and speakers. In addition, please keep sidebar discussions in the room to a minimum, since the ceiling microphones are live.

For presenters, we remind you that these table microphones are unidirectional and you'll need to speak directly into the front of the microphone to be heard online.

Finally, if you have any feedback for the ACRS about today's meeting, we encourage you to fill out the public meeting feedback form on the NRC's website.

During today's meeting, we will consider the topic of X-energy's Topical Report on Mechanistic Source Term. But before I pass the microphone to Bob Martin, our Subcommittee Chair for today's meeting, I want to note that Dr. Ballinger completes his third term with the Committee in August. Ron joined us on August 4th of 2013. So he's our ancient mariner on the Committee. And I want to note that, in addition to being a professor emeritus at MIT, notably, Ron has led several major projects for the Committee.

The APR-1400 review, that was the C-E 80+ that Korea Hydro and Nuclear Power brought to the NRC for review by both the agency and the Committee. He also led the SHINE Medical Isotope Project. That was an interesting one because it was a fusion-fission hybrid approach to medical isotope production. And, most recently, he's led our review of increasing enrichment rulemaking activities.

So, we thank you for that, Ron. I want to note Ron will continue as an ACRS consultant after his term ends. And so, on behalf of the Committee, I want to thank you for your service, your expertise, your collegiality, and your random acts of kindness, which I was the beneficiary of, as well as others.

So, Ron, thank you very much. And would you like to make any comments, Ron?

MEMBER BALLINGER: No.

(Laughter.)

PARTICIPANT: Another random act of kindness.

(Laughter.)

CHAIR KIRCHNER: Okay. So, with that, let me turn to Bob Martin, who will lead us in the morning's topic. Go ahead, Bob.

MEMBER MARTIN: Okay. Thank you, Chairman.

As Walt noted, we are discussing X-energy's Mechanistic Source Term Topical Report. We are reviewing this particular report because it presents foundational methods that directly support the offsite dose calculations required to demonstrate compliance with 10 CFR 50.34, "Contents of Applications," for the Xe-100 high-temperature gas reactor.

Reports its novel aspects include the reliance on TRISO functional containment, event-specific mechanistic source term modeling, and the applicant's in-house XSTERM codes. Early examination of these features ensure they align with regulatory expectations and provide a robust and performance-based safety case for good licensing.

Of course, as you noted, we had a Subcommittee meeting last month where we had presentations from X-energy and, of course, our own staff. And we will be doing letter deliberation after these formalities.

But right now, we have X-energy -- unless anybody from the staff wanted to say anything to introduce anything. But other than that, X-energy, you can proceed with your presentation.

Please introduce yourself.

MR. HANUS: Thank you. Thank you very much for having us here and for your offer for coming here. I heard it was that a tape from an interview. So, we really appreciate you coming here and being here today.

My name is Milan Hanus. I am the software Engineering Manager at X-energy and, also, developed the mechanistic source term model and the code XSTERM, as mentioned. And today, I'll be presenting the mechanistic source term approach, which we provided to the NRC for U.S. licensing Topical Report.

So I will first introduce some generic efforts that X-energy has taken to model the source terms for the Xe-100 paper, and then the actual models with how we are doing the system generation and propagation through the system, and at the end there will be the time for focused questions and answers.

In the Topical Report that we presented to the NRC, we included the description of the mechanistic system with us that is used to determine the radionuclide transport phenomena for the preliminary analysis and deliberation of the Xe-100 and for establishing the safety case.

What is not included in this Topical Report, in this Topical Report, is the actual implementation details and the evaluation of the cases and outputs, which we are planning to include in a future Topical Report on the goal to XSTERM which implements these models.

As a basis for the Topical Report and for the whole mechanistic system modeling, we used some documents which are listed here:

The Risk-informed Performance-based Licensing Basis Approach which provides the link to NEI 18-04 methodology that we adopted for the system and engineered the safety analysis modeling and application.

The Topical Report on the Transient and Safety Analysis Methodology, which was also presented last time, the December report, which describes the approach that X-energy takes or took to elevate the DBAs and to basically evaluate the transients and safety of the reactor.

Principal Design Criteria and the TRISO-X Pebble Fuel Qualification Methodology provides the data, the parameters, for the models.

And the last document defines the dispersion factors that we used to calculate the final dose of the system.

CHAIR KIRCHNER: Milan?

MR. HANUS: Uh-hum?

CHAIR KIRCHNER: Would you pull your microphone closer to you? You're soft-spoken.

MR. HANUS: Yes. I will hold it like this.

CHAIR KIRCHNER: Okay. Perfect.

MR. HANUS: Sorry about that, yes.

So, X-energy looked at and model the mechanistic source terms. It's risk-informed, performance-based, and we had the guidances in Regulatory Guidance SECY-93-092, in which we justified the approach by attempting to model the deterministic generation of the source terms in such detail using sufficient data and adequate events.

The systems are different from the usual systems which are based on severe core damage and accidents. They are event-specific, determined mechanistically using models of the fission product generation and transport and account for the inherent and passive design features of the reactor design and all product release barriers that constitute the functional containment.

Here, on the left, you can see the fuel element that is used in Xe-100, the pebbles with the TRISO particles within them. The container itself, the layers of the TRISO particles, the matrix of the pebbles from the first radionuclide release barriers. Out of these barriers we have the helium pressure boundary, which forms another level, another functional containment layer.

And even in the case of the break in the pressure boundary, if the helium tries to escape to the reactor building, which technically forms another release barrier for the radionuclides, but we looked at it, the reactor building in the safety calculations, as we have enough safety margin on the first barriers actually for the TRISO fuel, you know, the fission product capabilities.

So the fuel is represented by this sphere, and it shows the different TRISO layers, as well as the mechanisms by which the radionuclides can potentially escape or get past those layers.

So the fission products are generated by fission of the -- but also to the fission of the heavy metal contamination in the pyro carbon layers in the matrix. They can potentially diffuse out of the pebbles under high temperatures and get released to the core with the helium that, you know, is flowing around the pebbles, and get transported --

Another mechanistic source term, the model and the events that can happen in the fission boundary regarding the fission product transport. They go to the fission boundary surfaces. They lift off by the helium from those surfaces, actually, the helium steam. And also, the postulation and attachment or absorption of the helium plates to the dust and transport to the fission boundary.

As I mentioned previously, we do not credit the reactor building. So here, I'll not speak about that reactor building in this presentation and sort of looking for the --

MEMBER MARTIN: Milan?

MR. HANUS: Mm-hmm?

MEMBER MARTIN: At our Subcommittee meeting, the staff noted the lack of a PIRT, but, you know, to do mechanistic source term, you've obviously identified a lot of the PIRT. You know, there's kind of a formality involving the application of Reg Guide 1.203 to have that exercise where you bring in the experts to determine what's important, and then, of course, downstream it usually feeds the design of these codes.

So I'm certainly going to give you credit because you can't do a mechanistic source term without some insight onto the phenomena, but at the same time, do you have a plan now in place to kind of complete that formality of the PIRT document.

MR. HANUS: Yes. So, we already went through one iteration of the PIRT process.

MEMBER MARTIN: Okay.

MR. HANUS: So you have a table for phenomena identification and ranking. And we are planning to revise it, as per the suggestions of the Committee as well. You know, some of the phenomena might be assessed as important, especially those related to the fuel particle -- the particle barrier operations. But if you have that --

MEMBER MARTIN: So it's a process you started already?

MR. HANUS: Yes, yes.

MEMBER MARTIN: And, certainly, by the time we get to the operating license activities, we'll be seeing that document?

MR. HANUS: Yes. And that document is also used -- I will just focus to this site. We, yes, will continue the process of validation and verification of the code that implements these methods. And that validation, the case is selected for the validation now based on the PIRT. So, you know, the specific phenomena.

MEMBER MARTIN: Okay. Thank you.

MR. THOMAS: Matt Thomas, Licensing Manager at X-energy.

So the PIRT that we're referring to is the one that's included as part of the TSAM Topical, and that's where this will be documented at.

MEMBER MARTIN: Okay. Okay.

MR. THOMAS: Is that right, Milan?

MR. HANUS: Mm-hmm. Yes, yes.

MEMBER PETTI: Milan, just a question. And I can't remember from when we had the Subcommittee. Do you account for vessel breathing as a barrier? Do you know what I mean by "vessel breathing"?

MR. HANUS: Vessel bleeding (sic) --

MEMBER PETTI: Vessel breathing. You know, when you have the break, the helium goes out; the temperatures go up. Then, eventually, the temperatures will turn around and you'll pull gas back into --

MR. HANUS: Oh.

MEMBER PETTI: -- the reactor. There's no --

MR. HANUS: Air exchange?

MEMBER PETTI: Air exchange, and you call it -- "vessel breathing" is the short term vernacular of the gas reactor we're talking about.

Is that part of -- if the model says that, you take that -- hydraulically?

MR. HANUS: No. Yes, we don't do it either way.

MEMBER PETTI: Okay.

MEMBER MARTIN: Well, that might just fall out of the codes that you're using, right? I mean, if it depressurized, you know, there's a momentum, terms that going to have that vessel or the system below the pressure of whatever you have modeled outside. And that, it should suck in, just kind of inherent with the governing equations and standard constituents --

MR. HANUS: Yes, you know, that's a question for --

(Simultaneous speaking.)

MR. HANUS: In terms of the mechanistic data, the XSTERM models, they get the flow rates from outside, from performance operations. Those operations are taking this into account and ensure the task (audio interference).

MR. NIGH: Yes, this is Drew Nigh, Manager of Risk-Informed Safety Analysis. I can speak to that.

Dave, yes, we do take credit for, I guess take credit for it, and we do account for vessel breathing as part of the mechanistic source term calculations. So we reduce the source term -- well, we quantify the source term that escapes from fuel pebbles, and then we only release a fraction of that source term, based on what percentage is released or what portion is released while there's a driving force, like pressurized helium, to carry it out of the vessel. And then, afterwards, we do release a little bit more, based on continued heat-up of the helium and air in the vessel.

MEMBER PETTI: Okay.

MEMBER MARTIN: For points driven in a later term and --

MEMBER PETTI: Yes, thanks.

MR. HANUS: All right. So thanks. Thank you for saying that.

And now, I'll get into the overall picture, a summary of the mechanistic system models that are part of the MST approach of X-energy.

Those models are detailed in the Topical Report in appendices A through G. And the first, FPM, the Fuel Performance Model. The second, THM, Thermodynamics Model. SOLM, the time-dependent radionuclide release and diffusion. And GASM is the steady-state gaseous fission product release and transport. And DUSTM is the Dust Production Model. HPBM models the helium fission boundary. CORRM is the corrosion model that we can use for the moisture and gas calculations.

Other models and methodology are documented in the code, as well as the case statements, but they are not (indiscernible due to accent) the mechanistic source term methodology (indiscernible due to accent) that are mentioned in the introductory section of the Topical Report.

And, basically, this simulates the reactor power operation, the transient, and orchestrates the other modules to provide a source term picture in the fully indicated calculation. These are used mainly to establish the basis for the transient calculations by generating the (indiscernible due to accent) in the plant. And it's used, also, as a basis for the DTM (phonetic) calculations by the feedback model, but they are outside the scope of this Topical Report.

This version and those models are based on the Topical Report that we included previously. That was the previous version and dose calculation methodology, which defines the appropriate dose conversion factors combined with the plant operations.

In this table, the (indiscernible due to accent), I included the different codes. There are many more (indiscernible due to accent) know about, but they (indiscernible due to accent) particle bonds of the system, generation, propagation, and transport. Our approach is to run coherent code and coherent methodology that contains all the models, and therefore, there are a couple of ways we can easily modify and adjust these models, as a result of being in contact with the authors of the codes that might not be available anymore.

MEMBER MARTIN: Milan, so one of the points you made in the Topical Report is that you're doing mechanistic source term for each licensing basis event. Now, the events will be characterized by the phenomena, of course, associated and there will be different phenomena and they'll be weighted different.

I'm going to kind of lead the witness here a little bit. I feel like that you're not going to be turning anything off with an XSTERM, right, as far as phenomena is concerned to capture it? You're really just using the thermal hydraulic boundary conditions from, say, the Flownex or the GOTHIC, and that mass flow rates and such are really what's driving the transport?

MR. HANUS: Yes, to --

MEMBER MARTIN: But it's XSTERM is the same XSTERM in every case? There's no tweaking of phenomena, phenomena models, constituent packages?

MR. HANUS: No, the code is the same. The methodology is the same, and the selection of the options in the code is the same. V&V changed a bit the options, for example, for the validation, which is a different -- you know, it's not Xe-100. So, that's why the scope of the code is bigger, is larger than is presented here with the same model. But probably the phenomena that are patented for that, defined by the code, use the same code.

MEMBER MARTIN: It does kind of create a V&V challenge. I mean, it's a classic challenge of doing the V&V for the separate effects, as well as the integral. And maybe you're going to be talking about this here in a few slides, about, you know, the approach to V&V where you do target separate effects, and then, also, have some integral tests that can verify or validate the relative contributions of the different phenomena.

MEMBER HALNON: This is Greg.

Yes, that kind of asked my question. Maybe we'll see it in a few minutes. But I'm not a code guy, but I'm an operator. So, when I look at a lot of procedures and I look at pieces being put together, I get concerned about the bounding -- the assumptions for each procedure and relative to the applicability of that to the final product, whether or not they're all in sync and applicable.

So, when I see all these codes, it makes me wonder if all the input assumptions and the assumptions that the code uses to say these are the boundary conditions that I'm working on -- how do you fit all that together and make sure that everything is copacetic or in sync, so that your final product doesn't have some inappropriability [sic] because there was some bounding assumption for one code that doesn't get met down the path?

I don't know if I asked that question -- I asked it in an operator way, trying to mix it? But do you see what I'm trying to --

MEMBER MARTIN: Sure, sure. It's a similar question. I mean, there is just XSTERM, right? I mean, obviously, this slide has codes implementing similar capability. So those codes are really -- I mean, I don't know if you can do a code-to-code comparison as part of some V&V exercise. Right?

MR. HANUS: Yes. Yes, we do.

MEMBER MARTIN: That certainly gets to your question a lot when you're trying to --

MEMBER HALNON: Yes, but I need you to translate.

MEMBER MARTIN: It makes sense of all the individual models and how those two codes could relate to each other. That is its own challenge. And, of course, we can't really review that in this setting.

MEMBER HALNON: No, no. But at the end, if things all fit together, that's great. And if they hand off appropriately, they're handing off, also, their input assumptions as part of that for the codes. I want to make sure that there's not something being invalidated downstream, based on the fact that you didn't put assumptions for something downstream that's different.

MEMBER MARTIN: So I'm going to answer your question. So XSTERM is basically going to have all this capability. There will be, say, lower-scale phenomena that is happening, of course, beginning in the core. And it's going to be kind of feeding in the same way that you might feed these other codes, you know, if you had stacked them together, a couple of them together. So it's all being taken care of within

XSTERM term. So there really is no human touch involved in packaging all these different phenomenon into one package.

So, does that help?

MEMBER HALNON: Yes.

(Laughter.)

MR. HANUS: I don't know if that answered the question. The question, the fundamental question is, you know, it is a difficult question because each of those models has its own uncertainties within it, which can be obtained from the original authors of the models, and we try our best estimate the different answers and to quantify these answers as well.

And the combination of the uncertainties, they can stick up, obviously. What I can say is that, in the decision of making the code parameters, the parameters for the code, we generally adopt a conservative approach. When there is an uncertainty, we use what is conservative. (Unintelligible.) It's like more and more conservative, eventually.

MEMBER HALNON: Okay. So you've biased everything to the conservative side to make sure that the end product is also conservative?

MR. HANUS: Yes.

MEMBER MARTIN: You biased it within the

code itself or as inputs to the code? Or both?

MR. HANUS: It's both. I would say it's both, but -- well, (indiscernible due to accent) the code balances calculations and if there's a choice between using two different calculations, we use the more conservative calculation.

MEMBER MARTIN: Okay. So, then we have within XSTERM a way to do best estimate as well as, say, evaluation model type also?

MR. HANUS: Yes, yes. So the code has different options. For the purposes of the safety analysis, we used the most conservative ones. For the purpose of scoping and design, we use the --

MEMBER MARTIN: So, like when you present your V&V, I mean, would you turn on -- would you run XSTERM twice, once with kind of the conservative EM approach, and then, one with a more best estimate selection?

MR. HANUS: We use the more conservative assumption. And, you know, we can do both. The calculator now (indiscernible due to accent) is focused on the safety analysis, so we use the more conservative pathway.

MEMBER MARTIN: Well, I might suggest, again, going down the road -- this is just the beginning -- that when you present that information, since you have that capability in the code to select, there be more best estimate models; that when you present your V&V, you run it twice. And so, you know, for your external reviewers, they can very easily see those deltas, you know, between the data that you might have and the best estimate models. And when you put it in sequence, to have the more conservative models, do you know immediately where those conservatives are and the effect of them?

MR. HANUS: Mm-hmm.

MEMBER HALNON: So it's very informative to do that twice, and you have that capability.

MR. HANUS: Yes, and thank you. Thank you for this suggestion. It sounds --

(Simultaneous speaking.)

MEMBER BIER: One other question. This is Vicki Bier. Following up on Greg's point, or I think Greg's point, about that you may be conglomerating different models or submodels with slightly different assumptions, and whatever, this is kind of abstract. And my point may not even apply to what you're doing. But is it possible that what seems to be conservative in one submodel may then turn out not to be conservative in another? And you can have, you know, conservatism throughout that ends up being physically unrealistic or impossible. Or, you know, have you thought about that? Have you encountered that in what you're doing?

MR. HANUS: Yeah, I would say yes. We encountered that. You know, there is an example (indiscernible due to accent) in some DTM calculations that, because the wall thickness of the steam generator tubes, the wall base, the less conservative -- or the more important variation -- the less thick the tube is, the more (indiscernible due to accent) out of the tubes. But it has the opposite effect on the (indiscernible due to accent).

That's why we need to study the source term for each event and take into account for the final --

MEMBER MARTIN: Well, certainly in that particular example, you'll think about a case where you look at how rapidly the temperature of the tubes will change. Right? There's oftentimes about 100 F, or whatever, in it. And clearly, if you had a thicker -- if you assumed a conservative from a heat transfer standpoint, that would slow it down. If you used, of course, a thin one, you know, or thinner than realistic, it would be too conservative. So you really would want a best estimate in that particular case, but it would be counter to maybe other scenarios.

So that kind of gets back to the question of event-specific -- not only event-specific, but figures of merit-specific. You know, I think with a lot of these advanced reactors, we're always concerned with the fuel, but I think we're also concerned with every other thing that could possibly break, including generator tubes are probably pretty close to the top of that list.

And so, I think you might find that staff or a body like ours will be very sensitive to those kind of assumptions. Because, to Vicki's point, on one setting, it's conservative.

MR. HANUS: Yes.

MEMBER MARTIN: And at another setting, it's not.

MR. HANUS: Yes.

MEMBER MARTIN: You know, it's not just we're looking at fuel temperature. We'll be looking -- you know, you've really got to look at anything that is certainly a pressure boundary barrier or a safety system, you know, in those particular cases. So we're sensitive to that. But, good question.

MR. HANUS: Okay. So now, I'll talk about the code itself, which the code is the foundation of the models. So it is part of the whole safety analysis evaluation model which is planned in the TSAM report. And we developed it under our qualifications program with the goal to (indiscernible due to accent), for which you always need to perform extensive validation and EQ. And (indiscernible due to accent) is being performed after we staged the validation of phases, depending on the (indiscernible due to accent) are covered by each phase.

And, as mentioned previously, we used the PIRT to determine the events to be evaluated in each of those phases. We try to get some specific effect test as well, which is difficult to get that. Validation is also data for that. But it's all planned in the validation plans we are using.

We also performed the verification of the code by line-by-line comparison with the defenses. And we saw adequate solutions which (indiscernible due to accent) change the code, basically. So, that's the one slide on the validation. Again, the validation, the validation process is ongoing. We will present the Topical Report on the code itself (indiscernible due to accent) when we are presenting the methodology itself.

MR. THOMAS: Hold on. Just one point here I wanted to make. So again, Matt Thomas, X-energy Licensing Manager.

I appreciate the discussion, the suggestions, and whatnot, from the members. And while Milan is talking much about the code itself and V&V of the code itself, the Topical Report that we have in front of the staff right now is for the MST theory only. So, you know, maybe one day these questions and suggestions will be relevant to, like, XSTERM topical code -- or an XSTERM code topical. But for the topic at hand right now, we're just really focused on that theory.

Thank you.

MEMBER MARTIN: Of course. And our comments -- obviously, it's very, very early and we're telling you what we're sensitive to. So that, when you get down to those things, you go, you know, I remember that meeting. So this is for your benefit, too. Okay?

I mean, I'm a little preachy. So I recognize that. But at the same time we're hoping that you're listening and we're helping you prepare for the next time.

MR. THOMAS: Great. Thank you.

MR. HANUS: Yes, and I appreciate these comments as well, this guidance. I appreciate this time and your guidance, in fact, as well. So the earlier, the better. Thank you.

MEMBER PALMTAG: This is Scott Palmtag. I had a comment on your previous slide.

MR. HANUS: Oh, yes.

MEMBER PALMTAG: I have some questions on NQA-1 qualifications as the goal. So it's not NQA-1 right now?

MR. HANUS: It is not, because we don't -- we do not have the fully validated code. It is developed using NQA. We suggest we need a recommendation. That is needed. We follow the rules. But it's not quite there yet because we did not finish the whole thing yet. So we do not have the full set of recommendations in this data that is finished.

MEMBER PALMTAG: Because NQA-1 isn't something you do at the end.

MR. HANUS: No.

MEMBER PALMTAG: It's not something you develop code and then you -- I mean, it's a process on which you develop the code.

MR. HANUS: Yes.

MEMBER PALMTAG: You actually don't have to have validation and verification done for NQA-1 because NQA-1 is a process on how to get there. So you are following the NQA procedures?

MR. HANUS: Okay. Yes.

MEMBER PALMTAG: Okay.

MR. HANUS: Yes.

MEMBER PALMTAG: So it's not something you're just at the very end?

MR. HANUS: No, no. It's not that. Regarding the procedures, there's the NQA-1 -- we recommend based on that. But, as I said, it's a work-in-progress.

MEMBER PALMTAG: You might want to check because it should be NQA-1 as you develop it, not --

MR. HANUS: I would say it's --

MEMBER PALMTAG: It's not something you do at the end.

MEMBER MARTIN: At the places I've been, we have not called it an NQA-1 code until we completed it all. But, yes, we apply the quality program.

MEMBER PALMTAG: But you should have the quality program under the procedures.

MEMBER MARTIN: Well, so you might call NQA-1 as an open item, so that you can do your safety analysis and call it "safety" with an open item.

I assume you have a whole open item. It's all in the QA space.

CHAIR KIRCHNER: Yes, the other thing is it's qualification under NQA-1 approvals.

MEMBER PALMTAG: So that would be NQA-1, not --

MEMBER MARTIN: I would say, some people say it's terminology. As long as, like I say, if you have an open item and you're tracking, I guess you could call it that, but I'm kind of with Milan, that I would just say it's not quite there yet. It's not done.

MEMBER PALMTAG: I would say NQA-1 is a process in which you develop --

MEMBER MARTIN: Yes, if you say that in front of QA people, they figure you're done. And it's very dangerous.

MEMBER PALMTAG: You might want to just check it and check your terminology on that, whether you're NQA-1 -- so you don't have to be done to do NQA-1 qualification, but you should be doing your development.

The other piece of the validation or verification and validation, it seems like you're kind of late in the process for doing this, because you're doing design calculations. Right? You're doing design calculations. You're calculating your release rates. But yet, your codes haven't been verified and validated. So the timing seems strange to me.

I mean, I would think, when you're starting to do these source term calculations, these design term calculations, design calculations, you will want your verification and validation to be done, so you know that your results are going to be good.

The danger, of course, is you design the system, and then you do your verification and validation and you find out, oh, no, your source term is going to be much higher. And then there's sort of a -- there's a lot of political thing to kind of make your answers match. It just seems like the V&V should be done before you do the design calculations.

MR. HANUS: Yes, so the V&V has been ongoing since before at X-energy, but the code capabilities that we developed have been added as part of the development process. So, for example, the PIRT table identified some of the things that the code, the methodology was not able to capture originally. So that was added. And that added a few additional requirements for validation.

And so, the process is ongoing. The code is not fully validated. It's verified to a big extent. Then we added the features that have not been verified yet.

MEMBER PALMTAG: But it sounds like you have enough V&V done to have confidence in your results?

MR. HANUS: Yes.

MEMBER PALMTAG: You just haven't quite, you know --

MR. HANUS: Yes, and, you know, my purposes at presentations at the NRC in 2019 about V&V. I have identified now that that presentation is in the design already. But I'm sure even before I joined X-energy.

So the code has been verified/validated and the design has changed, and the plan, to continue the requirements which, again --

MEMBER PALMTAG: Oh, okay, I understand. I don't want to cut you off, but --

MR. HANUS: Yes. So that's how I tell you that.

MEMBER PALMTAG: Okay. Thank you.

MEMBER SUNSERI: This is Matt. Just two easy questions for the Regulatory Affairs Director.

One is, do you have a quality assurance program that follows NQA-1?

MR. HANUS: Yes.

MEMBER SUNSERI: Okay. And are you using that program in the validation of this code?

MR. HANUS: Yes.

MEMBER SUNSERI: Okay. I wanted those two answers clearly stated --

MR. HANUS: Yes.

MEMBER SUNSERI: -- so at least I know where it is. Thank you.

MEMBER PALMTAG: You sound like you do know.

MEMBER MARTIN: I don't want to belabor it, but it sounds like you do have NQA-1 answers. Okay.

MEMBER SUNSERI: I'm sympathetic, Bob. Having been in your shoes, sometimes it's the messaging in different audiences, you know. Like I said, you're saying it the way I used to say it. But other people --

MEMBER MARTIN: Matt and I are both I think are on the same page.

MEMBER SUNSERI: Exactly.

MEMBER MARTIN: You either have a program that's approved or you don't.

MR. HANUS: Right, right.

MEMBER SUNSERI: Usually, the QA topicals are the first thing that's like approved. Right? And we don't see that typically; that's all done.

MR. HANUS: So with NQA-1 code, (indiscernible due to accent) NQA-1. But the main topic here is not the code itself, actually. So that's the methodology and the models, but we obviously do describe the source term. And at least for the purpose of models, as I mentioned previously, form a system, an integrated system, that there are second iterations in between each other, each of those models. It's (indiscernible due to accent) schematically, but I will go into (indiscernible due to accent) and kind zoom in on this diagram.

Here, I just want to mention that we do have a small amount of input from (indiscernible due to accent) models or codes, (indiscernible due to accent) for the neutronics and Flownex for the (indiscernible due to accent) and the temperatures. So these are the external codes and the discussion on those, again, is using dose conversion factors that have been developed separately. They have been represented in a separate Topical Report. And, basically, it's the input from the source term, the source term release, and converted into a dose.

So, the thermodynamics model is the basis of most of the calculations, because it provides the temperatures in Flownex and provides them to the other source system models. It is based on the geometry of the pebble -- or, I should say, on the particle of the pebble in the reactor.

And we also include a model for the (indiscernible due to accent) compact for the validation purposes, so that you can simulate them, the AGR experiments themselves.

The basic thermal model, as expected, are the heat transfer phenomena, the conduction, convection, radiation, and the heat sources from, let's say, decay heat and the fission and gamma sources. And by using the traditional, let's say, (indiscernible due to accent) for the pebble bed convection and the (indiscernible due to accent) for the conductive heat transfer. We raised the temperatures in the old system going from the particle all the way to the reactor nodes. In case we simulate only the pebble, we can use the pebble temperatures to be shown by assuming the heat conduction, the decay heat conduction to the pebble using the temperatures above (indiscernible due to accent).

Those calculations are (indiscernible due to accent) from the heat conduction. It depends on the temperature. We use the (indiscernible due to accent) calculations, presented in terms of gas,(indiscernible due to accent) into (indiscernible due to accent) that are used within the model.

And as I mentioned previously, we input for the THM input data from the VSOP and Flownex. From the VSOP input, we perform a transformation, I think, of the (indiscernible due to accent), using (indiscernible due to accent). We choose to (indiscernible due to accent) nodes to each other zone (indiscernible due to accent) to simplify the temperature calculations. So we first perform (indiscernible due to accent) in the VSOP to the source term, the source term model, and then perform the calculations on the grid.

The method that is employed is (indiscernible due to accent) simple, the (indiscernible due to accent) method, and we use it for the (indiscernible due to accent) calculations and to match towards the steady state, just to be the basis for the transient calculations.

The Particle Failure Probability Model --

yes?

MEMBER PETTI: Just a question on the pebble trajectories.

MR. HANUS: Mm-hmm.

MEMBER PETTI: How many trajectories do you run to get the source term? You know, a pebble can come in; it can come into any of however many radial nodes you've developed. Do you do some bounding trajectories or do you try to do a map probabilistically? How do you do that? How does that fit into the model?

MR. HANUS: Mm-hmm. Yes. So we look probabilistically. I will not mention the actual numbers. This is proprietary information, how many runs we do. But the method distributes the pebble towards the channel. The pebble goes through the channel. Then it's put through a random channel again, a different one or potentially the same even. And once again, until it emulates the target burn-up and generate (indiscernible due to accent) the pebble, the time that it stays in the core, and then it's discharged.

We do this many times, many times over, to get statistically significant information and collect the pebble information, and inventory, the burn-up effluents and all this, as the pebble moves through the system.

And that forms a library that is used in (indiscernible due to accent) at the beginning. And then we use that as the basis for other subsequent calculations. So in the subsequent calculations, in each transient operation, we can look at that pebble at a given location in the core at a given path. Because the pebbles are going on so many paths through the core. And by this approach, we can retain the full history of the pebble, as opposed to using the RESO (phonetic) data. The RESO data has that information as well, but it averages the pebbles at each path. We would not get the information, the different information about the history of a given pebble at the given path that we need for the inventory.

MEMBER PETTI: I just wonder about how you validate that. Well, it's also very complicated. And I know you've got a lot of margin here. So it might be worth just looking at some bounding things, like worst-case trajectory, average trajectory, least harsh trajectory sort of thing, and see how big a difference it really makes. Because that's a lot of information that you --

MR. HANUS: It is.

MEMBER PETTI: And again, helpful probably in the design sense, but I do worry about it in validation sets. That could be a heavy lift.

MR. HANUS: I agree. Thank you for this comment, because, you know, currently, the code is more capable than it probably needs to be, good code capable, of course, pending the validation. But the capabilities are there. So we can actually quantify all the defense, how much we actually are needing, the detail that we need. And these are our data points that --

MEMBER PETTI: Yeah, I mean, if we were talking UO2, and historically, this was a huge area of questioning by people because UO2 had hard limits on burnup, temperature, and the like. So knowing trajectories is really important. UCO doesn't have those limits. You know, it's a much bigger design window. And so, again, more capability than necessarily needed for the UCO than were it for the UO2.

But, you know, there used to be questions about pebbles sticking in the core, you know, the old German designs. And what if it goes above the burnup because of that? Those are not really relevant today and to your design, from what I can tell.

MR. HANUS: Okay. Thanks.

CHAIR KIRCHNER: How many cycles does a pebble make before it's removed? And what's the burnup target that you're looking to?

MR. HANUS: I don't want to disclose something that might be proprietary. Anything on the code knows that the burn-up is public information. There's a number of passes. It's six on average. As I mentioned, as the pebbles go through different channels, it may be less. We can imagine the pebble going through hottest channel, you know, neutronically, all the time. But it can be less. But that would be the bounding pebble. But, yeah --

CHAIR KIRCHNER: From a design standpoint, when you use this, how many passes can you make, assuming that the pebble goes down the hot -- the equivalent of what would be a hot channel? It gets the most burnup. It's also running at the highest temperature.

MEMBER PETTI: Well, I mean, you can do the math. It's not that difficult. Six passes always in the hot channel. You can calculate that pretty easily. It's pretty small, a small number.

So I'll just say, my guess is that the

burnup is, quote, high.

CHAIR KIRCHNER: High?

MEMBER PETTI: Typical of pebble beds, they get excellent fuel utilization because of it.

MR. HANUS: Okay. So the Particle Failure Probability Model, this model is designed to provide the information about the detection of particles that could undergo failure.

Another model, (indiscernible due to accent) means that the silicon-carbide layer fails, the most important layer of the containment, so the (indiscernible due to accent) abilities. And we do models that show effects of phenomena due to which the particle can fail, which are listed here. And (indiscernible due to accent) phenomena (indiscernible due to accent). We still model them, we do actually see a low particle failures due to some of these, like the kernel migration, for example, the Amoeba.

We still include these models because there -- you know, partially, because we also want to validate other models using old UO2 designs which are certainly well-documented. And for these, we want to match the UO2 performance, even though it's not part of the UCO. But, for example, the (indiscernible due to accent) through the matrix, through the speed of the pebble, is what you can, if you can validate why it is you get compact particles debris.

And so, I don't know if I'm going into details much here, because we model the manufacturing effects, which are, you know, non-operating conditions that are defining particle failure effects, the other limited ones.

MEMBER MARTIN: Yes, go ahead, Scott.

MEMBER PALMTAG: I just had a question about these failures. I know some of this may be proprietary. So I'll keep it at a high level.

But you are going to have some pressure vessel failure rate and some manufacturing defects in the system. How well do you know these? And is your fuel pellet very different from operating experience? Is it close to it? Is this going to be something that you're going to calculate? How well do you think you know these failure rates? How are you going to determine the failure -- how do you know if your failure rates are -- have confidence in your failure rates?

MR. HANUS: Basically, the question of validating those models.

MEMBER PALMTAG: Okay. So you have a fuel pellet. Is your fuel pellet very different from what's been used before? Or is it similar or? There's measured values out there. How applicable are they to your fuel?

MR. HANUS: It is similar. So I would have to ask the fuels lead which would be James.

MEMBER PALMTAG: Okay.

MR. HANUS: This is his end. He would probably be able to answer the question as to how different we are from the other --

MEMBER PALMTAG: Okay. Yes, my question is, how different are -- how much are you going to rely on the measured data that's out there and how much you're going to rely on your calculational capabilities?

MR. TOMPKINS: Hi. James Tompkins, X-energy ARDP VP, Nuclear Fuel Lead.

Yes, we are performing a qualification test at INL. And as part of that, we've fabricated test fuel. So we will have some data to validate fabrication failures, and then, in-tile performance indications from -- it's a test that's fairly similar to AGR, to lead out with short-lived fission product gas monitoring.

So we will have some data that we can use to point to demonstrate how similar we are in performance to AGR and other data that we plan to use for validation.

MEMBER PALMTAG: I guess my question, I'm looking for some confidence that you know these values well. I mean, you're doing the testing in Idaho. That's good. But these failure rates are going to be relatively small. So, if you only test a few particles, how do you estimate a larger, you know, PPM-type?

MR. TOMPKINS: We're testing over several hundred thousand particles. So I guess it depends on what you consider statistically relevant. Right?

MEMBER PALMTAG: No, that's good. That's what I wanted to hear. So you are testing a large amount of particles. That's going to give you some confidence in these failure rates. Okay.

All right. Thank you.

MEMBER PETTI: And, Scott, they should note the manufacturing stuff is going to vary batch by batch.

MEMBER PALMTAG: Manufactured, but I was thinking more of the question of failures.

MEMBER MARTIN: Yes, they won't get any pressure vessel failure. It's designed not to fail.

MEMBER PALMTAG: There haven't been in the past, right?

MEMBER PETTI: No, it is the most often, but incredibly rarely found failure records. That's because you can analyze it, that we know it.

MEMBER PALMTAG: So there's not going to be any --

MEMBER PETTI: The silicon-carbide should be in compression. So it shouldn't fail. That's the, like, No. 1 design rule for TRISO fuel, is that you make sure that design -- that you don't push it so that you go into tension. If you go into tension, you will get failure.

MEMBER PALMTAG: Okay. So you shouldn't expect any pressure vessel failures?

MEMBER PETTI: It would be like 10 to the minus 12. It would be a number so low that you can't validate.

CHAIR KIRCHNER: No, that's the real problem.

MEMBER PETTI: The real problem is that a lot of these failure mechanisms, that they are so low --

CHAIR KIRCHNER: So low.

MEMBER PETTI: -- that it is very difficult --

MEMBER PALMTAG: Right. That was my -- I guess that was my question.

MEMBER PETTI: So that's why it's so low. You'll see. But the defects, they're going to move around batch by batch, block by block.

MEMBER PALMTAG: I understand that, yes.

MEMBER PETTI: But there will be a spec, and then there will probably be in the safety analysis a margin of that spec.

MEMBER PALMTAG: Yes. No, I understand that.

MEMBER PETTI: Yes.

CHAIR KIRCHNER: So are you, in your testing at Idaho, are you going to intentionally drive to failure, so you can try and see some of these effects? Otherwise, I don't think you're going to be able to do any validation. Right?

MR. TOMPKINS: Yes. James --

CHAIR KIRCHNER: Individual mechanisms, Jim?

MR. TOMPKINS: Yes. So we have -- it's a full, I mean, irradiation test campaign. We're essentially performing the irradiation to demonstrate in-path performance, and then, as soon as -- this is kind of the condition of the fuel, and then, once we get it out, we will do post-irradiation heating, oxidation testing, and, you know, attempt to draw bounds around the design and safety basis numbers.

So, yeah, the idea would be less to drive to failure and more to demonstrate performance under the operating envelope of, you know, selected LBEs, then, specifically to see how difficult it is to fail the fuel.

MEMBER PETTI: So, James, I tend to think of it as a proof test. Because what's been made in the past is a compact. This is a pebble. It's different. How you make it is different. The forces that are imparted potentially to the particles are different. So, you've got to irradiate it to convince yourself that you haven't done something, introduced a new mechanism or something in that, you know, in this new fuel form. No, it's just like German fuel. So, you know, it's not anticipated, but you have to go through that step.

CHAIR KIRCHNER: And I know testing is going to be of pebbles, not just loose particles.

MR. TOMPKINS: Yes, that's correct, 16 pebbles.

CHAIR KIRCHNER: Okay.

MEMBER PETTI: Sixteen? Wow.

MR. TOMPKINS: Well, we had to put them on a diet to put it an ATR, so they won't be full-scale, but close --

MEMBER PETTI: Aw, okay.

MR. TOMPKINS: -- close enough.

MEMBER PETTI: Yeah, the Germans had to do the same thing. These are big fuel elements for test reactors.

MR. TOMPKINS: Yeah. The Chinese HTR-PM or HTR-10 validated fuel as well. I think they had to reduce the diameter.

MEMBER PETTI: Pretty common.

MEMBER MARTIN: Some of my question is, this is really taken off of something Dave is going to have in our letter, or is put in our draft letter, related to the use of UO2, you know, for UCO fuel. Or maybe I put words in your mouth. I think that was unfair.

I guess my question is, in XSTERM, in back-to-back, in models that are able to say that the failure mechanisms, are they generic for the fuel form in this case or do you say, all right, well, I'm looking at UO2 data, so I'm going to run this code with a UO2 model? I'm asking your --

MR. HANUS: Yes, and is most generic. I

would have to really look into each model separately. I believe we would have some models that use the UO2 data because they still use UO. But --

MEMBER MARTIN: But okay. So the next obvious question was, what's the value of the UO2 if you used UO2-specific -- unless, of course, you are in some way planning to have UO2 pebbles. Or, I mean, no, you're not, of course. The failure rates are higher.

If the code itself is distinguishing through its constituent package a UO2 fuel form, but you're not planning to have UO2 fuel, what would be the value of including that in any validation package?

MR. HANUS: We use the UO2 calculations, specifically the UCO2, for the similar thing that the German -- the old German experiments with that. And it was done before we started this through qualification, as it was the only sphere of fuel that had the validation data.

But the AGR (phonetic) compacts, they are the UCO kernels, our kernels, but not our geometry. And the AGR irradiated pebbles, they are using the kernel, but they are not pebbles. And so, you know, when validating, when using the data validation, they focused on the heavy-weight transporter to the (indiscernible due to accent) to the pebble. And so, we had to validate, to some extent, the geometry effects. But we need to compare it with the results that were generated by --

(Simultaneous speaking.)

MEMBER MARTIN: And I'll put some words in your mouth again. So, interval test data is limited. Right?

MR. HANUS: Yes.

MEMBER MARTIN: Some of it is really old, where they used UO2. Right? And I do know that XSTERM is at least 10 years old, if not longer. I don't know if you've ever said that in our meetings.

MR. HANUS: Yeah, probably in 2016.

MEMBER MARTIN: Okay. So, since developed, it would have been actually ongoing.

MR. TOMPKINS: Yeah.

MEMBER MARTIN: I just remember the first paper I think I looked at was, like, a 2016 paper.

MR. HANUS: Yes, yes.

MEMBER MARTIN: It was probably line an ANS conference or something.

So part of your answer is this is a bit legacy because that's what you had back then.

MR. TOMPKINS: Right. Yes.

MEMBER MARTIN: So you started with that. As the data from AGR was coming out, okay, and you're pivoting. You brought in the UCO models. You may also have some needs related to just the limited data out there. So it allows you to do some, say, interval validation. I mean, it might not necessarily be directly applicable to Xe-100 down the line, but it covers the package as a whole. So there certainly is value in there.

But I'm trying to understand, it's really about the data is limited out there. The timeframe in which you started all this work and what was available at the time. So you've carried it on, even though, when it's all said and done, the code, as far as the NQA question, is applicable only to UCO? You're not going to make a claim that --

MR. HANUS: Yes. Yes.

MEMBER MARTIN: -- in some ways, it's safety-related for UO2. It will never happen. So what's the point?

MR. HANUS: Right, right. Yes. And that's also, you know, there are more validations we don't include. We include those only that are (indiscernible due to accent) data and which are needed. We could select (indiscernible due to accent) different correlations for something related just to UO2, but we just use one because it's not the main focus of the code.

(Simultaneous speaking.)

MEMBER MARTIN: So the one failure mode you'd be worried about would be if a user accidentally put, say, UO2 in the input file. You would hope they would always have the --

MR. HANUS: Yes, yes. Yes.

MEMBER MARTIN: So you'll get a different package.

MR. HANUS: No, that's right. Yes, that's very correct. We would in that case.

MEMBER PETTI: Let me just note that we are falling behind schedule, Mr. Chairman.

(Laughter.)

MEMBER PETTI: So let's try to pick up the pace.

MEMBER MARTIN: Okay. Just general advice. You're using the same presentation as you had at the SC. That, of course, is not necessary. Just for future reference, you can abbreviate that for full Committee. Because this is the danger of doing the same slide set. We rehash the --

MEMBER ROBERTS: Yes, this is Tom. I have one question. It might be for Dave. But I wanted to ask it while the applicant was still here.

If I understood your assessment, basically, all the phenomena listed here are designed out to UCO fuel, but there's a phenomena not listed here that is not designed to use UCO fuel and it's very difficult to model. And currently, the INL is working on how to model it.

So, as I understood what your testimony, it is that, basically, they're monitoring more phenomena, and what they're modeling is not a problem for UCO fuel and what they're not modeling tended -- do I have that right? And I'd be interested to get X-energy's perspective on that.

MEMBER PETTI: No, I think that's a fair assessment. And again, it's easily accounted for, like, pressure vessel failure. Yes, there will be fission gas pressure, but it's always at the bottom of the list in terms of what's important.

But, yes, all these -- the U.S. approach to fuel, particle fuel design, was always to design it away. You either change the particle design, you change the temperature run-up effluents. You limited it so that you didn't have -- it's like you cut the grass lower and lower and lower, and that was their theory. So there's nothing left.

And the failure that was observed is very difficult to model. But again, it occurs at about 10 to the minus 5. And so, that's really difficult to model. What it means is the DOE modeling focus has taken it out. As a challenge plot, it's so difficult to model.

MEMBER ROBERTS: I'm not aware of X-energy agreeing with that characterization that, with the testing of a large number of pebbles and a lot of particles coming up, it may be your long-term view is to refine this model to more closely resemble what it is you're actually producing? Is that right? Or is this the way you plan to go into the operating license?

MR. HANUS: Yes, that's generally right. Like we always look at the results that we will get from the qualification. You know, it's very nice. And, you know, we haven't made any decision yet on the models that showed this effect, for example. We might as well use just the facts that comes from the experiments that is beyond what we can pull out with the count for this elegant mechanistic model. We will need to first see the results and we will try to quantify the needs for this.

MEMBER ROBERTS: Okay. Thank you.

MR. HANUS: Let me continue quickly with the SOLM, the Fission Product Transport Model. It's based on basically the fission equation, the time-dependent fission equation. That's been between the production and removal of the radionuclides from the particle (indiscernible due to accent) and into the pebble graphite.

And we will have a set of radionuclides that have been determined previously to be (indiscernible due to accent) TGR systems. And the scope of that SOLM model is either single sphere or, again, for all core meshes. This goes back to the question of taking the pebble as use of the core. So, in that type of calculation, that's when a model is used to accumulate the other isotopes in the pebble as it moves towards the core. And the output of the SOLM model is (indiscernible due to accent) release over birth, basically the release ratios (indiscernible due to accent).

The model is based on the diffusion coefficients, dependent on time, through this (indiscernible due to accent) law. The diffusion coefficients are mostly taken from the (indiscernible due to accent) the IAEA (indiscernible due to accent) performed a study of the more recent papers and (indiscernible due to accent) determination of the diffusion coefficients of (indiscernible due to accent) energies from multiple different papers. They do not infer as much bias. So, we use these diffusion coefficients to close the model, basically.

MEMBER ROBERTS: So that document that I recall is -- you know, there's not data for every radionuclide. Right? I mean, they get the big ones. So how do you kind of fill in the gaps for all the other radionuclides that you're considering?

MR. HANUS: So we look at the different properties (indiscernible due to accent) there are similar properties. And then we use the same diffusion coefficient. So we use, you know, examples of the iodine and (indiscernible due to accent).

MEMBER ROBERTS: I mean, everybody has the same problem. Right? The data is limited in this particular case. Do you have a strategy to be conservative in this, you know, with this?

Again, I understand the challenge that you've had. I've dealt with it myself. But my goal wasn't to be necessarily conservative; just as accurate as possible, which, of course, introduces uncertainty, which I never got around to actually quantifying.

MR. HANUS: Yeah, we base the selection on the diffusion corrections on the properties of the atoms (indiscernible due to accent) selecting at higher -- you know, a higher diffusion coefficient, let's say, or lower, that needs to occur for conservatism.

It's hard to quantify what is conservative here. (Indiscernible due to accent) gets more dust abated and the dust includes all (indiscernible due to accent) in the pebble. In this case, you would want the juncture of chemical and physical properties.

MEMBER ROBERTS: Right, right.

(Simultaneous speaking.)

MEMBER PETTI: It's just a point in a subsequent report. Almost every applicant we see has a table that says, here's the fission product where we have data and it represents the following elements. You know, you're going to assume iodine behaves like noble gas. What are you going to assume about 2RM (phonetic)? You know, that mapping is pretty standard, so that everybody understands sort of the rules of the road at the very beginning, how you're going to fill that in.

It's not in the document; make a note of it. We'd love to have that table. You guys have it in your head and in your coat, I'm sure.

MR. HANUS: Yeah, mm-hmm.

MEMBER PETTI: It's just making it explicit.

MR. HANUS: Okay. Yeah, thanks.

CHAIR KIRCHNER: The table that you have on slide 20, which are the dominant actors and where do you have the most uncertainty? And how do you bound that?

MR. HANUS: At the moment, the cesium-137, the silver-110. In terms of uncertainty, (indiscernible due to accent) which has the most uncertainty in the data.

CHAIR KIRCHNER: So, with your current model, which are the dominant radionuclides in terms of the contribution to eventual source term?

MR. HANUS: Yeah. That is the cesium.

CHAIR KIRCHNER: The cesium.

MR. HANUS: The 137.

(Simultaneous speaking.)

MR. HANUS: Yes, so, (indiscernible due to accent) a solution (indiscernible due to accent). You can choose. But the solution of the equation start being solved eventually (indiscernible due to accent) methodology. Right?

And next we'll do -- or next model is the Gaseous Fission Product Transport Model, which is similar calculations -- this is similar output, again, (indiscernible due to accent) but for the gaseous radionuclides. Compared to the SOLM model, this is a (indiscernible due to accent) model. It's much simpler. It doesn't solve any (indiscernible due to accent) equations. So it's basically a solution (indiscernible due to accent). It was based on the (indiscernible due to accent) solution of the (indiscernible due to accent). It takes into account a (indiscernible due to accent) basically, (indiscernible due to accent) of areas, of capabilities of other types of areas.

But we use this model mainly to inform the SOLM model, to generic diffusion coefficients for the gases that -- the effective coefficients for the noble gases, which were not included in the defenses that we have available. So we basically use this model to calibrate the SOLM for the gaseous radionuclides.

Optionally, we can use the GASM model as well in the main calculations (indiscernible due to accent) for the noble gases with the fast or slow half-life, except for the few which are long-lived.

The Dust Production Model is based on the distribution of dust particle sizes, which comes from the previous AVR data that is available. And we modeled the pebble-pebble and pebble-reflector abrasion, the pebble abrasion (indiscernible due to accent), and the control rod abrasion as the controls in the shaft with operating period.

And the in-core dust production is proportional to a geometry-dependent dust production rate parameter, which is calibrated against the AVR data. So, it is too much dust is produced in AVR, scaled to our design and get that dust production parameter.

And the dust production in the fuel handling system is based on a dust generation rate per meter of the movement comes from the reactor model requirements, design requirements document.

(Indiscernible due to accent) for the RCS for how much dust about to be generated in the reactivity control system. And, all together, we have the dust production parameter that is important to the helium pressure boundary module to obtain the dust production distribution throughout the plant, through the helium pressure boundary, as a function of time, which is then used in the statistical operations.

MEMBER PETTI: Milan?

MR. HANUS: Mm-hmm?

MEMBER PETTI: Do you guys have access -- have you seen anything from the Chinese HTR-PM? Because everyone has always wondered. They've got them operating. Because, you know, there's a lot of controversy about how much dust you really get. And it's actual operating reactor. Have you guys seen anything from them that you'll be able to --

MR. HANUS: Yes. So we (indiscernible due to accent) some documents from the HTR-PM. Yeah, I haven't gone through the (indiscernible due to accent) looked into these. There was no information -- there was very little information from HTR-10.

(Simultaneous speaking.)

MR. HANUS: Yeah, there's no dust there, almost. So, yeah, it's (indiscernible due to accent) what we can get from the Chinese. I need to get some data (indiscernible due to accent).

MEMBER PETTI: Yes, if you could, I mean, certainly bringing operating data to the party here would be really valuable.

MEMBER MARTIN: Of course, you calculate the dust source term. So, during a depressurized loss of forced circulation, do you just assume 100 percent of that gets out? Or do you use some fraction of that?

MR. HANUS: Essentially. We calculate that depressurization. So we calculate the release of the dust, along with (indiscernible due to accent). Yeah, so we do calculate (indiscernible due to accent) everything out.

MEMBER MARTIN: Okay. So that would be very conservative.

MR. HANUS: Then, it only depends on the reactor without a vent. We are looking at -- in some cases, we do increase everything out and it's almost conservative. But we do have calculations that actually track the dust to the HPV.

MEMBER MARTIN: Okay. And so you have to make a separate transport model for the dust outside of the reactor or?

MR. HANUS: No. So that adds to the -- yeah --

(Simultaneous speaking.)

MEMBER MARTIN: And it's really the source term, but the overall plume itself --

MR. HANUS: Yeah.

MEMBER MARTIN: I think, as I recall, like with AVR data, I mean some assessment of dust, as I recall, it just said that the dust got all over the nooks and crannies. It was highly unlikely to really get a significant liftoff at a relatively -- some missed this, but, again, you never know until you know. But if you use 100 percent, it probably could be as much as five times or more, you know, a conservative in that particular case.

But that's what I wanted to hear. You're using a conservative assumption on dust. Okay.

MR. HANUS: Okay. The last barrier that we take into account in the reactor building is the Helium Pressure Boundary. It is also probably the most complicated model because it takes into account phenomena that can happen in the pressure boundary. And it's listed here. We model the migration of the radionuclides in the multiphase flow, taking into account actions, the mass exchanges between the dust phase and the radionuclide. We model the gas propagation through the system.

It's simplified into, essentially, a 1D pipe kind of geometry, although we take into account the multiple inputs. So, one component can get flow from multiple different components, not just from the upstream. There can be multiple (indiscernible due to accent) data for a given component.

The phenomena I'll skip for the sake of time. And, here, this slide shows a schematic of those phenomena in a given node or movement of the pressure boundaries. And as you can see, it takes into account the radionuclides, deposition, dust liftoff, absorption, and graphite de-sorption back into the helium. And, again, we calculate the standard method of putting the (indiscernible due to accent).

And the Corrosion Model at the end can be used for other (indiscernible due to accent) calculations. Basically, the increase of (indiscernible due to accent) due to oxidation. And this one is based on, also, the General Atomics fuel manual, actually, for the calculation (indiscernible due to accent) models for MHGTR and based on (indiscernible due to accent).

All right. So that's the end. Again, that is the final slide. It shows the connections of all those models together. And we are going to simulate the source term transport as a whole, mechanistically as much as possible. Of course, there are many assumptions involved which we have (indiscernible due to accent) to be on the conservative side. Optionally, we have some design models as well that you can use for the scoping calculation and for the safety. We are biased towards the conservative side.

MEMBER HARRINGTON: This is Craig Harrington. Just as a practical matter, this flowchart, basically, on the screen, when you execute this code, is it one -- I mean, do you execute it as in its entirety all at once? Or are each of these major modeling elements executed individually and there's manual handoffs between the pieces? Do you do both? Can you speak to that?

MR. HANUS: It depends on the event and the part of the operation. And the code execution, again, is to get more detail in the XSTERM Topical Report. It's modeled in the methodology. But in the (indiscernible due to accent) methodology we describe how the source term methodology is used to do things for certain different events.

For example, for the steady state and the helium pressure boundary, we use the core integrated model to calculate everything from release to transport to the fission boundary.

As part of the Flownex criteria, from the previous presentation, that technology involves calculation of individual pebbles under those specific conditions, temperature and burnup and extreme conditions, in which case we will go to HPBM. The DUSTM and all these models are inactive. They are not used because we are looking at one single pebble, given conditions. So we only execute the THM, FPM, SOLM.

It's the same code practically, you know. The (indiscernible due to accent) code is the same code. It just uses different paths, the old code. And here, the (indiscernible due to accent) are using all the different (indiscernible due to accent) separate models with all them.

MEMBER MARTIN: So it's an integrated execution, but may or may not use all pieces at any given --

MR. HANUS: For practical reasons. But that's all defined in the safety analysis methodology, how we use the XSTERM code or these models in conjunction with the safety analysis. So, each safety analysis for a given event is using this methodology. And it differs. It differs by event and it's driven by the practicality.

In essence, we could use the full integrated code all the time, but it would not be necessarily the most time-efficient, considering the (indiscernible due to accent). And it would be too much, too time-consuming, for example.

MEMBER MARTIN: And so, I assume, from a V&V standpoint, you have a combination of V&V for individual models, as well as an integrated V&V package? Is that the plan?

MR. HANUS: Yes, that's right. That's why we are focusing on the individual models, because they all feed into a package as well. So, yes, the validation proceeds step by step, essentially, in those phases. So that we don't have to repeat in order to do the validation. Because it's for the full period and pace of operation.

MEMBER MARTIN: Okay.

MEMBER HALNON: This is Greg. I've got one question that I asked during the Subcommittee meeting, but I asked the NRC staff. So I wanted to ask you all, anticipating that they're going to come back and say: lots of good, but we can make no conclusions based on all this work.

What are you going to use this Topical Report for?

MR. HANUS: We use this as a specification for the code. Obviously, the actual -- what we have on this is a code. The code is to implement models.

The verification of the code basically looks at those models and checks that the code implements these models.

This Topical Report provides the justification file that goes with us, right, for our design and safety case. And if we implement those models correctly, then we get confident in the safety case.

MEMBER HALNON: But as you go forward, the NRC has not approved. I mean, they can make no conclusions. So, are you proceeding at risk, hoping that you will get more technical review down the road, that this XSTERM is going to be acceptable to use? Yes, conceptually, yeah, it sounds like a great idea, but we can make no conclusions. So I don't know how you're going to use this going forward as a technical justification to use in your continued evaluation of safety.

CHAIR KIRCHNER: Or is it part of the V&V package in general?

MR. HANUS: Well, we will provide the XSTERM Topical Report which asks NRC to make conclusions about this methodology. And so now, if now we get -- you know, you can provide a conclusion, but it is information for us. And we'll take notice of the suggestions.

But this should be used in something like ODAD -- But we see the need of the future XSTERM application in this regard in this particular domain, so that the application will be, hopefully, much easier to approve, since it's already been seen before. The methodology has been seen before.

I don't know how identical it is --

MR. THOMAS: Yes, I'll just -- again, Matt Thomas, Licensing Manager at X-energy. So I'll just add onto that.

So, you know, based on the recommendations of the Subcommittee or the suggestions in the Subcommittee, the ultimate goal is to present the XSTERM Topical Report to the NRC and get approval on it, but we're also looking at, you know, a contingency in case -- right? And kind of in parallel, looking at a more validating type of approach that can be used maybe as verification or just another method to maintain our current schedules and stuff for our project.

MEMBER HALNON: I guess, normally, when we get these Topical Reports, the methodologies, we get NRC's buy-in on it and we can reference and just use it going forward. This one, it doesn't seem like --

it's more of a white paper when the NRC reads it and agrees, "Yeah, okay, it looks great to us, but you've got a lot of work to do." It kind of feels more like a white paper than a Topical Report.

And I just want to make sure that, if we see this referenced in a construction application down the road, we understand what we're seeing. And what we're seeing for this Topical Report especially is it's not able to be referenced as an approved methodology.

And so, unless you do all the work that you need to go through -- that the NRC is planning on you in an SE. So it just feels preliminary. It feels like we've not wasted time, but we've spent a lot of time kind of agreeing to agree that this looks good.

(Laughter.)

But I'm struggling with the endpoint of where we're at with this.

MR. THOMAS: It's here to support the CPA, right?

MEMBER HALNON: But it's a non-conclusion. You can't support it with --

MR. THOMAS: Well, I mean, it's kind of what the staff had touched on their -

MEMBER HALNON: But they finally came out and said, to put words in your mouth, that it's probably good enough. But we'll see it again.

(Laughter.)

CHAIR KIRCHNER: May I ask a specific question? You've got in process your irradiating pebbles up in Idaho. I don't know the timeframe for that and subsequent trying to tie thermal testing to trying to release rates and such, but this activity up at Idaho will give you data that will validate the THM, FPM, and SOLM modules, right? And maybe then the gas transport?

MR. THOMAS: Yes.

CHAIR KIRCHNER: So what you're working on up at Idaho will allow you to do V&V for the four boxes in the middle of this diagram?

MR. HANUS: Yes, that's right.

CHAIR KIRCHNER: And then, presuming that you get pretty high quality -- you have high quality particles that you're irradiating, you're going to see low release rates and such, as was the case with the AVR experiment. So, what's your sense of where are the big gaps? You'll complete that. You'll be able to validate the middle models on this diagram. Then, you'll go forward with the dust model as you have it now.

I'm trying to just kind of get a sense for how much V&V effort is needed to have this package in a state where it's validated and you know what -- you can then do an assessment where the biggest uncertainty is and use it effectively as a licensing tool.

Right now, you're using it to make bounding estimates. As you go into the CP application, it is my assumption -- but when do you expect to have it validated and how does that fit into your overall timeline, your schedule?

MR. HANUS: The validation completion out of the full validation can only happen after we obtain the data from INL, which is a couple of years from now. James can say a bit about that schedule and share this with the public.

But that will take time. We have this phased validation approach here which we do, the fact that it is being validated at the same time as we have data available from the previous experience, and this provides validation for the other models as well.

But the fuel qualification is now ongoing, and right now it's where the best validation that you can get for the fuel. But we will not get any new data. We are looking for the verification, especially for the dust model and for the HPBM, to get the data from the Chinese. But I can't say when we are getting that data. But this continued validation is waiting for verification.

MEMBER BIER: Thank you.

MEMBER SUNSERI: This is Matt again. And perhaps I'm a little bit more optimistic about where we are in the process and the state of this thing. It seems to me, with the fact that we're tying this to functional containment, which you guys are going to be one of the first out of the door on that approach, having a mechanistic source term approach for the development.

That is, I'll stop short of having it approved by now with the regulator, but at least having agreement on where it's going to be, based on the level of effort it's going to take to push this over the finish line. It seems prudent and important at this stage of where you're at as far as, you know, to build and operate.

I think the effort right now seems worthwhile and useful, but that's my opinion.

MEMBER PALMTAG: This is Scott. I'm just trying to think this through.

But my understanding is this is the

procedure you're going to have to determine your source terms going out of it, but you're not going to have validation. So it sounds like we're not going to see this XSTERM for years, right? At least a couple of years? So you're saying, "This is the path we're taking for the validation." You must have some number for what you think your source term is going to be, and then, that's going to be enough to go ahead with construction permits.

So it's kind of like what Greg says; there's some risk there.

MR. HANUS: Yes.

MEMBER PALMTAG: If you have some number for your construction permit, and then all this validation comes and it's higher, then you're at risk. But it sounds like --

MR. HANUS: Yes.

MEMBER PALMTAG: Is that kind of the plan?

MR. HANUS: Yes. Again, you know, the validation is not now waiting; I mean, it's ongoing. The qualification of gamma is not the only validation data that we have for these models, these first few.

So here we are with these validations. They are looking good, but, of course, they are not the other fuel. So we are now getting back to the --

you know, we have the AGR results. We have the AGR results of the pebble. And all these, all these results are -- we have confidence that we are not doing something wrong, but to get the actual validation, to create something that we could -- we need to perform for fuel realistic.

MEMBER PALMTAG: Sure. So, in my personal opinion, it sounds like this is the right track. You've give us kind of what you plan to do, but just to acknowledge what Greg said, there is risk here, right, that the validation won't --

MR. HANUS: There is risk later, yes, that the qualification uncovers something that we have taken into account.

MEMBER PALMTAG: Yes, I think this LTR is very important because it tells what's going to be coming in the XSTERM in a couple of years.

MEMBER HALNON: Well, it is typically in a white paper to get kind of conceptual agreement on how they're going to develop a methodology.

MEMBER PALMTAG: Even for a CP?

MEMBER HALNON: Well, they're not in the CP yet. They don't have a CP.

MEMBER PALMTAG: Yes.

MEMBER HALNON: We don't know what the CP is going to look like and how much detail is going to be.

MEMBER PETTI: The source term is going to be low. I could on one piece of paper calculate what their source term is, because I've done this for a while, you know. You don't need all these codes.

What I worry about is not that -- I worry that, for instance, the irradiation testing in Idaho will not be able to unravel, because it's an integral test, what you need to validate each of the models. This happens all the time. Everyone who says, "We're going to use AGR," I say, "Good luck." Go look at these papers. We've tried this. Idaho tried this. It's not that simple. These are very complicated, because it's a very complicated fuel.

But the benefit is, you know, you get this benefit. So that's why I keep saying it's nice to have a strategy in your back pocket of something simple, that you either compare it to that, and if, in fact, you can't get there, you have a simple thing. And you can do this. It's not difficult, because there's lots of margin here.

You know, if you're right against the dose limit, you're going to need the sharpest pencil you have. That's not where they are. And so, they can be more, quote, "cavalier," if you will, in terms of the model. It could be a lot simpler and still show they meet all things.

CHAIR KIRCHNER: I concur with Dave's assessment because my sense is that you're going to need to have a really low source term for almost all your transients, except one, and that will be when you have intrusion of H2O.

So, we have a steam generator tube rupture; that is probably going to bound things. And as Dave put it, I mean, all the other detail in these other models, that kind of event will mask everything that you'll see during normal transients and operation of this particle fuel, assuming you get good fuel from your vendor.

So that box in the lower right there, I presume that's your mechanistic model for steam interacting with graphite. It's probably your dominant worst-case source term.

MEMBER PETTI: It was in the MHTGR.

CHAIR KIRCHNER: So I know this is a design detail, but assuming that that module works the first order, you can run your projected worst-case steam generator tube rupture kind of events and see what your bounding source term is and use that, Matt, for the CP application, as appropriate.

My sense is that lower right-hand box will dominate.

CHAIR KIRCHNER: So it's good enough at this point?

MEMBER SUNSERI: Yes, I mean, look, I can't speak for the Committee, but it almost seems like we're being overly critical of the effort they're putting in. They're refining the calculation. Maybe they could do a bounding or whatever, but what do we care what their motivation is? They have their motivation. If they want to get increased operational margin on whatever it is through this effort, then they should be able to pursue that. Is there anything from a safety significance that we should be concerned about now?

So we're having a pretty extensive debate over something that you're acknowledging has marginal safety implications.

MEMBER PETTI: It's the matter of proving it. This is what it always is. And how difficult that can be when you get into the details.

I had a question for Matt. You raised the steam question. Is there a dump system off the steam generator in the event that there's a leak? Some gas reactor designs have that to limit how much steam can get into the systems, how much moisture can get into the system.

I don't remember in any of the meetings we've had whether that was discussed. Do you --

MR. THOMAS: Yes, Brian Froese on the phone, do you happen to have a response to that?

MR. FROESE: Yes. This is Brian Froese, X-energy, Project Manager, Analysis Integration. Apologies I'm not there in person again this time, but this has been a really interesting discussion.

The Xe-100 does have a dump system. It's not safety-related.

And one point of clarification: our limiting accident right now is our long-term DLOFC right now instead of our tube rupture. We've done a little bit more analysis on tube rupture. Our oxidation of graphite is fairly low and the amount of radionuclides, assuming that we get the fuel that we're hoping to get, the amount of radionuclides throughout the primary system is -- we're seeing it is fairly benign.

So the driver for our limiting dose accident is long-term DLOFC and those peak fuel temperatures and associated diffusion out of the fuel from that.

MEMBER MARTIN: We think we're done here with X-energy.

MR. HANUS: Yes.

MEMBER MARTIN: Yes, I think we should take a break.

We do have a presentation by the staff, about nine slides, I think, plus their title and their acronyms.

So, 10 minutes? Fifteen minutes? Okay.

CHAIR KIRCHNER: Let's take a break until 10:40 local time. Okay? So we are in recess.

(Whereupon, the above-entitled matter went off the record at 10:26 a.m. and resumed at 10:42 a.m.)

CHAIR KIRCHNER: Okay, we're back in session.

I'll turn it back to Bob Martin.

MEMBER MARTIN: Okay. We've wrapped up X-energy's presentation and we're going to move over to the staff's presentation. I believe it's being done remotely; I'm not sure. Do we know who's going to be doing that?

Speak into the microphone and just introduce your colleagues.

MR. DRZEWIECKI: Yes, this is Tim Drzewiecki from the staff.

Oh, sorry, was that for me?

(Laughter.)

MEMBER MARTIN: You can introduce yourself. It is perfectly all right.

MR. DRZEWIECKI: Yes. So, yes. I'm Tim Drzewiecki. I'm the lead tech reviewer for the Xe-100 which also extends to the Long Mott Generating Station CPA, which is currently in-house.

With me is my Branch Chief Travis Tate, as well as the Project Manager for this review. That's Denise McGovern.

Did I miss anybody?

(No response.)

MR. DRZEWIECKI: Okay. I do want to give a bit of context to this, and that's to basically state that this Topical Report is referenced in the current Long Mott Generating Station CPA, which is in-house now. And so, there are comments in this presentation about doing a detailed review of those models and we do plan to look at those in more detail, and are planning to do that and started to do that now actually. So I just wanted to give that just as context.

By the way, just as a sound check, I just want to make sure that I'm being heard clearly.

CHAIR KIRCHNER: Yes, we hear you well. Thank you.

MR. DRZEWIECKI: Thank you.

Okay. So, as far as some background, this Topical Report, it was submitted in May of 2024 with an update earlier this year. That update, it includes updates of Section 1.5 and 7.1 to clarify that it applies only to preliminary analysis. There were some typos that were corrected, as well as an update to Appendix H, which shows all the model interfaces. And that was shown a few times in the previous presentation.

Also for context, there were no RAIs issued on this topical. Everything was handled as part of the audit.

Just for some background information, there is a lot of information that is out there that is relevant to gas reactor source term analyses. This is a subset of them that staff did not bring to bear during this review, but are relying on these as part of the current review that we're doing for these models as part of the PSAR.

Also, I just want to highlight the fact

that there were several references that were brought up at the Subcommittee meeting that have been brought to our attention. We're so grateful for that feedback from the Committee.

As far as the regulatory basis for this, there are several.

50.34(a)(1), it does require an evaluation of a postulated fission product release to evaluate offsite radiological consequences.

50.34(a)(4) does require a preliminary analysis and evaluation of SSCs, and the ones that are most germane to this area include PDC 10, which is SARRDLs for reactor design; RFDC 16, that's your functional containment, and PDC 19, that's your controllable.

Also, 50.43(a)(8), this is something that is pretty unique to a construction permit application under Part 50. And this is having the need for an R&D program to resolve any safety questions that would need to be done before you complete construction of your plant.

Relevant to this -- and this was discussed at the Subcommittee meeting -- is this 50.43(e). This is the requirement that you have data to assess the tools that you use in your plant analysis. This requirement does not apply to a construction permit, but it does apply to an operating license, pretty much everything under Part 52. We had some discussion at the Subcommittee about how this impacts this review, as well as CPA reviews.

Scope of staff review, Section 4.2 of this topical, it describes that the models that are in XSTERM code are used to calculate dose consequences for licensing basis events, as well as deterministic evaluation of design basis accidents.

Staff reviewed the MST modeling approach to address radionuclide transport phenomena to support preliminary analysis of the Xe-100. However, staff's review is limited to and focused on high-level physical phenomena of interest and whether the approach and methods can reasonably support future licensing applications or actions. That is because this design is preliminary.

The development and assessment of the methods were in progress or planned, and therefore, you know, the evaluation of models within XSTERM for acceptability will be conducted during the review of an application that relies on the results of XSTERM evaluations. And that includes of current CPA that they're looking at now.

Just for some more background, you know, I was looking at the functional containment. It's largely in the fuel kernel, your SiC and your PyC layers, the fuel matrix, and the fuel-free zone of fuel pebble within the helium pressure boundary.

There is a reactor building which is actually present and would hold radionuclides, but it is not credited in this methodology.

As far as the XSTERM itself, I don't want to go into these models too much, but I want to highlight these three here as far as a thermodynamics calculation model.

This is one that we think is going to be of a high importance because a lot of the radionuclide release from the fuel, we expect it to be diffusion dominant, and so, therefore, having a model that can get that. So this is a model that we plan to look at in more detail.

And the Point Kinetics Simulation Model, the way it was described inside of this Topical Report, it looked like it was a novel approach to point kinetics. And so, that's one thing that we want to make sure that we understand it and see how it's used, and how it's different from what we consider, like, a more traditional-type point kinetics approach.

And as far as the Tritium Model, it was still under development at the time of this Topical Report. So there was no -- there is no information on this model.

There are six other models that were discussed -- the Failure Probability Model, the Solids Products Transport Calculation Model, Steady-State Gaseous Fission Products Transport, dust generation, Helium Pressure Boundary, and the Core Corrosion Model.

Again, not looked at in detail, but staff had determined that these models address phenomena needed to predict source term to support preliminary analyses. And that is based on the fact that these models rely on previous modeling and operational experience from gas-cooled reactors, such as the AVR, and then, based on staff's experience with the light water reactor and non-LWR source term analysis, there were not significant gaps that were seen in these models.

Section 4.2 does state that the source term modeling as described may be revised. So staff did not perform a detailed technical review of the models as described in this Topical Report and made no conclusions regarding the acceptability of these models.

MEMBER MARTIN: Excuse me. It's Bob Martin.

Just some question here. X-energy, of course, acknowledges that there are inputs that come in from other codes, like Flownex and VSOP. So we reviewed Flownex as part of our last Subcommittee. When it comes to VSOP, you know, what it is, the Very Superior Old Program, where does that get reviewed by the staff? Is it part of this? Is it part of something else? I mean, I would say Flownex is part of something else.

MR. DRZEWIECKI: Yes. So, yes, at the Subcommittee meeting, this Topical Report, it was submitted as a group of four. So it was source term. It was safety analysis methods. It was GOTHIC/Flownex, and it was the core design methodology.

MEMBER MARTIN: Okay. That's our fault because we chose not to --

MR. DRZEWIECKI: Exactly. Yes, yes. It was just the core design methodology was, yes, yes, that was not subject to our previous meeting.

MEMBER MARTIN: Okay. Thanks for the reminder. Okay.

MR. DRZEWIECKI: Yes. Okay. Yes.

So, as far as the code assessment plans or the V&V, Section 6 of this Topical Report, it does state, you know, yes, that the effort is underway to ensure the XSTERM is qualified to support final safety analyses. Validation plans are developed to cover high- and medium-ranked phenomena that are identified through the PIRT process. The phenomena modeled by XSTERM are extracted from an earlier version of the PIRT.

So, just to kind of clarify that, it does state that a PIRT was done and that the V&V efforts are informed by the PIRT. So, based on that, staff determined that this process is acceptable because of the identification of code assessment requirements through the PIRT process. That's an established approach. It's called out in 1.203.

However, we were unable to assess the adequacy of the V&V plan because the validation plan is not based on the latest PIRT information, even though it's based on some PIRT information, not the latest. And we had asked the information would describe the knowledge level of the phenomena identified in the PIRT. Just again, it's important for us to know generally how important the phenomena is, but how well understood it is, so that we have an idea of what testing is needed. Also, the plan is preliminary and subject to change.

As far as staff's conclusions, we concluded that this Topical Report provides a reasonable plan for the development of the source term methodology. And that's because several of the models appear to cover phenomena needed to predict source term to support preliminary analysis and evaluation of the Xe-100 design, and it describes an acceptable approach to V&V, which is largely of informing what is needed for code assessment based on a PIRT.

However, staff makes no conclusions regarding acceptability of the models in XSTERM for source term analysis because the models are still under development. A detailed review of the models was not completed, in part, because of that. Details regarding key phenomena identification of associated knowledge levels are not provided in this Topical Report, and the models and associated validation plans are preliminary and subject to change.

Additionally, this last bullet here, the staff expects that a detailed technical review of XSTERM model applicability to the Xe-100 reactor will be addressed as part of the review of a licensing application that makes reference to this Topical Report.

To that last point, it is currently referenced, again, in the Long Mott Generating Station construction permit application, and we are to look at these models in more detail now. So we just started doing that, and I do expect that we will have further engagement on this topic as part of that review.

So I think that's my last slide --

MEMBER PALMTAG: This is Scott Palmtag. I just had a question on that.

So, from what we heard earlier, I thought the XSTERM was going to be -- it was going to be several years before that was finished because they were waiting on validation from the INL. But it seems like you are saying that this is going to be reviewed in a construction permit?

MR. DRZEWIECKI: So, I will say, yes -- so what we do need to make a finding on is the fact that there are consequence evaluations performed in the construction permit application that appear to make use of XSTERM. And so, we do need to come to a reasonable assurance or conclusion in terms of the outcome of those calculations. Or, basically, to get to some reasonable assurance finding of the fact that, you know, the consequence analysis is acceptable.

Now, we understand that there are risks associated with that. And so, we do have plans in place to manage that risk, and that includes us doing our own independent confirmatory calculations. I believe this was discussed at the Subcommittee meeting. But, as well, we just want to get a better understanding of the capabilities and details of these models, because they do appear to be used to support findings in the CPA.

MEMBER HALNON: This is Greg. I just looked at the CPA, since I wasn't aware that it is in a different folder. But it does say that a separate licensing Topical Report for XSTERM will be submitted for the OLA. So we should see a specific Topical Report for the XSTERM that would sort the rest of the references that he was talking about.

MEMBER PALMTAG: At the OL?

MEMBER HALNON: At the OL stage, yeah.

MEMBER PALMTAG: I think that kind of agrees with our first discussion.

MEMBER HALNON: Yeah.

MEMBER PALMTAG: It's consensual that these models are --

MEMBER HALNON: Right, the Topical Report will come before the OLA. So that's what's in progress I think. I'm just reading into what this paragraph says in the CPA.

MEMBER MARTIN: This is Bob Martin. I'll throw out -- just to get a personal experience.

My last employer, implementation of NQA-1, computer software development, we had a two-stage qualification approach where the first feed of V&V was taken care of. We called it commercial grade software verification, which is oftentimes much easier to do than gathering up all the data.

And I'm kind of looking over at X-energy. Do you have anything like that where you can kind of get that queue. You know, that's our designation. We would put the queue, and then, down the road, we would get the safety, where the second "V" would come in. Do you all have any -- it's not, of course, explicitly required by NQA-1, but it did allow you to have kind of a demonstration of progress earlier in the development than waiting until the end for everything.

I don't know, Milan, from that, if you could speak on that?

And I don't know, Tim, if whether you've ever seen anything like that by an applicant, where they had kind of a two-step process with computer software.

MR. DRZEWIECKI: Well, yeah, so I can speak to this. And so, it's going to be somewhat scattered and I could talk to you about, okay, so as far as my background, I was NRC for a while. I was Duke Energy for a while. About eight or nine months ago, I was employed at Kairos Power. So, I'm familiar with what they had done there. I was the Safety Analysis Manager.

A lot of my experience at NRC was largely in Part 52. And so, those methods were more further along. They were supporting -- you know, because they had to meet the 50.43(e) requirements.

MEMBER MARTIN: Right.

MR. DRZEWIECKI: I will say for the test reactor, like what was done for Hermes, some of the methodologies were further along. Source term was. They had a Source Term Topical Report that was already reviewed and approved and it was a little further along, well ahead of their CPA.

However, their safety analysis methodology was not. That was submitted as a tech report that was supporting the Hermes CPA. And, in fact, I believe you'll probably be seeing the safety analysis Topical Report later this year.

So, it's been a mixed bag. So, in terms of that, have I seen it staged like that? I've seen people come in with preliminary information certainly under a construction permit.

However, I do think source term is one of those items, when it comes to like the siting evaluation, where I think it's a little more important to get that a little earlier.

MEMBER MARTIN: That's only fair.

Milan, if you want to say something, come up underneath the green light.

MR. HANUS: Yeah, it's not -- X-energy. We have the validation. So it's important. So we have some preliminary. It's also very -- I wouldn't call it a staged approach by design where it designates stage one, stage two.

We can provide some information already on the validation results. It has been done. But, yeah, it's preliminary.

MEMBER MARTIN: I guess, as Tim said, they've seen a lot of different examples. I guess, as we kind of feel through the CP application review process, you know, I think in the moment, are we letting a lot of -- are we allowing for that ambiguity? We find it acceptable?

But something else to consider is, at least from traceability, since that first "V" is a lot easier, it might help in-house to have that specified in your procedures to have it earlier. It also helps with, like, if you're having turnover and you can kind of put a stamp on it, and then, pick it up again. But that's another story.

Anyway, all right. Thanks for that clarification.

CHAIR KIRCHNER: Tim, did we let you complete your presentation?

MR. DRZEWIECKI: Yes, yes, yes. That was all that I had.

CHAIR KIRCHNER: Okay. Thank you.

MR. DRZEWIECKI: Yeah, yeah, outside of the acronym slide.

CHAIR KIRCHNER: Okay. So, members, questions for the NRC staff?

(No response.)

CHAIR KIRCHNER: Okay, Bob. I think that's it for the presentations.

MEMBER MARTIN: Yes, good.

CHAIR KIRCHNER: At this point, should we take public comments?

MEMBER MARTIN: Yes.

CHAIR KIRCHNER: So, for any members of the public online, if you wish to make a comment, just raise your hand or open up your mic and speak out. And state your affiliation, if appropriate, and your comment.

(No response.)

CHAIR KIRCHNER: Hearing or seeing none, okay, thank you. With that, then, Bob, I think, and Dave, we're ready to entertain a letter.

Okay. So we may need to take a short pause break here, and then we'll bring up a draft letter we've worked for reading into the record.

And then, with that, we can excuse the court reporter, I believe, for the rest of the meeting.

So just hold for a bit while we bring up our letter report.

CHAIR KIRCHNER: While we're doing that, I'll thank both X-energy and the staff for their presentations today.

(Pause.)

For those online, we're just taking a short break here. We'll resume within a couple of minutes.

(Whereupon, at 11:06 a.m., the foregoing matter went off the record and went back on the record at 11:08 a.m.)

CHAIR KIRCHNER: Okay, I think we're ready to go.

And I'll turn now to Dave Petti, who is our lead author on this letter report. Go ahead, Dave.

MEMBER PETTI: Okay. This is the X-energy Topical Report Mechanistic Source Term Approach.

"Dear Mr. King:

"During the 727th meeting of the Advisory Committee on Reactor Safeguards, held from July 8th through 11th" -- that should be "9th" -- "2025, we completed our review of the X-energy Topical Report entitled, "Mechanistic Source Term Approach," and the associated Draft Safety Evaluation.

"Our X-energy Subcommittee also reviewed this matter on June 3, 2025. During these meetings, discussions with the Nuclear Regulatory Commission staff and X-energy were beneficial, as were the methods documents.

"Conclusions and Recommendations.

"One, X-energy is developing a sequence-specific mechanistic source term through the use of a functional containment concept for the Xe-100 pebble bed reactor. This functional containment consists of the tristructural isotropic fuel kernel and coatings, the pebble bed matrix, and the helium pressure boundary.

"Two, we recommend caution regarding the verification and validation of the models in the mechanistic source term code. This process will be challenging due to the numerous models and submodels involved, their complexity, the absence of a historical database, the lack of applicability of uranium dioxide TRISO fuel performance models to describe uranium oxycarbide TRISO fuel performance, and residual uncertainties associated with the constitutive models and material properties.

"A simpler semi-empirical approach, tied more directly to the statistically significant failure data from the U.S. Advanced Gas Reactor UCO TRISO testing program with appropriate margins would overcome these shortcomings and better represent the performance of the fuel that will be fabricated for the Xe-100 and the resulting source term.

"Three, the Topical Report should be issued and the concerns mentioned in the letter should be considered for the future licensing application.

"Functional Containment Strategy.

X-energy is implementing a functional containment strategy to retain fission products within their design. The functional containment consists of the fuel kernel, the silicon carbide and pyrocarbon layers of the TRISO coating, the fuel matrix surrounding the particles and the pebble, the fuel-free zone on the outside of the pebble, and the helium pressure boundary. No credit is given for fission product retention in the reactor building.

"The release of fission products is calculated based on the as-manufactured heavy metal contamination and silicon carbide defects, in-service failures under irradiation, and incremental failures during licensing basis events. For certain radionuclides, silver diffusion through intact coatings is also considered. Additionally, plate-out on the surfaces of the helium pressure boundary and dust in the system is accounted for, as well as resuspension of" -- quote -- "`liftoff' of the dust during licensing basis events.

"Evaluation Model Development.

"The X-energy evaluation model known as XSTERM comprises several computer models and submodels to describe the generation, release, and transport of radionuclides from the fuel to the environment. The evaluation model includes codes to calculate the thermal hydraulic response of the fuel pebbles in the core under normal operation and licensing basis events; the production, decay, and transmutation of radionuclides in the pebble and their transport to the coolant, including the effects of dust; the transport to the reactor building, and evaluations of radiological dose to compare to regulatory limits.

"The Topical Report does not present a Phenomena Identification and Ranking Table (PIRT) to identify key phenomena, as required by Regulatory Guide 1.203, as an early step in the development of an evaluation model.

"Key submodels in XSTERM include the Particle Failure Model, which considers pressure vessel failure, kernel migration, fission product corrosion, thermal decomposition, inner pyrolytic carbon layer cracking, and manufacturing defects.

"Solid fission product release and transport is based on diffusion through the kernel, coating layers, and fuel matrix using detailed nodalization of each pebble in the analysis.

"The thermodynamics module calculates temperatures in all the reactor components necessary to support a mechanistic source term.

"Steady-state fission gas release is calculated using two different, German and U.S., release models that account for (a) diffusion through the kernel and buffer porosity for failed and defective fuel, and (b) through the matrix for the initial heavy metal contamination.

"Dust production is estimated using the measured particle size and estimated generation rates for the German pebble bed AVR scaled to Xe-100.

"Fission product transport, deposition, and liftoff behavior in the helium pressure boundary is based on models for absorption of fission products on dust, plate-out of the dust, and condensable fission products -- for example, cesium and strontium -- during normal operation and subsequent liftoff under licensing basis events.

"Core corrosion models describe the response of the core to oxidation events, including models for mass transport and chemical reactions during an air or steam ingress event, using data and air and stream oxidation behavior of graphite, and data from industrial chemical synthesis technologies.

"The tritium behavior module tracks the production, decay, permeation, and absorption of graphite release upon oxidant ingress into the core, separately from other fission products.

"The Reactor Kinetics Model uses two-dimensional kinetics for steady-state and steam generator tube rupture events.

"Atmospheric dose calculations are based on traditional Gaussian plume dispersion and appear to be consistent with NRC dose models for use in siting and control room habitability assessments.

"The isotope listing used in XSTERM is consistent with previous high-temperature gas-cooled reactors safety assessments.

"Staff Safety Evaluation.

"The staff safety evaluation concentrated their review on the evaluation methodology. They found that the overall plan appears reasonable. However, they noted that the verification and validation plan is not based on a PIRT. The details of the individual models of XSTERM were not examined and no conclusions were made about the acceptability of the models, as they are still under development. A detailed review is expected as part of the licensing application.

"Discussion. V&V Plans.

"X-energy intends to verify and validate the modules of XSTERM using a combination of historical German and Chinese data related to UO2 TRISO fuel with more modern U.S. UCO TRISO fuel and analytical benchmark problems from HTR-10. In some cases, separate effects data are utilized to validate individual submodels, such as SANA pebble bed heat transfer testing, the German VAMPYR plate-out data, the Chinese Lifting Line Platform Facility data on dust generation.

"The following sections outline our assessment of these plans, their limitations, and some recommendations to enhance the validation process. Staff is now looking to additional data not mentioned in the Topical Report.

"Defects, Failure Fractions, and Performance Envelopes.

"The performance of TRISO fuel in a high-temperature gas-cooled reactor is a strong function of the initial level of manufacturing defects, contamination, and silicon carbide defects; the in-service failure through irradiation, and the incremental failures during accidents.

"Because of the importance to the overall functional containment strategy, the initial fuel failure fractions used in the X-energy safety analysis approach must be demonstrated with actual manufacturing data to be consistent with or better than the AGR UCO data. The values used for these fractions should align with the results from the AGR UCO TRISO testing, along with any additional fuel qualification testing planned by X-energy.

"Finally, the Service Conditions.

"Burnup, temperature, fast fluence experienced during normal operation and postulated licensing basis events should remain inside the testing envelopes associated with the U.S. AGR UCO database, as supplemented by any additional testing planned on UCO by X-energy.

"Fission product groupings.

"The database on fission product behavior in TRISO fuel focuses on measurements of noble gases, cesium, strontium, europium, silver, and in some limited cases, iodine. Consequently, grouping of fission products into classes based on chemical or volatility considerations is essential for estimating source terms for HTGRs, similar to other reactor technologies.

"For HTGRs, iodine and tellurium are recommended to be modeled as noble gases, while europium should be treated similarly to strontium. Lower-volume fission products such as lithium and cerium are not expected to be released from UCO TRISO fuel, according to measurements from the AGR program. These groupings align with previous HTGR safety and source term assessments.

"Steady-State Fission Gas Release.

"The report did not mention steady-state fission gas release data collected over a large range of temperature runup from the U.S. UCO TRISO program (AGR-3/4) that contained failed fuel. These data have been published (Reference 2) and can be used directly for fission gas release from exposed kernels or used to validate models for this part of the source term.

"Fuel Performance.

"The fuel performance validation plan has three major shortcomings.

"(a) The models predominantly describe UO2 rather than UCO TRISO fuel performance.

"(b) The failure mechanisms observed in the AGR UCO TRISO irradiations and heating tests was not accounted for in the evaluation model.

"© The uncertainties of material properties required to describe fuel behavior are significant enough to make validation challenging.

"A. UO2 versus UCO TRISO Fuel Performance.

"X-energy plans to validate the fuel performance models using a combination of irradiation and heating or safety data from UO2 (HFR K5 and K6) and UCO TRISO fuel (AGR-1 and AGR-2). While some of this data is acceptable, the UO2 data does not fully represent modern U.S. TRISO fuel. Many, if not all, of the failure mechanisms models in XSTERM have been engineered out of UCO TRISO fuel. This fuel development approach was adopted in the U.S. decades ago by modifying particle design, altering of fabrication conditions, and limiting reactor service conditions. These mechanisms are not optimal in UCO TRISO. It raises questions about the effectiveness of use such a validation effort for XSTERM fuel performance models.

"B. Failure Mechanism in AGR Testing.

"The applicant plans to use the results of AGR-1 and AGR-2 in their validation efforts. However, it is important to note that the failure mechanism noted for USO TRISO in AGR-1 and AGR-2 (Reference 3) is not modeled in any particle fuel performance code due to uncertainties in the material properties necessary to support the model. Advanced multiscale modeling efforts are underway in the Department of Energy's Nuclear Energy Advanced Modeling and

Simulation Program as a challenge problem because of its difficulty.

"C. Material Property Uncertainties.

"From a fission product release perspective, attempts to validate the diffusion of fission product release models using data from AGR-1 and AGR-2 have had limited success. This is due to the low level of releases that were measured and the potential multiple sources of fission products -- contamination, exposed kernels, or through intact particles -- and the uncertainties of the underlying diffusion coefficient database.

"The report also does not address many of the well-known uncertainties in the thermomechanical properties that significantly influence model traditions. For example, the silicon carbide strength data in the Topical Report is based on German TRISO fuel and shows considerably greater strengths than the more recent U.S. UCO TRISO fuel. This difference is likely due to differences in the microstructure of the silicon carbide layer.

"Additionally, the pyrolytic carbon shrinkage rate data used in XSTERM that determined the survivability of the PyC layers are simple fluence-based estimates from old German testing. They do not represent the more contemporary data used in a recent International Atomic Energy Agency Code benchmark that are temperature-influence-dependent. These data are based on a compendium of historical U.S. and international data and are considered to be more representative for UCO TRISO fuel behavior.

"The uncertainties in these fundamental material properties are impacted even by the small scale of the samples and no limitations in testing. These thermomechanical properties -- the silicon carbide and pyrocarbon strength data and the pyrocarbon shrinkage and creep data -- drive failure probability predictions, and the uncertainties are large enough to make validation of failure probabilities challenging.

"Overall, considering the significant performance margin in the Xe-100 core and the concerns mentioned above, it may be more beneficial to directly use the measured statistically significant failure data from AGR-1 and AGR-2 with appropriate margin as an estimate for the fuel failure fraction in source term calculations.

"Fuel Behavior Under Reactivity Events.

"Fuel performance under reactivity events is not mentioned in the Topical Report. Did it exist on such fuel performance. (See Reference 9.) This may not be a problem for the Xe-100 design, because of the low access reactivity in the core in their reactivity control strategy, but some mention of fuel behavior is worthwhile from a completeness perspective.

"Dust.

"The models for dust generation, transport, deposition, plate-out, and resuspension of liftoff are highly complex and challenging to determine if they are conservative. Sensitivity studies:

"A. Examine the timing of dust liftoff relative to fission product release during licensing basis events.

"B. Varying the dust generation rate.

"C. Performing calculations with and without dust are recommended to help establish the overall role of dust on fission product transport in the Xe-100 during postulated events and provide more confidence in the predictions.

"Beyond the VAMPYR plate-out data in Germany, the report does not mention the extensive testing done in the COMEDIE facility in the 1990s (See Reference 10) to examine deposition and subsequent liftoff under various break sizes.

"Additionally, the applicant appears unaware of the large amount of data on the suspension of metallic aerosols with dust in the aerosol literature (See References 11, 12, and 13) that could be useful for validation.

"Ultimately, validation through measurements of gaseous and metallic fission products during operation will be required to assure specified acceptable radionuclide design release limits, or SARRDLs, are being met.

"Core Corrosion/Oxidation.

"The existing database on the response of TRISO fuel to aerosteam ingress is quite limited. Some in-trial testing has been performed for short duration at specific temperatures, focusing primarily on fission gas rather than fission metals that tend to dominate the radiological dose. There are some limited data on particle testing in air that show high failure rates. (See Reference 9.) However, there are no data on the effects of steam ingress on UCO TRISO coated fuel particles, as would be expected in a steam generator tube rupture. The assumption index that has determined that steam will not result in particle failure is unsubstantiated.

"During discussions in our Subcommittee meeting, the applicant mentioned that in their simulations the steam never reaches the particles due to the fuel-free zone on the surface of the pebble. This behavior will need to be validated. Nevertheless, given the importance of these events, as highlighted by the results of the MHGT, modular high-temperature gas-cooled reactor probabilistic risk assessment, the U.S. AGR program depends on testing fuel compacts in steam and air under a wide range of temperatures and partial pressures of oxygen. (See Reference 14.) The testing will measure fission gas and metallic fission product release during such exposures.

"Historically, such testing of this nature has been planned in the U.S. TRISO fuel qualification programs for decades. However, it was never carried out, per the requirements of special furnaces and fission collect detection systems. These systems have only recently been developed under the AGR program.

"In summary, X-energy is developing a sequence-specific mechanistic source term using a functional containment concept for their Xe-100 pebble bed reactor. The functional containment consists of the TRISO fuel coatings, a pebble bed matrix, and the helium pressure boundary.

"We recommend caution regarding the verification and validation of the models in the mechanistic source term code. This process will be challenging due to the numerous models and submodels involved, their complexity, gaps in the historical database, the lack of applicability of UO@ TRISO fuel performance models to describe UCO TRISO fuel performance, and residual uncertainties associated with the constitutive models and materials properties.

"A simpler, semi-empirical approach, tied more directly to the statistically significant failure data from the U.S. AGR USO TRISO testing program with appropriate margins, would overcome these shortcomings and better represent the performance of the fuel that will be fabricated for the Xe-100 and the resulting source term.

"The Topical Report should be issued and the concerns mentioned in the letter should be considered for the future licensing application.

"We are not requesting a response to this letter."

CHAIR KIRCHNER: Thank you, Dave.

Any comments, Members?

MEMBER MARTIN: In that category, just one as it relates to the EO. The EO expects this new, novel, and unique and maybe in the statement, maybe in the beginning of the background, that captures that thought? It might be a P&P topic, too.

CHAIR KIRCHNER: It might be a P&P topic.

MEMBER PETTI: Yes, I developed most of the letter before the EO came out.

MEMBER MARTIN: Right.

MEMBER HALNON: Yes, that's what I was going to say. I think we have some things that we need to finish up, regardless, and we just can't chop off what we started. But I think your point is good that we need to mention that or something to that effect.

MEMBER MARTIN: Well, my suggestion was I'd just take the words that I used today -- well, I'll hand it off. I guess the message that came to me prior to the meeting was that we would say something on the "novel and unique." And so, I had the three or four sentences.

MEMBER HALNON: Okay. We'll look into it, maybe put those in.

MEMBER MARTIN: For your consideration. No, no, that's fine.

MEMBER HALNON: Yes, I had just one

recommendation. I just think that Recommendation No. 2 can be shortened and take credit for what you have in the body of the letter. I mean, we can point to it.

MEMBER MARTIN: Well, my thought with 2 is that there's actually two points, and that you split it with the two.

MEMBER PETTI: Yes, I'm open to that.

MEMBER HALNON: We can do that, too. I mean, I just think it's laborious reading through. You kind of lose the -- but I think you do a really good in the body describing the shortcomings that need to be checked-out as we go forward.

MEMBER PETTI: It was hard to think of it.

MEMBER HALNON: Yes, I think you had a statement in there that said that it was not based on a current PIRT. What I thought I heard was -- I mean, I've heard, what I thought I heard was that there was a PIRT, but it needs to be updated, and the updated PIRT is not reflected in this. I just want to make sure that we talk a little --

MEMBER PETTI: It was not in the -- they have done it, but we haven't seen it.

MEMBER MARTIN: Exactly. Yes, I had --

MEMBER MARTIN: I'm happy to take it --

MEMBER ROBERTS: Greg, the only think I suggest is taking out that paragraph in our discussion because it's in the staff discussion. I don't think we need to talk about PIRTs at all

MEMBER HALNON: Yes, that could be the answer, but my point was --

MEMBER ROBERTS: It kind of breaks up the flow of the background anyway.

MEMBER HALNON: -- that it wasn't based on a PIRT, but it really sounds like, from what the staff said, that the PIRT was done, just that it was preliminary and they've got to update it.

MEMBER MARTIN: An alternative that I pitched to Dave yesterday --

MEMBER PETTI: Which I haven't seen yet.

MEMBER MARTIN: Oh, okay. Which was basically give them credit for that big laundry list. Right? Because, effectively, they identified phenomena. Right? And they incorporated XSTERM. And so, I have words to that effect about, you know -- well, I don't really mind --

MEMBER PETTI: I'm willing to take it out because if we're going to put in stuff on new and novel, this letter is going to get really long.

MEMBER MARTIN: Right, but it diminished

the PIRT point and just elevated what they did do.

MEMBER PETTI: I noticed little things. First of all, X-energy looked at it. XSTERM is not in an evaluation model. So I need to know -- but it's a conglomeration of codes together. And I'm trying to -- I need a term for it, Bob, as the evaluation model. But it's a piece of the evaluation model? Is that how it should be? I mean, how do we describe it? And are those are modules inside? Is that a way to --

MEMBER MARTIN: "Evaluation model" has this motherhood kind of definition, and the codes themselves are just a piece. It's really the responsibility of X-energy to give us the right word for it. Look over there.

MEMBER PALMTAG: But it is a code. It's not --

MEMBER PETTI: Yes, it is not the evaluation model. I describe it as the evaluation model. But the evaluation model, this is one piece.

MEMBER MARTIN: Yes, but it's not like a whole bunch of codes. It's just one code.

MEMBER PETTI: Correct. Yes. So we can just call it a computer code. That is part of the evaluation model. That's what I was thinking.

MEMBER BALLINGER: I come away with this

thinking: you think these guys are fools. It's very damning. It may be correct. It may be correct, but it's not very complimentary letter. It's not a complimentary letter at all.

The implication is these guys should have known about this. They didn't or they did know about it and decided not to deal with it. But there's something very negative here and I'm wondering whether or not that's -- if that's the message you want to send, okay, but it comes across to me as quite negative.

MEMBER PETTI: It surprised me when I read it, that I had to reference what I consider all the contemporary stuff there is about TRISO fuel.

MEMBER BALLINGER: So you are intending for it to be negative?

MEMBER PETTI: Well, I'm trying to highlight to the staff that, okay, here's their view of the world, but, no, there are these other 10 references that are absolutely seminal if you're going to do a proper review.

CHAIR KIRCHNER: And they all have many failures.

(Laughter.)

CHAIR KIRCHNER: I had a couple of

comments along this line as well. You know, there's a statement towards the back and near the summary, or something, that says, that it's summarized on the bounding approach, however we say it -- it will provide a result that is more representative of fuel performance. That seems pejorative to me. That's saying that the work they're doing is going to produce a result that is so wildly inaccurate that, if you just do a back-of-the-envelope calculation, it would be better than that.

So I think this is kind of what Ron is pointing at in his comment.

MEMBER PETTI: My point was, their models sit on UO2, not on UCO. So what they're doing is calculating to a fuel system that's not going to be used in the reactor. If you go back to the data that is going to be used in the reactor, you get a source term that's representative of that. That's all I was trying to --

MEMBER MARTIN: You're saying they're basically false, right?

MEMBER PETTI: There's very little, though, that's UCO. There's one model that they put in, but, again, that was engineered away. It was put in, and then it was engineered away.

MEMBER SUNSERI: And then, a second comment or point, and this will express probably some ignorance on my part. We go into a lot of depth and discussion about failure of the fuel and, you know, the data and all that stuff. I am under the impression -- well, first off, when we reference fuel like that, are we talking about the particle, the TRISO particle, which I think is the fuel, right?

MEMBER PETTI: Mm-hmm.

MEMBER SUNSERI: So, I mean, we've approved a couple of Topical Reports on how to build a particle and do it in a quality manner, and, I mean, all of the release and failure mechanisms and all that. Why are we dragging all this stuff into that? Build the TRISO particle in accordance with established guidelines. That's what they need to do.

Now, if you want to compose the particles into a pebble, and then, if we've got some concerns about that dust, or whatever, then that's another story. But it just seems to me we're going into an area that's already been reviewed and approved when we talk about failure mechanisms of the particle.

Because a couple of years ago, we did approve a Topical Report for the quality -- and this really is about a particle.

MEMBER PETTI: Yes, and this report does not leverage -- it does not truly leverage what's in there. That's what I'm saying: guys, here's this report. If you read it and you really understand what it says, this is what it means. It says: don't use German models on UO2 that aren't appropriate for UCO.

MEMBER MARTIN: When do we expect, though, the UO2 performance to be worse, meaning you would get higher source terms? And can you make an argument that these are conservatively applied to UCO? I mean, obviously, they have to prove it, but, I mean, if your whole point was bringing in UCO because it eliminates certain failure mechanisms, this should be -- and if they could live with UO2, and then that --

MEMBER PETTI: You can make a pebble bed with UO2. It may not be economic, but you can make one. That's why UCO exists.

MEMBER MARTIN: But if you're calculating a source term with UO2 data, would you expect it to be worse than UCO? And that's an argument for --

MEMBER PETTI: I don't have any problem with the calculation of the source term.

MEMBER MARTIN: Right.

MEMBER PETTI: I didn't say anything -- the diffusion coefficient, that's all completely fine, even the dust. I think they can -- we've talked about it in the Subcommittee. I put some recommendations in there, so the staff can think about, you know, if they're going to stand up confirmatories, hey, here's some sensitivity studies you guys ought to do because I'm sure the applicant's done it. And then, you'll be in a good place.

But using models from the 1970s for a fuel system that isn't this fuel system, it just raises the question. If the staff asks, well, why is this valid?

MEMBER MARTIN: Right. Well, this goes back to -- I mean, you can't stand on just UO2 alone. If you want to make an argument that --

MEMBER PETTI: One thing that I think that it may not be is they're using strength data to make the product super strong. The copies are very strong. They would make them super strong. You would never calculate a failure.

Some of the data I saw really jumped out me because it didn't -- it's not consistent.

MEMBER MARTIN: They talked about that they have a best estimate mode. Now, if this best estimate brought in more UCO data, or something like that, you might be able to make -- again, I'm advocating a little bit too much probably, you know, just for the sake of a discussion.

MEMBER PETTI: I also just think that, you know, there's already plenty of use of UO2. Every diffusion coefficient we know --

MEMBER MARTIN: Right.

MEMBER PETTI: -- is UO2. There's nothing on UCO.

MEMBER MARTIN: That's IAEA import data.

MEMBER PETTI: Right, that's all UO2. But when you get into the failure stuff, you get into just a really messy, messy area, where you can say something fails. You take the uncertainty band on a parameter. I could tell you what they're like. And it goes from everything's okay to you get a large failure fraction. So the uncertainty is right in the wrong spot. You can prove it.

But, yes, I mean none of the testing done in France on liftoff was mentioned, which was surprising to me. Those were multimillion experiments that they got. So there were just a lot of things that I was, like, well, gee, I wonder why that wasn't --

MEMBER MARTIN: They assume 100 percent gets out on liftout.

MEMBER PETTI: They won't. They've gotten enough correlations. They're not going to -- no.

CHAIR KIRCHNER: I think I heard Vesna trying to say something.

MEMBER MARTIN: Yes.

MEMBER DIMITRIJEVIC: Yes.

CHAIR KIRCHNER: Go ahead, Vesna.

MEMBER DIMITRIJEVIC: Yes. So I am really confused with this letter because I cannot really define what this letter is. Because how can we write such a long letter on just this preliminary? This is just mostly planned how to develop the methodology. It's not the methodology. All right. So this plan may have its shortcomings, you know, but, very clearly, they need the models, or the validation plans are just preliminary and they're subject to change.

So, then, I was thinking, okay, maybe we are giving them advice, what should they consider or to do. But are those already our concerns? I mean, it just happened that Dave has really a big experience of that and he can be helpful in there, you know, telling them to make sure not to miss that; to consider this data, and that this can be an issue.

But this is just a plan. This is not methodology. So, why are we going into so many details about it? Can we just phrase it differently, you know? Just say, in the development of methodology, as you are finalizing this, these should be concerns, blah, blah, blah, blah.

I mean, they identify phenomena, right? I mean, you know, I don't really know what is the -- it is not criticism of what is done, because nothing is done. It is just a preliminary plan. And so, is it our advice? What is it? How do you see this letter, Dave?

MEMBER PETTI: Well --

MEMBER HALNON: Dave, let me referee this a little bit because I've been trying to reconcile the same question that Vesna has in my mind, but I was doing it with the Topical Report, when I called it kind of "white paperish."

We're certainly in the pre-application stage for the operating license at this point and this is a little -- I don't know. It's actually that we're expecting the full Topical Report for this in the operating license.

So we're in this mode of it's a little bit unique from the standpoint that it was -- could we call it "preliminary"? But just like the staff in their SER is providing some assurances and some agreements on approaches on how to do this, and it looks like it's going to be good, and it's a similar mode of providing some assurance and some additional information -- you could call it "advice," if you want -- on what the Topical Report for XSTERM actually needs to look at when we approve it for use to actually calculate a number that would show acceptable release rates and source term calculations for emergency plans and other licensing basis events.

So I think, in my mind at least, we are in a mode of here's a lot of information that's already out there. It is a little bit damning, from what Ron was saying, the fact that you should have already included all this in our discussions. But part of the strength of the Committee is that we have depth of experience, that we need to make sure that it's not "Bring me a rock and I'll let you know if you got it right." It's "Here's what the rock needs to look like," or at least consider going forward.

So that's how I've reconciled that in my mind this is actually a pretty good letter from the standpoint of providing another level of information that can be used. So, whenever we see the final Topical Report, we won't have these same questions.

MEMBER PETTI: So my concern when I put this together was thinking about when the OL is going to be here. I won't be here when the OL is here. So, I thought I would give the staff the bread crumbs. As we've talked about in other letters, these are things you ought to be looking for.

I predict the OL is at least five years away. There's no way they can execute the experiments in Idaho and post-irradiation testing in a couple of years. It's at least two years in ATR. It could be even closer to two and a half.

Then, cool it down. Bring it into the hot cell. Stick it in the furnaces. You know, that takes time.

That's why I was kind of surprised when I heard that they were actually relying on that for validation. Relying on it as a proof test is a different thing than relying for validation.

But, you know, just fast-forward. There's only going to be a handful of us on the Committee in five years. So again, this is kind of a --

MEMBER SUNSERI: So, why don't we -- I mean, an approach would be to write a shorter base letter that strikes right at the point that Vesna and Greg just outlined, and then, put an appendix with all this technical "for your future consideration" stuff in the back. Because, quite frankly, all the discussion, in my mind, just distracts really. I don't even know what we're saying, as far as the Topical Report goes, until you get to the very end. But that's just me.

Once again, it would be clearer if there was a very succinct letter that says: go forward with the model or develop the model. But refer to the appendix portion for some potential shortfalls, and whatever.

MEMBER HALNON: I like the letter. I think it's appropriate. Remember, this TR is asking for a roadmap. You know, they're coming in. This is the roadmap we're going to follow for our licensing. And this is where we found some holes in it. There's some stuff missing. So I think it's very appropriate to have it here instead of waiting until later, until we actually see this XSTERM, and then, pointing out the holes. It's better to have the information early.

You're right that the full XSTERM TR is going to be the operating license, but the NRC presentation talked about a lot of the results are going to be needed for the construction license, too. So it wasn't really clear, but it sounds like they're not going to have the full XSTERM now, but they're definitely going to have results at the CP level.

So they are going to need this stuff sooner than later. So I like the tone of the letter.

MEMBER SUNSERI: Can we kind of make this kind of a simple change on the letter by -- Sandra, if you can go to 3? There's just a few lines there. Just kind of put that last conclusion in a more specific context about this being adequate for review of Xe-100 PSARs, which is basically what the staff says.

But the way it reads, it's just kind of one of our generic topicals. It's fine. And if we narrow it down to, okay, well, it has a limited application, acknowledged by the staff, go ahead and issue it, and then we'll see.

I think your point about the concerns kind of addresses what we're kind of talking about. It's that we're presenting some concerns. We hope to see those addressed down the road.

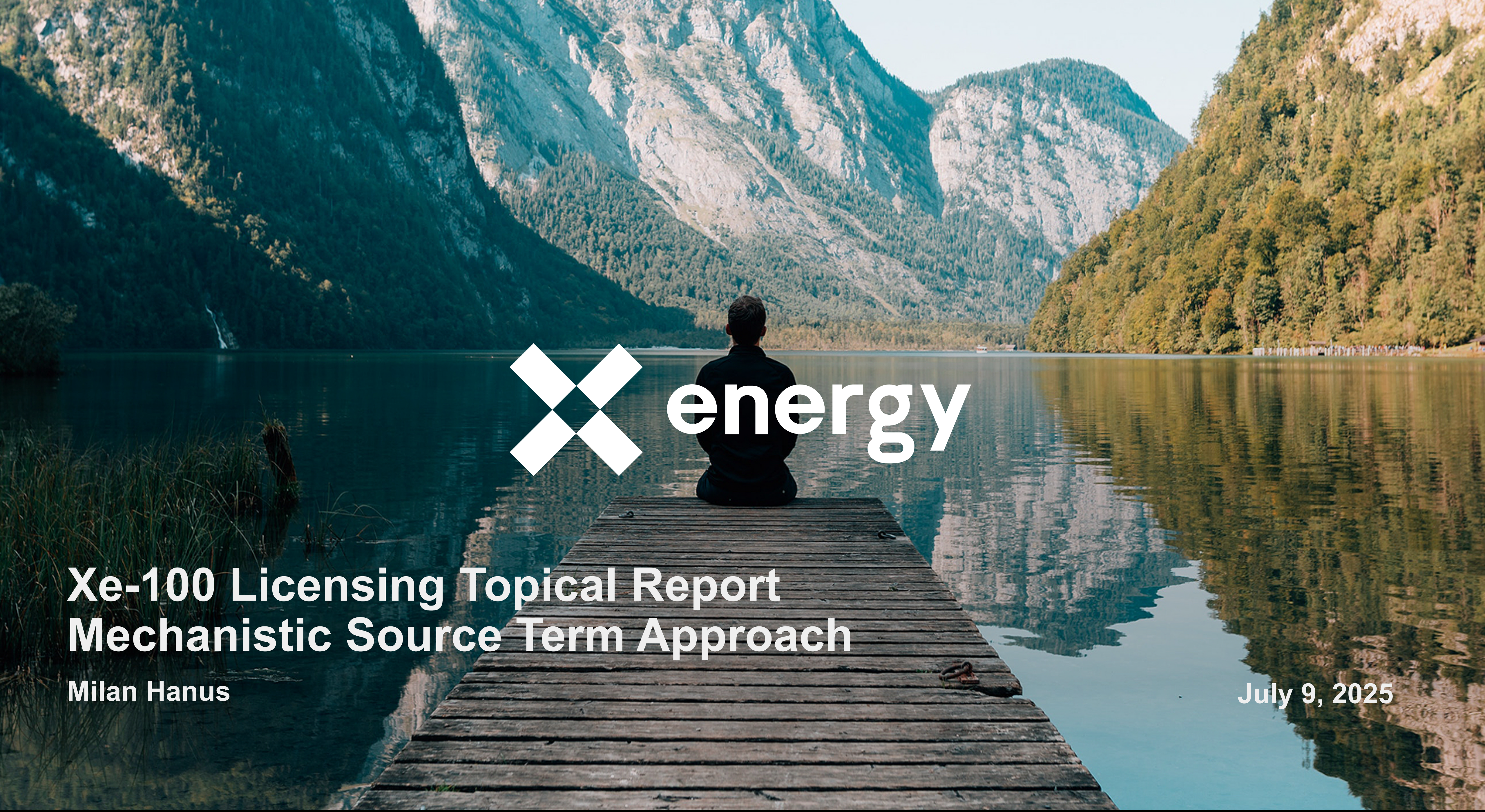
CHAIR KIRCHNER: I just would make two points.

One, that two of these points were actually in the staff's conclusions. One is that it's limited to preliminary analyses, and two, that it's a reasonable plan for development of an MST methodology. And I think somehow we ought to capture that.

I want to stop us here. We have the court reporter with us and we usually don't transcribe our letter-writing activities.

So, at this point, we can let you go for the rest of this meeting. So thank you for your services. And for the rest of the meeting today and tomorrow, we will not require a transcription. Thank you.

(Whereupon, at 11:47 a.m., the verbatim reporting of the proceedings was concluded.)



Xe-100 Licensing Topical Report
Mechanistic Source Term Approach

Milan Hanus

July 9, 2025

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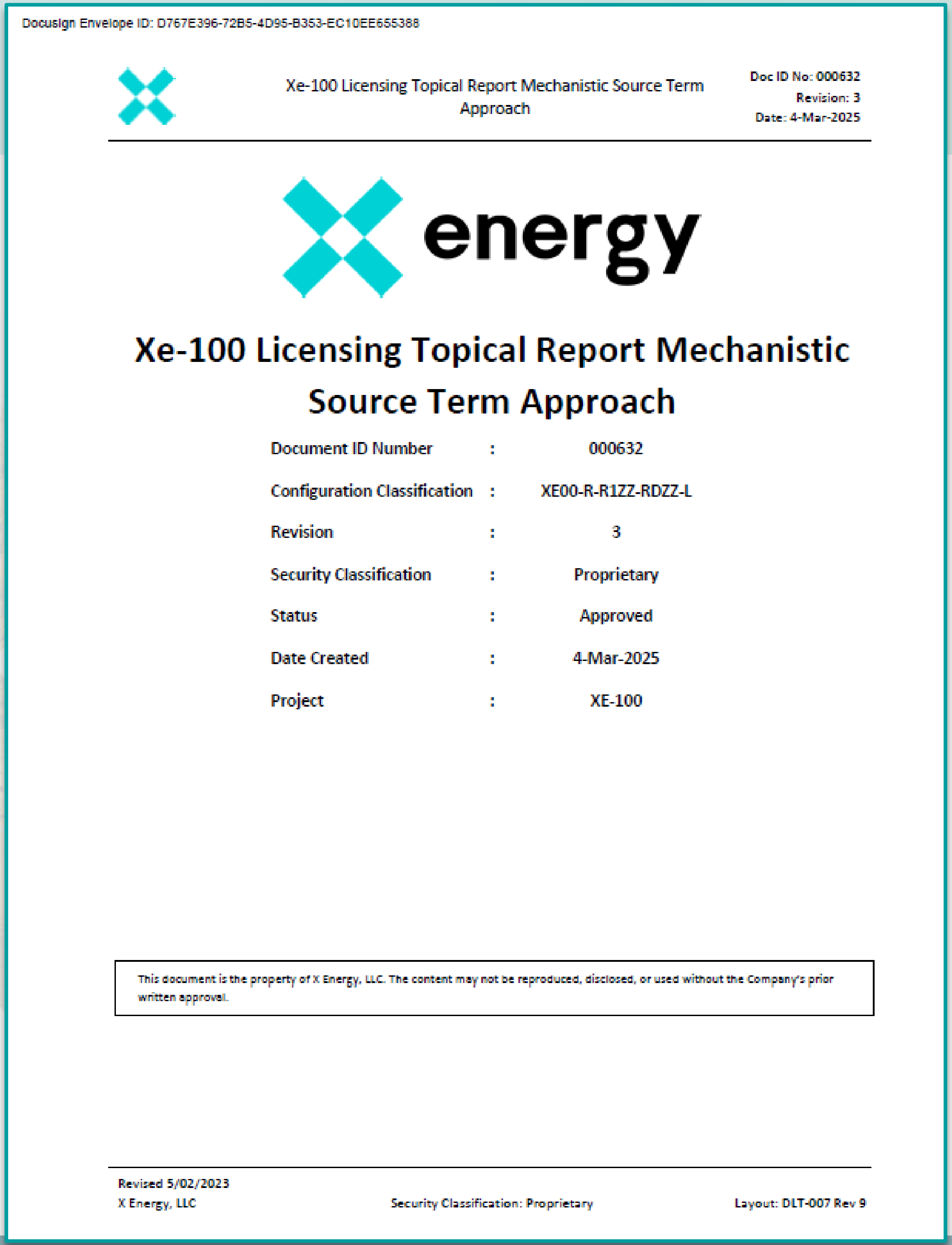
Outline

- X-energy's Mechanistic Source Term (MST) Approach
- Mechanistic Source Term Models
- Q&A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Xe-100 Licensing Topical Report Mechanistic Source Term Approach

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Xe-100 Licensing Topical Report Mechanistic Source Term Approach

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Mechanistic Source Term (MST) Approach

- **Scope:**
  - **Included:** Description of MST models used to determine radionuclide transport phenomena and estimate mechanistic source terms used to support the preliminary analysis and evaluation of the Xe-100
  - **Excluded:** Actual implementation evaluation cases and outputs (included in a future XSTERM Topical Report)

- **Interfacing Documents:**
  - Risk-Informed Performance-Based Licensing Basis Approach for the Xe-100 Reactor (ML21196A071)
  - Xe-100 Licensing Topical Report: Transient and Safety Analysis Methodology (ML25077A285)
  - Xe-100 Principal Design Criteria Licensing Topical Report (ML24047A310)
  - Xe-100 Licensing Topical Report TRISO-X Pebble Fuel Qualification Methodology (ML22216A179)
  - Xe-100 Licensing Topical Report Atmospheric Dispersion and Dose Calculation Methodology (ML23268A456)

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Mechanistic Source Term (MST) Approach

- Xe-100 MST methodology is part of the implementation of a **risk-informed, performance-based design and licensing basis** according to the Nuclear Energy Institute (NEI) 18-04 and Nuclear Regulatory Commission (NRC) Regulatory Guide (RG) 1.233

- **Regulatory Guidance (SECY-93-092):**
    - Reactor and fuel performance under normal and off-normal operating conditions is sufficiently well understood to permit a mechanistic analysis.
    - Sufficient data should exist on the reactor and fuel performance through the research, development, and testing programs to provide the adequate confidence in the mechanistic approach.
    - Transport of fission products can be adequately modelled for all barriers and pathways to the environs, including specific consideration of containment design. The calculations should be as realistic as possible so that the values and limitations of any mechanism or barrier are not obscured.
    - Events considered in the analyses to develop the set of source terms for each design are selected to bound severe accidents and design-dependent uncertainties.

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Mechanistic Source Term (MST) Approach

- **Xe-100 source terms** are:
  - Event-specific
  - Determined mechanistically using models of fission product (FP) generation and transport
  - Accounting for the reactor’s inherent and passive design features and the performance of FP release barriers that constitute the functional containment
  - Inclusive of the quantities, timing, physical and chemical forms, and thermal energy of the release
  - Different from light water reactor source terms based on severe core damage event(s)

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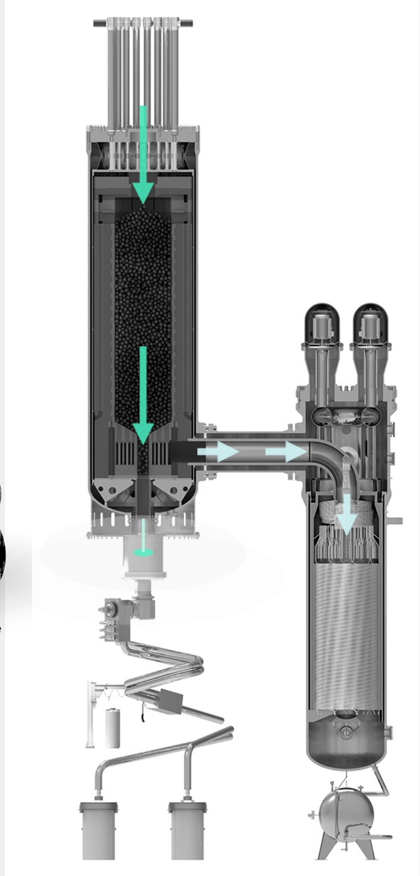
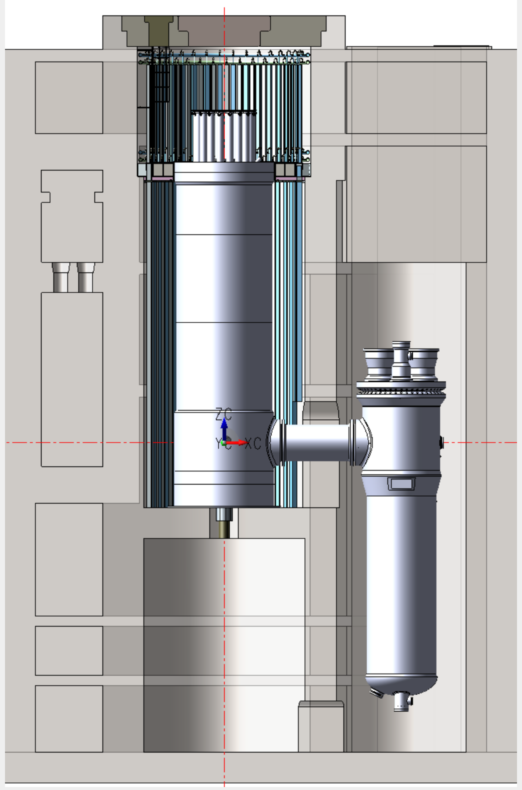
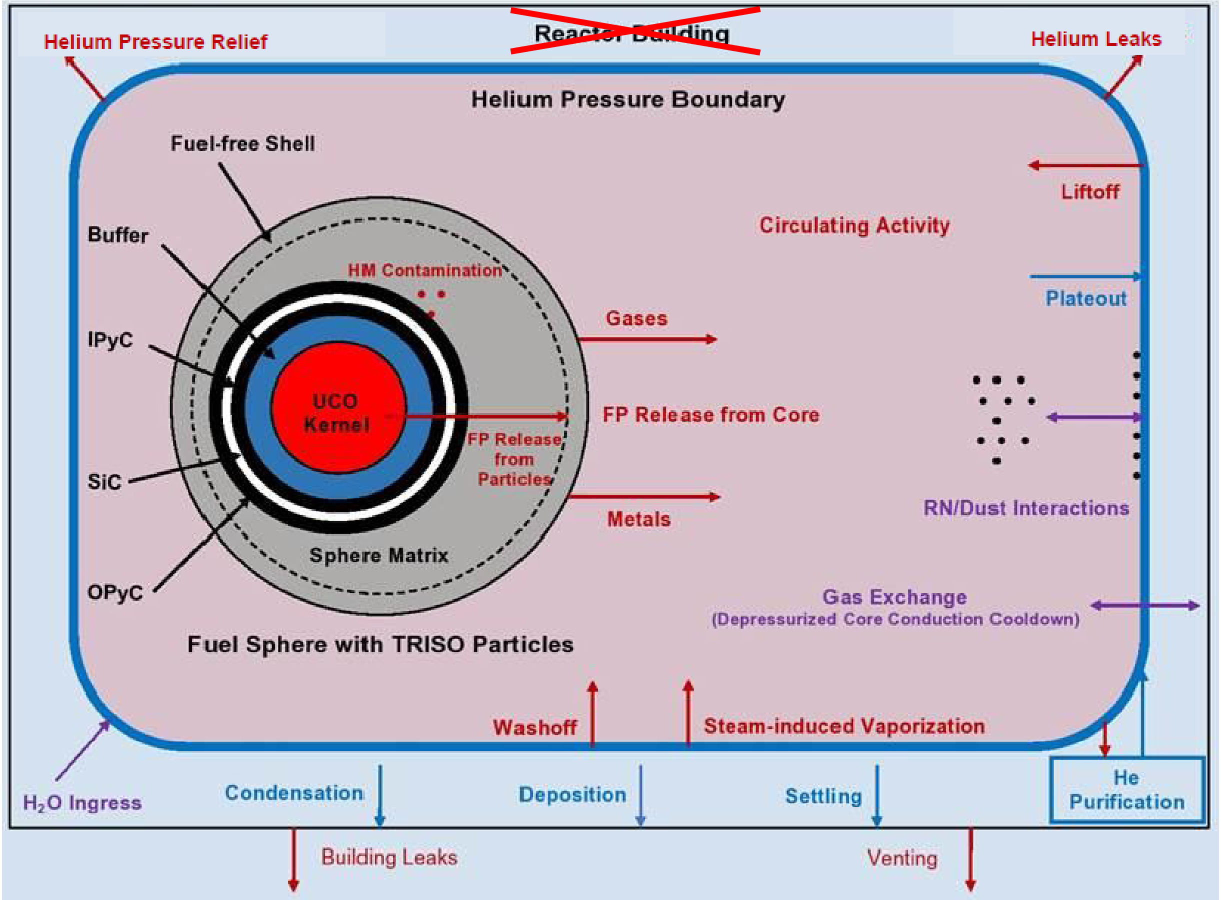
Mechanistic Source Term (MST) Approach







Radionuclide Release Barriers

Mechanistically Modelled Radionuclide Transport Phenomena

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MST Models

LTR Appendix	*Model*	*Scope*	*Codes implementing similar capability*
A	FPM	Fuel Performance (particle failure fractions)	PARFUME (INL), PANAMA, STACY
B	THM	Thermodynamics	VSOP-THERMIX-KONVEK, AGREE (UMich), STAR-CCM+ (Siemens)
C	SOLM	Time-dependent radionuclide production, transport & release from fuel elements	PARFUME (INL), GETTER, FRESCO, STACY
D	GASM	Steady-state gaseous fission product release	PARFUME (INL), NOBLEG, STACY
E	DUSTM	Graphite / metallic dust production	N/A
F	HPBM	Dust, fission and activation product behavior in primary circuit	DAMD (PBMR), PADLOC (GA), RADAX, SPATRA, RADC (GA), MELCOR (Sandia)
G	CORRM	Air/water Ingress, fuel materials corrosion rates	OXIDE-4 (GA), TINTE, GRACE (FE), STAR-CCM+ (Siemens), Fluent (ANSYS)
	KSIM	Plant simulator using point-kinetics core model with spatial and thermo-dynamics coupling	MGT / TINTE, AGREE (UMich), RELAP-7 (INL), Flownex (M-Tech)
	TRITM	Tritium plant mass balance	TRITGO (GA), THYTAN (JAEA), TPAC (INL), TMAP (INL), ORIGEN-S (ORNL)
	Dispersion/Dose	Off-Site doses	MACCS (Sandia), HotSpot (LLNL), RASCAL (NRC), ADDAM (AECL)

→ *Xe-100 Licensing Topical Report, Atmospheric Dispersion and Dose Calculation Methodology* (ML23268A456)

XSTERM

US-DOE Code

German (Legacy) Code

Commercial NQA-1 Code

Other

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XSTERM Code

- **Evaluation Model for the quantification of Xe-100 source terms and dose calculations**
- Implementation of the MST models presented in this TR, part of X-energy safety analysis code suite
- Developed under X-energy Quality Assurance Program
- Goal: NQA-1 qualification

- **Verification and Validation, Uncertainty Quantification** in progress
    - Line-by-line code verification, comparison with analytical solutions, automated testing in the continuous-integration framework
    - Phased validation – each phase aims at validating a set of medium and high ranked phenomena from the Xe-100 Safety Analysis PIRT
        - Phase 1: Activity Release and Transport (FPM, GASM, SOLM, HPBM)
        - Phase 2: Reactor Temperature and Power (TDM, KSIM)
        - Phase 3: Dust Production (DUSTM)
        - Phase 4: Exposure to Oxidating Environments (CORRM, TRITM)
    - Uncertainty Quantification Plan based on the Xe-100 Safety Analysis PIRT

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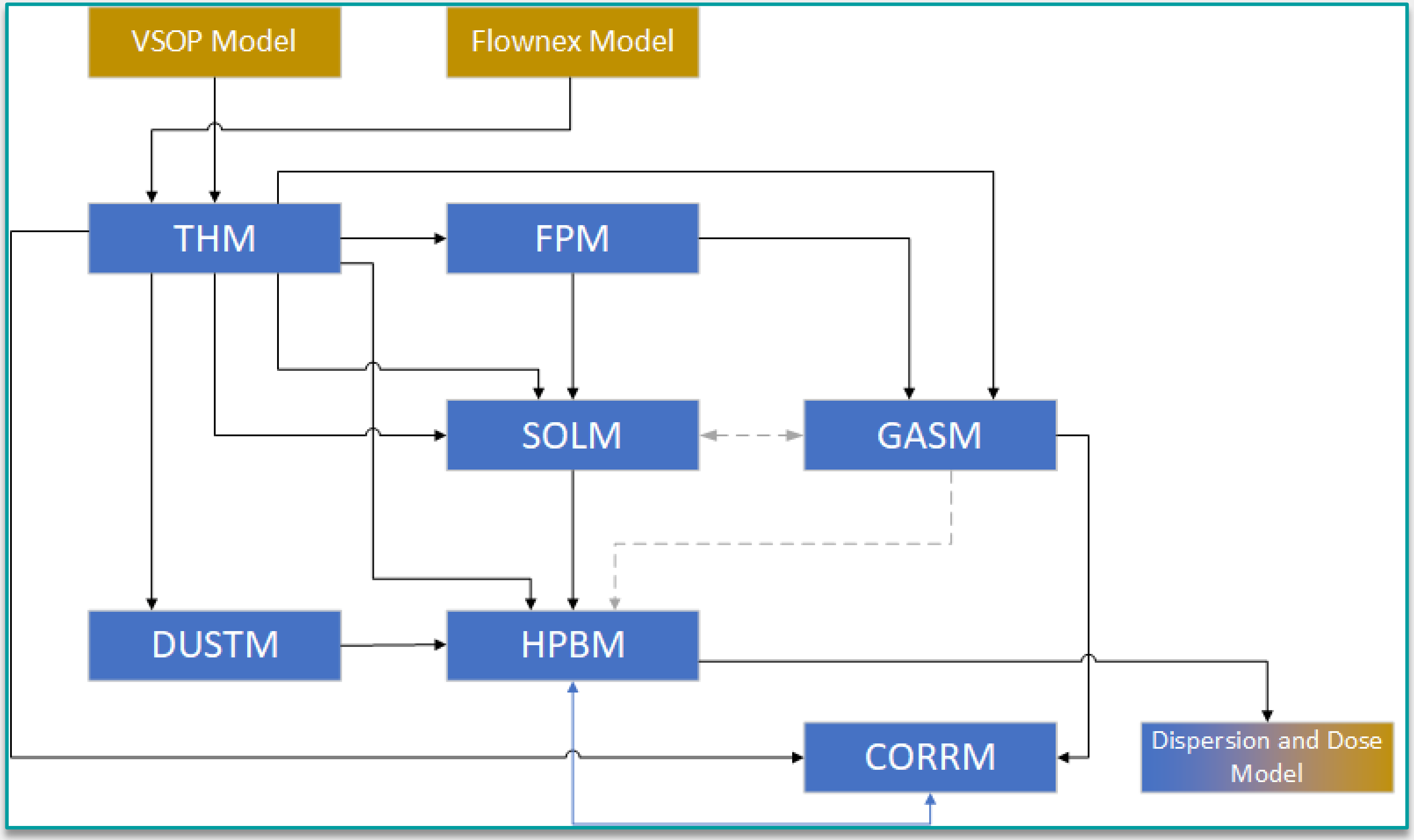
Core MST Models Relationship



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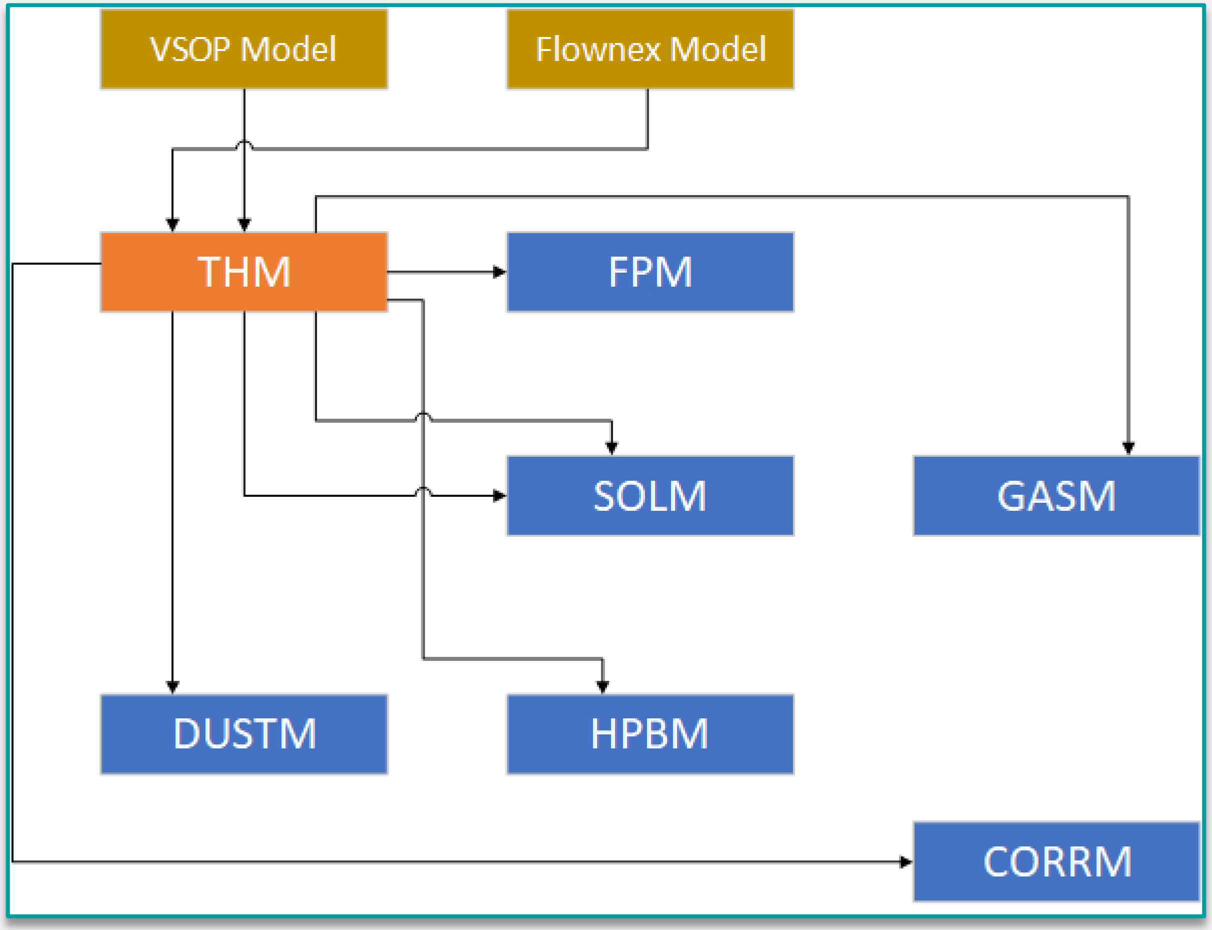
THM: Thermodynamics Model



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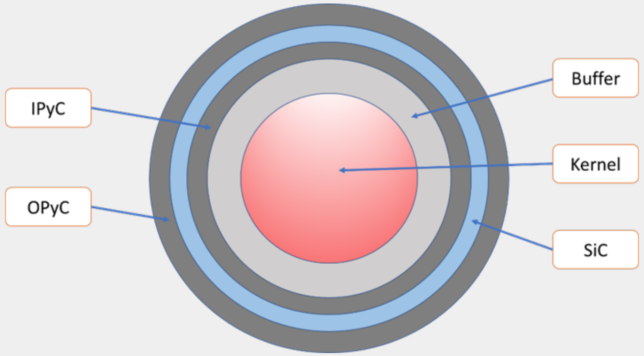
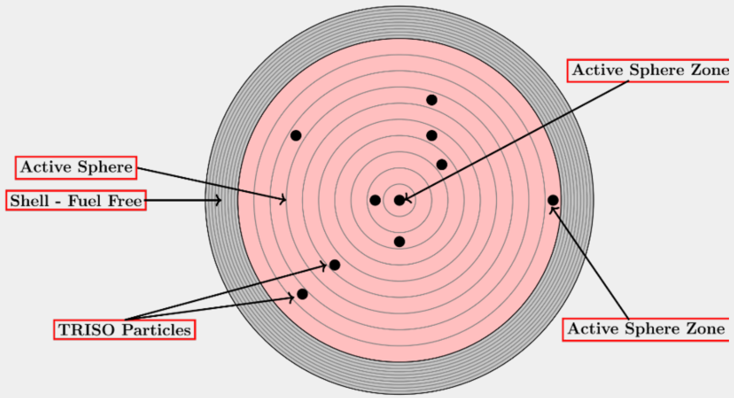
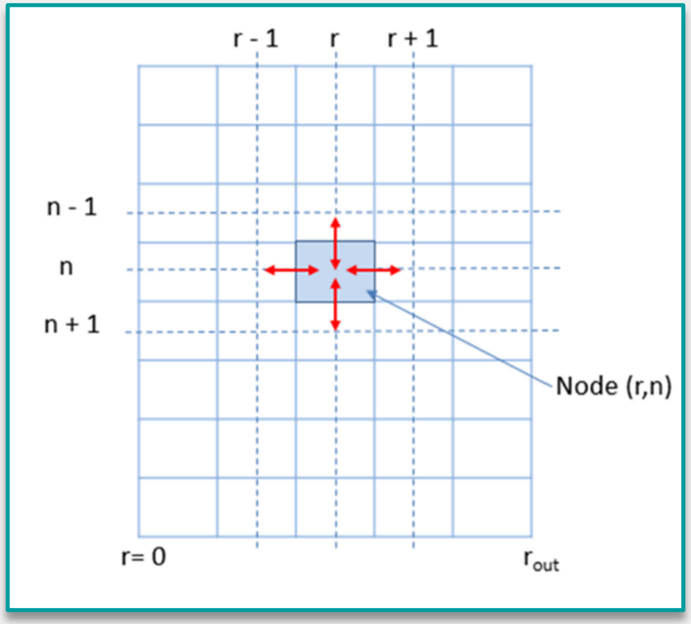
THM: Application Domain

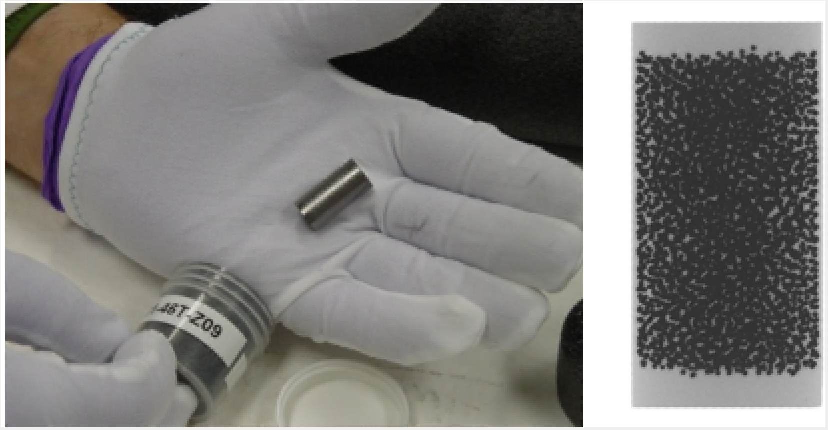
Xe-100 Single-Pebble / Core Calculations

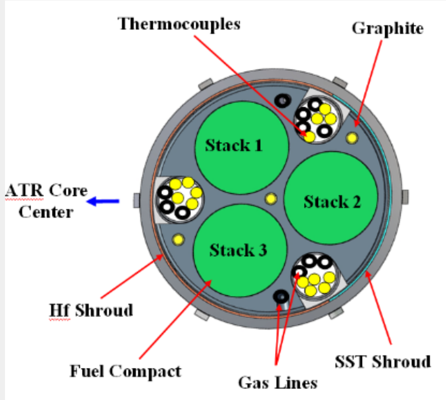






Fuel Compact Calculations (Validation)





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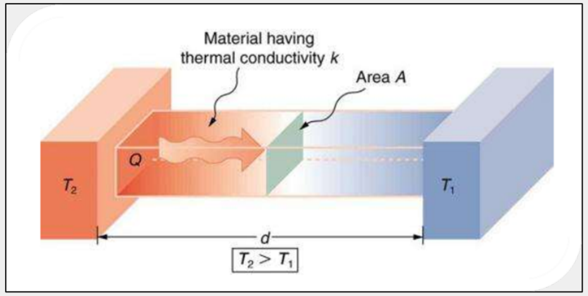
THM: Phenomena Modelled

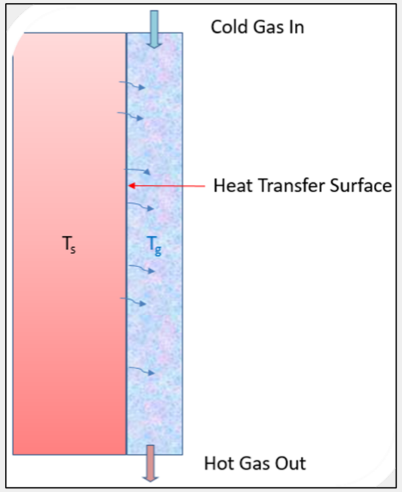
- Conductive Heat Transfer: Fourier law of heat conduction with space-, temperature- and dose-dependent conduction coefficients
  - Zehner-Bauer-Schlünder model in the pebble bed

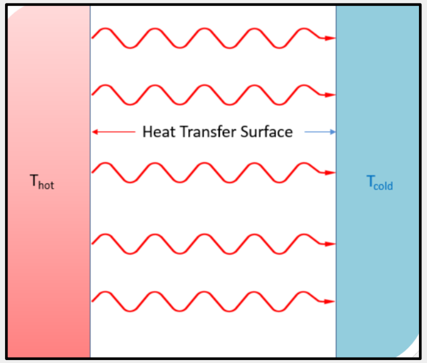
$$\lambda_{pb} = \lambda_{sc} + \lambda_r + \lambda_f$$

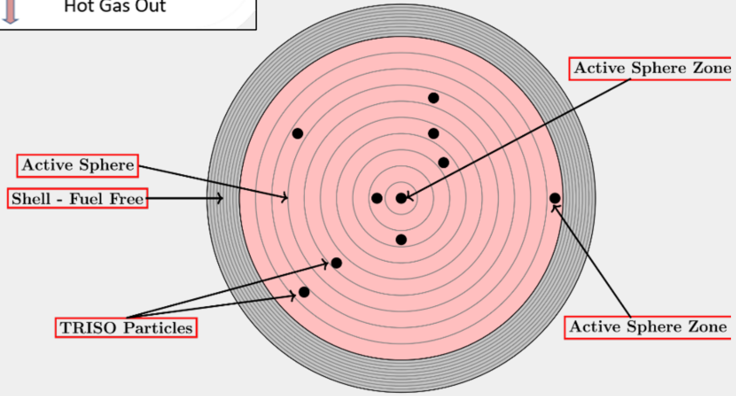
  - Reflector graphite model based on research of G. Haag
- Convective Heat Transfer: Kugeler-Schulten correlation
- Radiative Heat Transfer: Stefan-Boltzmann law
- Heat Sources: fission, gamma, decay heat (DIN-25485 standard)

- Pebble temperatures: 1D-radial heat conduction through pebble mesh zones with core node temperature as boundary condition – semi-analytic
- Particle temperatures: 1D-radial heat conduction through particle mesh zones with pebble zone temperature as boundary condition – semi-analytic
- Compact temperatures: 2D-axisymmetric heat conduction through compact zones with prescribed outer temperature – finite-difference discretization + successive-over-relaxation iterative method









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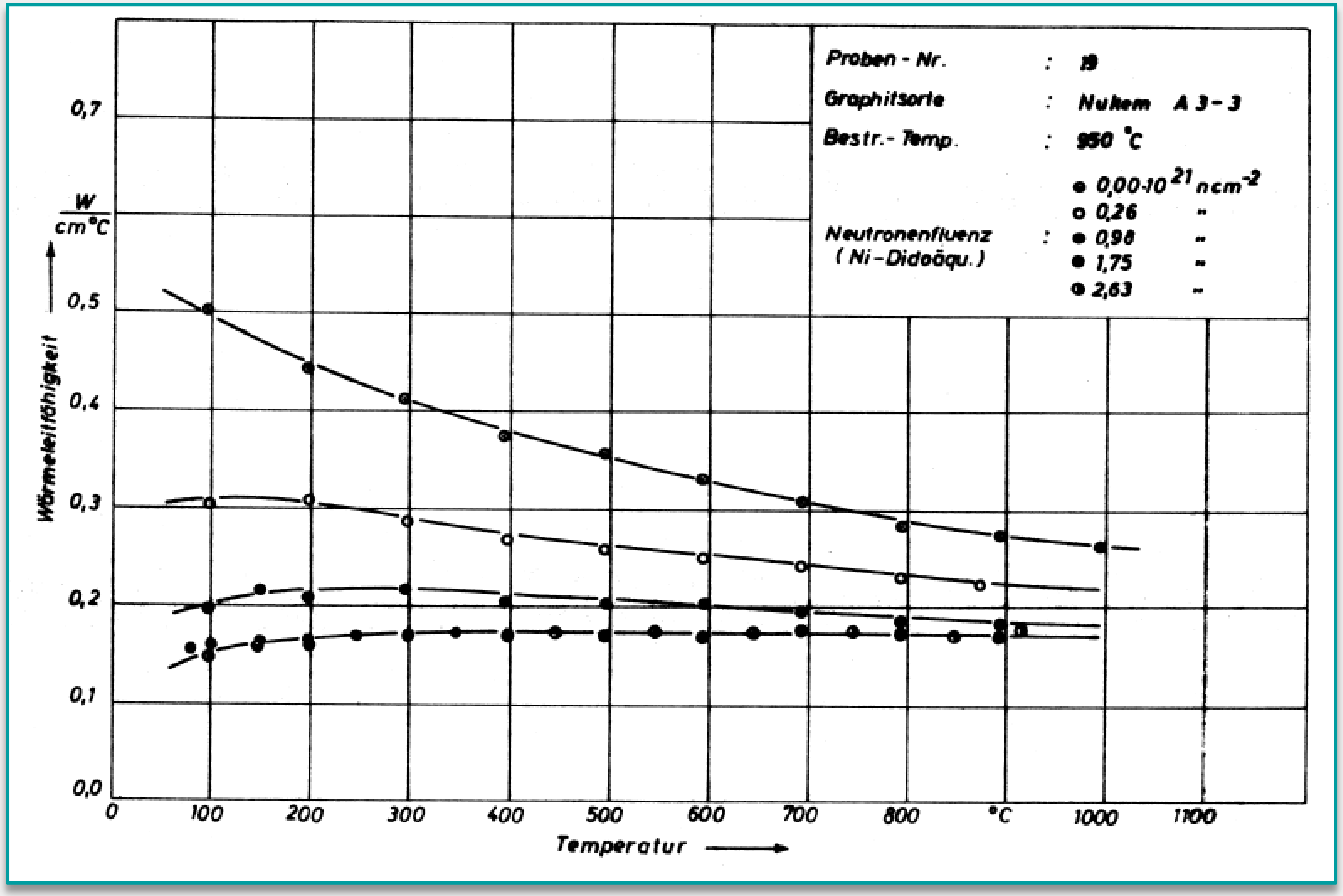
THM: Material Properties

- Explicit correlations or data fits
- Generally temperature-dependent => iterations



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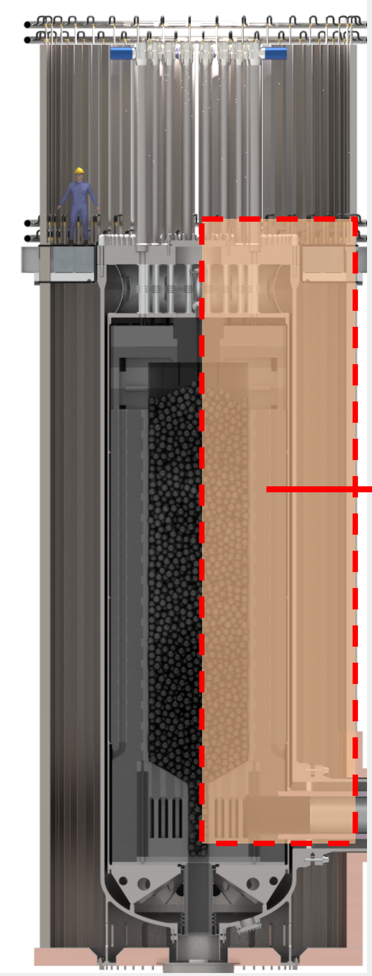
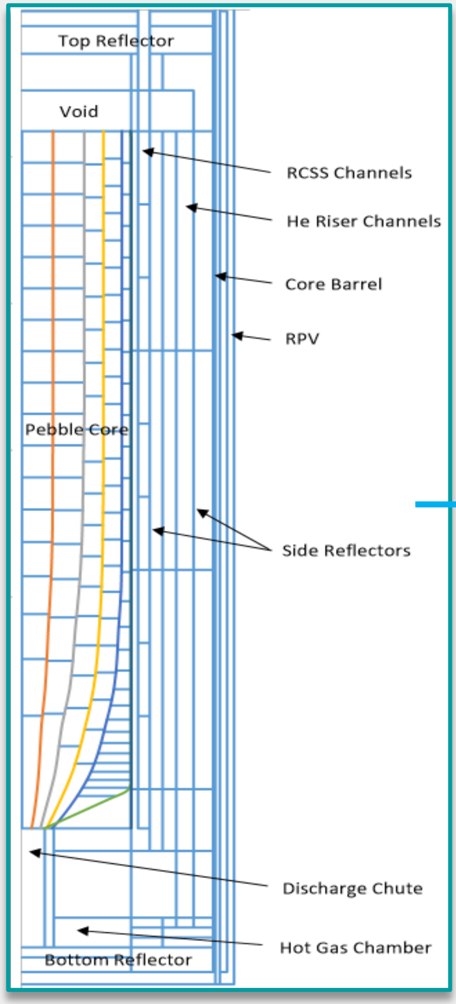
THM: Input Data and Boundary Conditions

- Second order least-squares mapping from VSOP grid to simplify heat transfer calculations

Xe-100 Reactor



VSOP Model



MST Model

Fuel 1	Fuel 2	Fuel 3	Fuel 4	Fuel 5	Reflector 1	Reflector 2	Reflector 3	Ref3/Barrel	Barrel	RBCS	RP
297.7	295.5	292.3	297.6	299.4	283.1	275.7	268.7	266.1	260.2	256.2	208.
337.3	332.4	326.0	332.4	347.3	300.6	285.9	275.9	270.2	265.4	259.5	213.
376.0	368.6	359.1	369.4	394.5	318.9	295.0	281.2	274.2	269.1	262.8	217.
417.4	407.5	395.2	410.3	439.8	341.3	307.0	287.4	278.5	272.6	263.7	218.
461.6	449.4	433.8	450.3	478.3	364.4	319.8	293.7	283.0	275.9	264.0	219.
503.3	488.7	471.7	488.8	510.9	386.9	332.9	300.3	287.4	279.4	264.4	219.
543.3	526.5	508.5	525.3	537.7	409.5	347.0	307.5	292.5	283.3	265.0	219.
581.2	562.4	543.5	557.4	559.7	431.3	361.0	314.7	297.6	287.2	265.6	220.
615.6	594.8	575.6	587.1	577.7	451.6	374.6	321.7	302.5	291.0	266.1	220.
646.6	624.2	605.7	613.2	593.0	469.9	387.1	328.3	307.2	294.7	266.6	221.
674.6	650.7	633.4	636.6	605.8	487.5	399.5	334.8	311.9	298.3	267.1	221.
699.8	674.5	657.4	657.3	616.6	502.9	410.5	340.7	316.1	301.5	267.6	222.
722.6	696.2	679.3	675.4	625.9	516.7	420.7	346.2	319.9	304.5	267.9	222.
742.2	714.7	699.1	690.9	634.4	530.1	430.6	351.5	323.8	307.5	268.3	222.
759.3	730.8	716.7	704.1	642.2	540.8	438.7	355.9	326.8	309.8	268.6	222.
774.4	745.3	732.5	715.6	649.4	551.0	446.3	360.0	329.8	312.1	268.8	223.
787.9	758.1	746.0	725.8	656.1	560.4	453.5	363.9	332.6	314.3	269.1	223.
799.2	769.1	757.7	734.6	662.6	568.1	459.2	367.0	334.8	316.0	269.2	223.
808.9	778.7	768.5	742.2	668.1	575.4	464.8	370.0	337.0	317.7	269.3	223.

Total core mass flow rate (Flownex)

Disclaimer: Values shown above only for illustrative purposes

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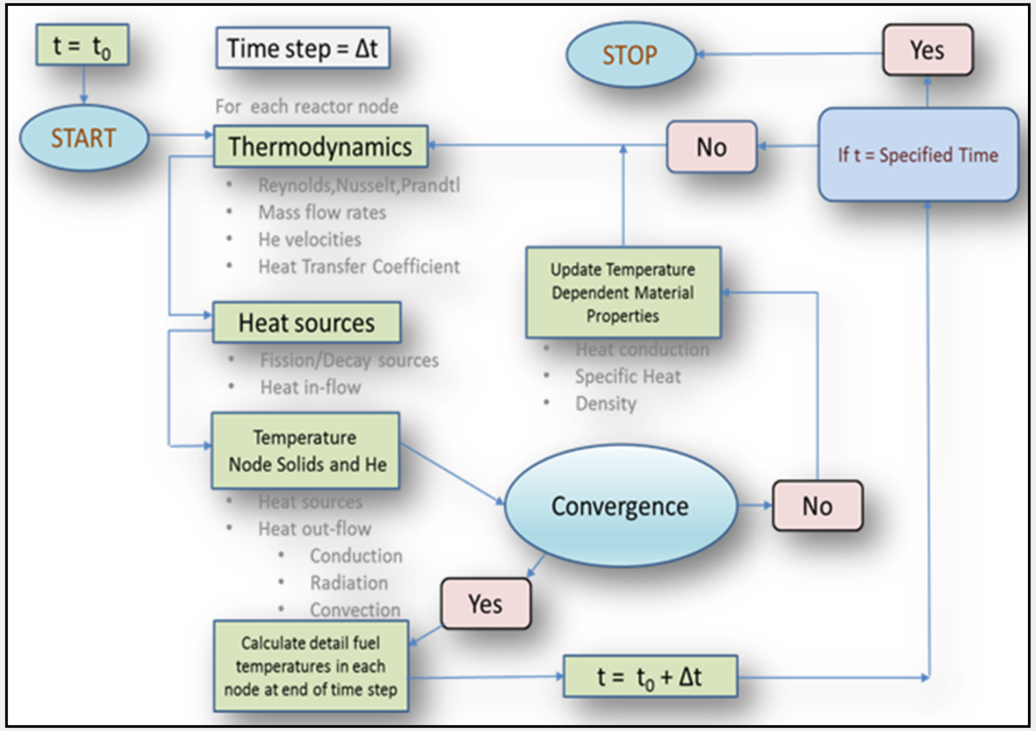
THM: Time-Stepping Algorithm

- Backward Implicit/Explicit Iterative Method
- Iterative calculation to converge reactor and coolant temperatures in each time-step
- Transient simulations
- Establishing steady state



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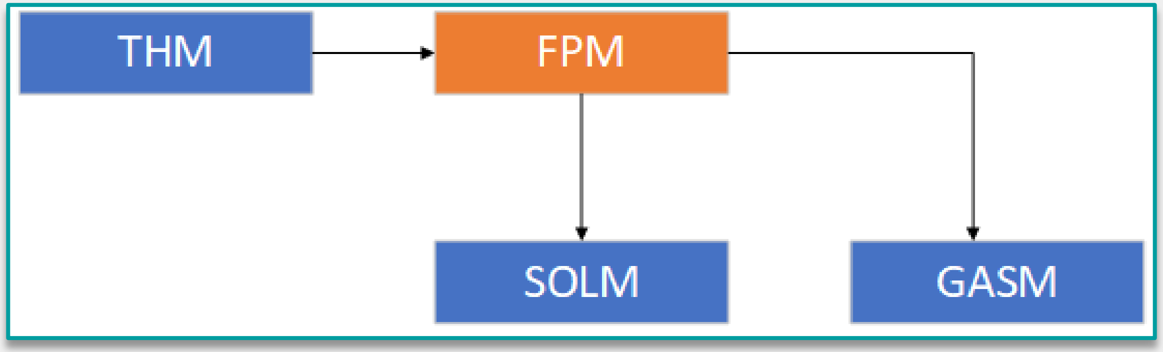
FPM (Particle Failure Probability Model)



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FPM: Phenomena Modelled

- **Pressure vessel failure** of TRISO particles
  - effects of pyro-carbon (PyC) irradiation-induced creep on the effective stress of the silicon-carbide (SiC) layer
  - Irradiation-Induced dimensional change of PyC layer
  - Fission gas pressure
  - Kernel irradiation swelling
  - Kernel thermal expansion
- **Kernel migration** (Amoeba)
- **Fission product corrosion**
- **SiC thermal decomposition**
- **Manufacturing defects**
  - Exposed kernel (i.e., defect of all coating layers)
  - SiC defect (i.e., defect of the SiC layer with at least one other coating layer intact)
  - Inner PyC layer defect
  - Dispersed heavy metal fraction

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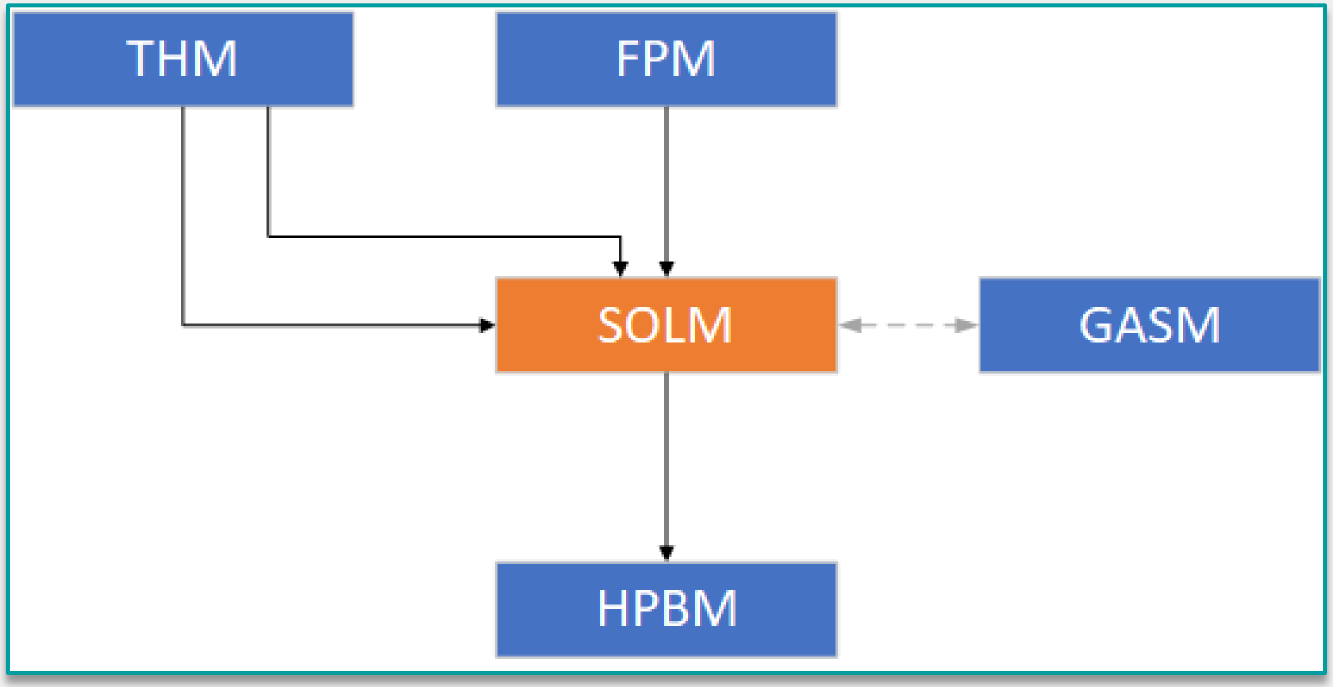
SOLM (Fission Product Transport Model)



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SOLM: Phenomena Modelled

- Fission product **production** by **direct fission** in kernels, **recoil** from kernels to the buffer layer, **decay** and **activation**
- Fission product **removal** by means of **decay** and **activation**
- **Transport and release** of fission products from particles and fuel elements by means of **diffusion**
- Effects on isotope transport and retention from **as-manufactured particle defects**, **contamination** and **particle failures** that may occur during operation

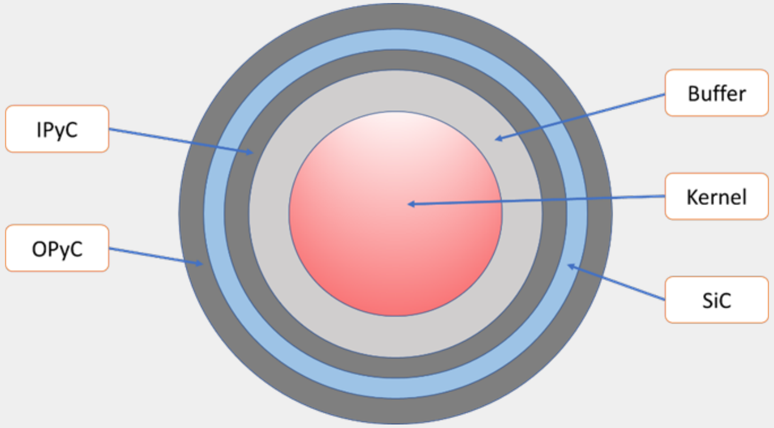

Table 4-2. Classes of radionuclides of interest for HTGR design.

Radionuclide Class	Key Nuclide	Form in Fuel	Principal In-Core Behavior	Principal Ex-Core Behavior
Tritium	H-3	Element (gas)	Permeates intact SiC; sorbs on core graphite	Permeates through heat exchangers
Noble gases	Xe-133	Element (gas)	Retained by PyC/SiC	Removed by helium purification system
Halogens	I-131	Element (gas)	Retained by PyC/SiC	Deposits on colder metals
Alkali metals	Cs-137	Oxide-element	Retained by SiC; some matrix/graphite retention	Deposits on metals/dust
Tellurium group	Te-132	Complex	Retained by PyC/SiC	Deposits on metals/dust
Alkaline earths	Sr-90	Oxide-carbide	High matrix/graphite retention	Deposits on metals/dust
Noble metals	Ag-110m	Element	Permeates intact SiC	Deposits on metals
Lanthanides	La-140	Oxide	High matrix/graphite retention	Deposits on metals/dust
Actinides	Pu-239	Oxide-carbide	Quantitative matrix/graphite retention	Retained in core

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SOLM: Modelling Scope

- Calculate **isotope concentrations** in fuel elements and particles
  - **for all core meshes**, following the multi-pass re-loading scheme to reach desired burnup to create an isotope library with the concentration distributions (initial condition for steady-state inventory and transient calculations)
  - **for a single sphere/compact** to model irradiation and safety (annealing) experiments (validation) and isolated fuel element calculations
- Calculate the **release over birth (R/B) ratios** for steady-state irradiations and **fractional releases** for transients

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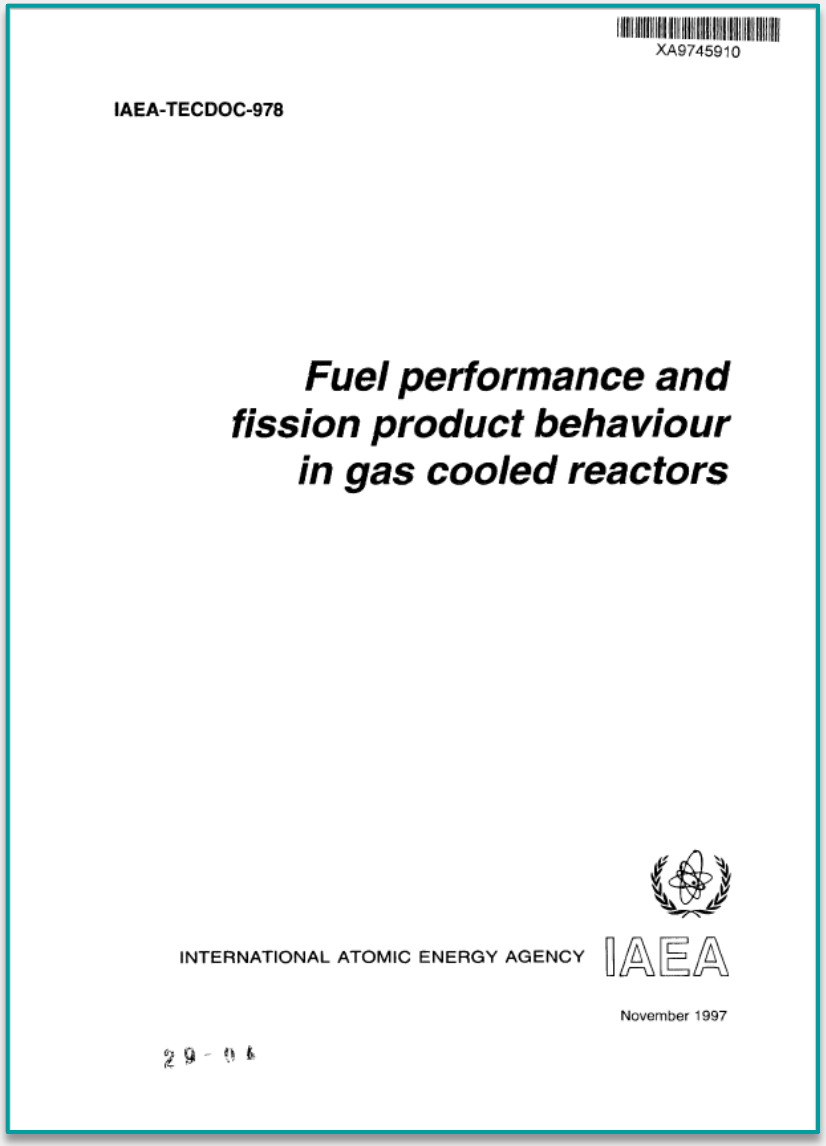
SOLM: Methodology

- Time-dependent heat conduction equation with temperature-dependent **effective diffusion coefficients**

$$D_{eff} = D_1 exp\left\{-\frac{Q_1}{RT}\right\} + D_2 exp\left\{-\frac{Q_2}{RT}\right\}$$

- 1D radial (pebbles) or 2D axi-symmetric (compacts)

- Boundary conditions: **Zero surface concentration** or **sorption transfer** via iso-thermic exchange between pebble surface and thin gas layer


XA9745910

IAEA-TECDOC-978

Fuel performance and fission product behaviour in gas cooled reactors

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

November 1997

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SOLM: Numerical Solution

- **Implicit Euler method** for time-stepping for pebbles and compacts, or **backward-difference method (BDF2)** for compacts

- At each time step, a **system of linear algebraic equations** arising from the **finite difference discretization** of the diffusion and source terms is solved:

  $\Rightarrow$ 3-diagonal matrix system for pebble geometries

  – solved by Gaussian elimination

  $\Rightarrow$ 5-diagonal matrix system for compact geometries

  – solved by the Gauss-Seidel iterations

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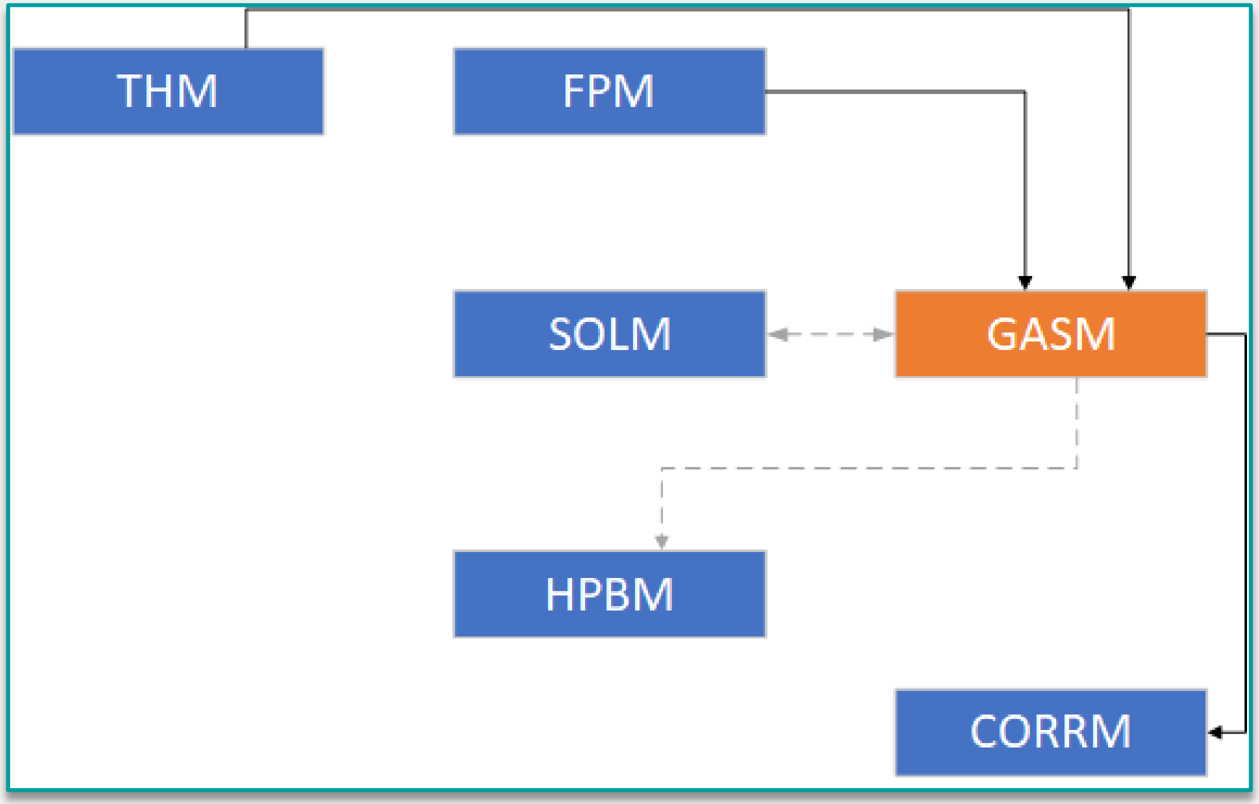
GASM (Gaseous Fission Product Transport Model)



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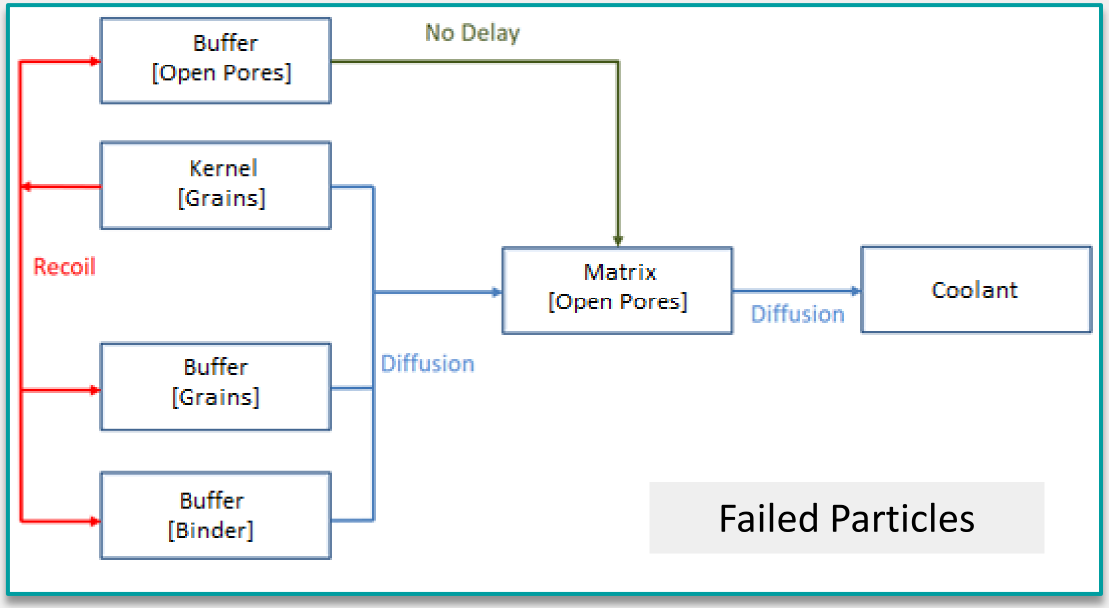
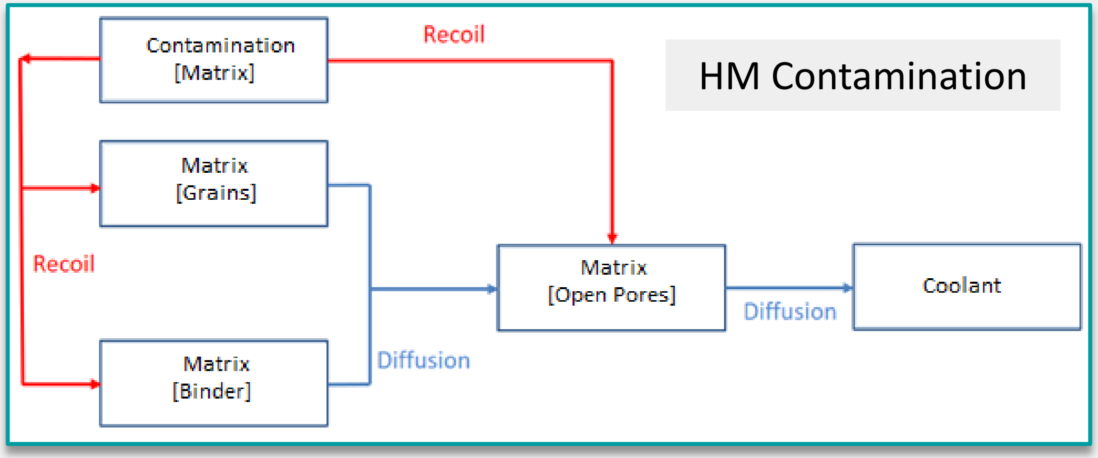
GASM: Phenomena Modelled

- Steady-state gaseous fission product (FP) release from particles and pebbles (R/B ratios)
- Short half-lives of the gas isotopes => transport from the fuel kernel through intact coatings can be neglected
- FP sources:
  - heavy metal (HM) contamination of matrix/outer PyC layers of particles
  - failed particles
- Two models dynamically switching based on fuel temperature: **Röllig Model** and **Richards Model**





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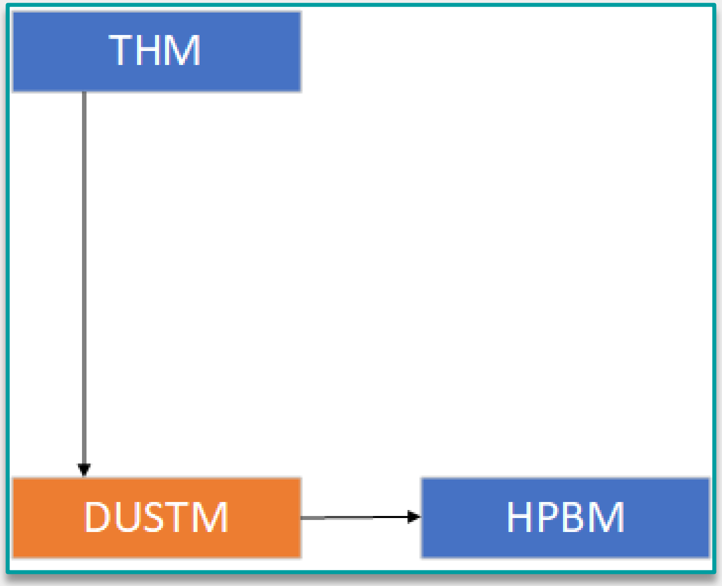
DUSTM: Dust Production



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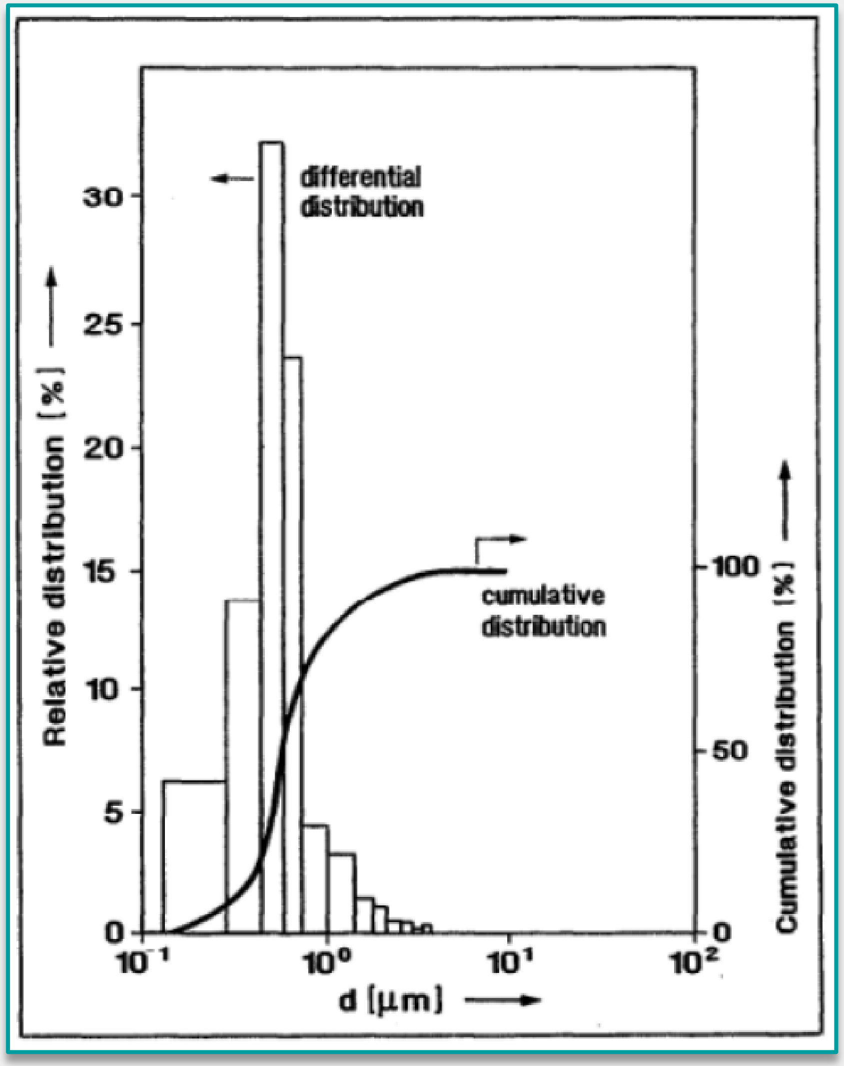
DUSTM: Phenomena Modelled

- Graphite and metallic dust production from
  - pebble-pebble and pebble-reflector abrasion
  - pebble abrasion during its transport through the fuel handling system (FHS) piping
  - control rod abrasion during its movements over the operating period
- Dust particle size spectrum lumped into bins, based on the historical measurements from the German pebble-bed reactor AVR



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DUSTM: Methodology

- In-Core dust production
  - Wear from friction based on the theory of asperity contact
  - Total dust production proportional to geometry-dependent **dust production rate parameter** and **frictional force**
  - Frictional force proportional to temperature-dependent **friction coefficient** and height-dependent load pressure on the pebbles
  - **Load pressure** on the pebbles computed by modified Janssen's silo pressure formula including the effects of pressure drop
- Dust production in fuel handling system (FHS)
  - Proportional to empirically determined dust generation rate per meter of pebble movement in the FHS, number of fuel passes and length of the FHS pipe
- Dust production in the reactivity control system (RCS)
  - Proportional to empirically determined dust generation rate per meter of RCS rod motion and the total RCS rod distance travelled during the operation time
- **Dust production rate parameter** determined by applying the model on the AVR reactor operation data and adjusting the parameter to yield the measured total lifetime dust in AVR
  - Graphite/metallic dust ratio obtained from the Vampyr II experiment data

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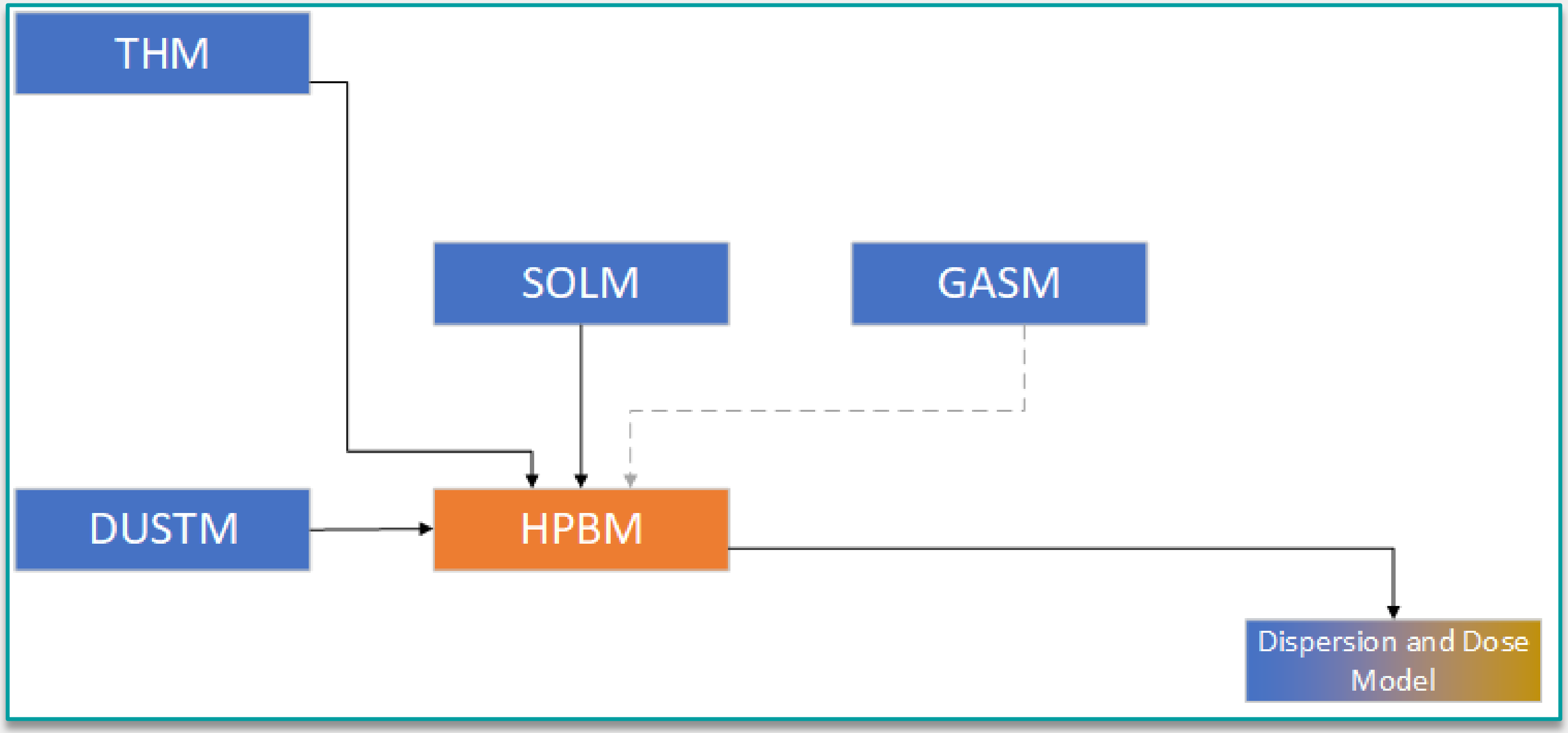
HPBM: Helium Pressure Boundary Model



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HPBM: Phenomena Modelled

- radionuclide (RN) release from pebbles,
- deposition on component surfaces (RN, dust),
- plate-out on dust (RN)
- re-entrainment into circulating He (RN, dust),
- intra- and inter-component transport (RN, dust),
- RN transmutation through activation and radioactive decay
- RN removal through radioactive decay
- RN sorption into the graphite dust and de-sorption into circulating helium

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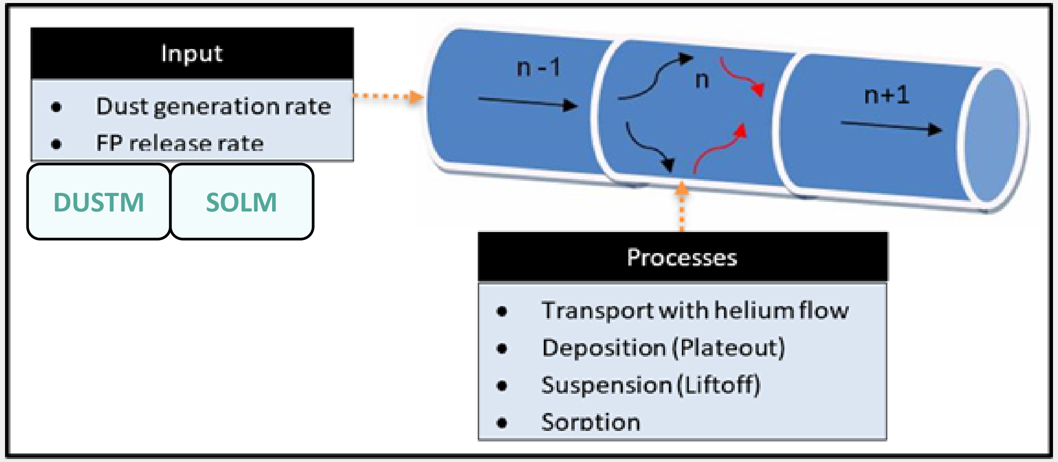
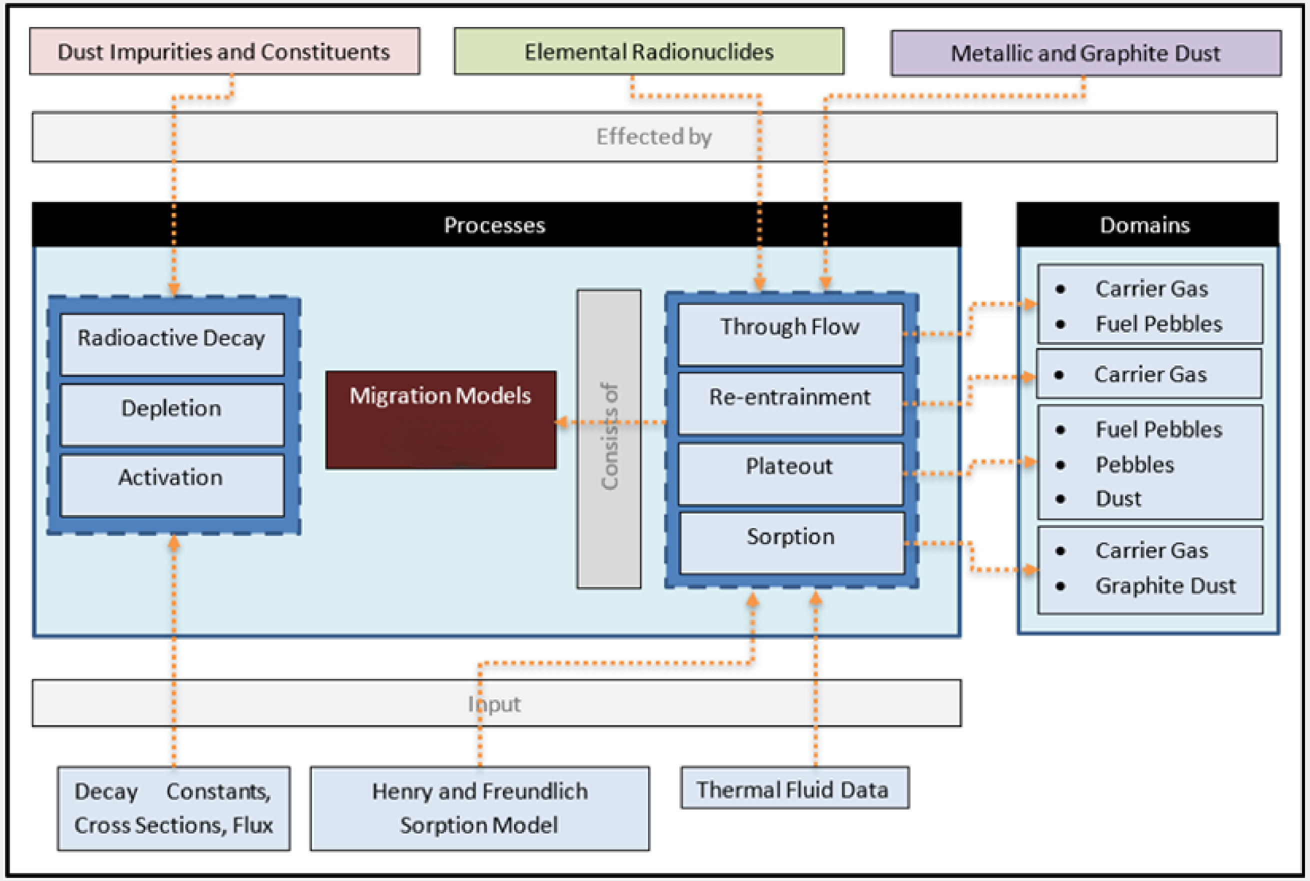
HPBM: Phenomena Modelled





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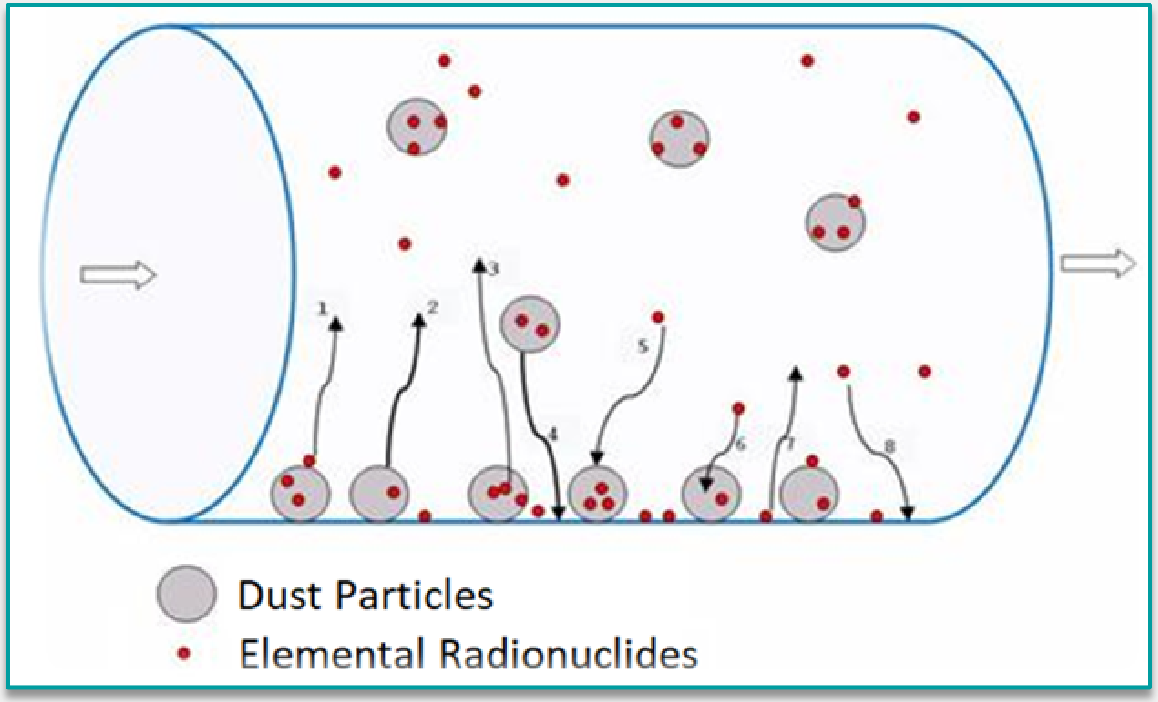
HPBM: Particle Mass Transfer



(1) Liftoff of elemental radionuclide from plated-out dust

(2) Liftoff of plated-out dust from component surface

(3) Sorption of elemental radionuclide from plated-out dust into helium

(4) Plateout of entrained dust onto component surface

(5) Plateout of entrained elemental radionuclide onto plated-out dust

(6) Sorption of entrained elemental radionuclide into plated-out dust

(7) Liftoff of elemental radionuclide from component surface

(8) Plateout of elemental radionuclide onto component surface

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HPBM: Numerical Solution

- Coupled set of 2D partial differential equations for multi-phase flow and mass balance
- Phases:
    1. Helium gas
    2. Circulating dust
    3. Deposited dust
    4. Circulating isotopes
    5. Deposited isotopes
- Finite volume + Backward Implicit-Explicit Method (IMEX) discretization

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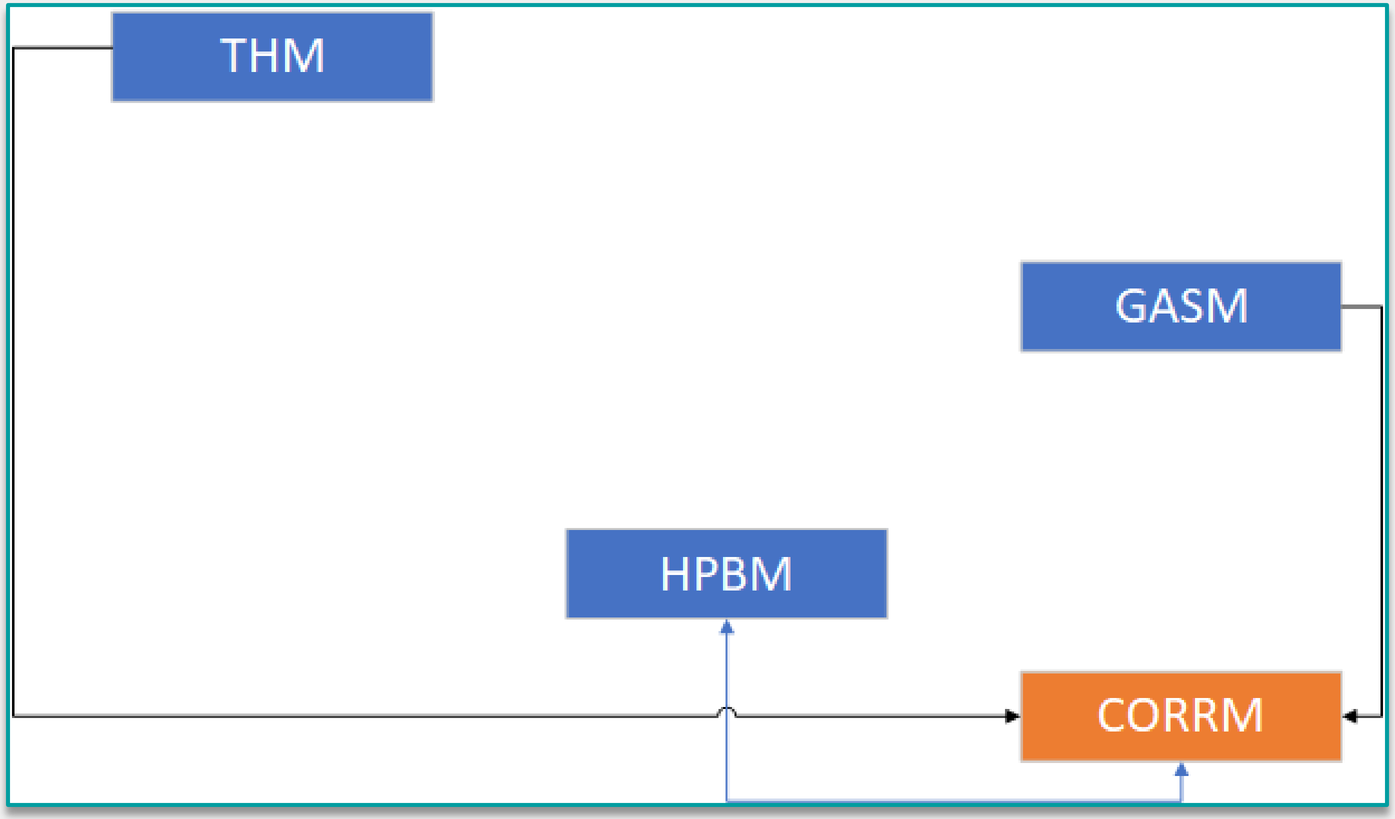
CORRM: Core Corrosion Model



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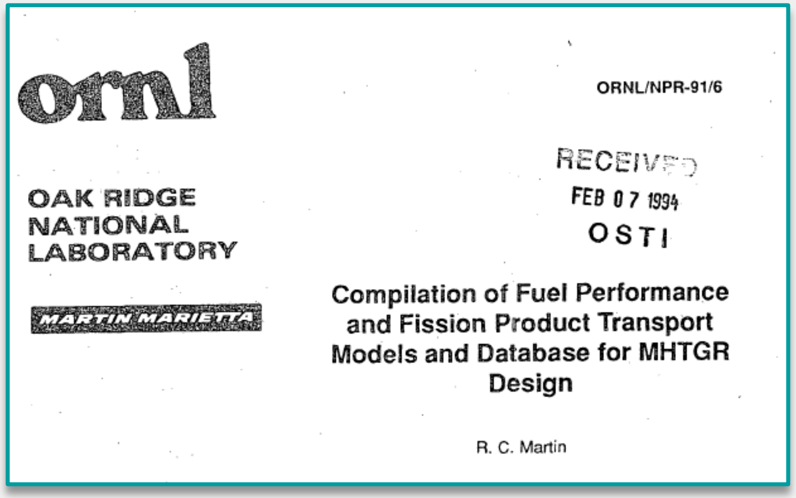
CORRM: Methodology

$$\text{Corrosion Rate} = \frac{(\text{Kinetic Factor})(\text{Driving Force})}{(\text{Adsorption Term})}$$

with temperature-dependency of kinetic factor and adsorption terms modelled by Arrhenius-type correlation

- Applied to fuel element graphite materials to determine the radionuclide release enhancement due to corrosion
- Based on correlation for H-451 fuel element graphite investigated at General Atomics

Material	State	Atmosphere
UCO kernel	Normal	Trace H_2O
	DLOFC	Air/He
PyC coating	H_2O ingress	H_2O/He
“US A3-3” matrix	Normal	Trace H_2O
	DLOFC	Air/He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MARTIN MARIETTA

Compilation of Fuel Performance and Fission Product Transport Models and Database for MHTGR Design

R. C. Martin

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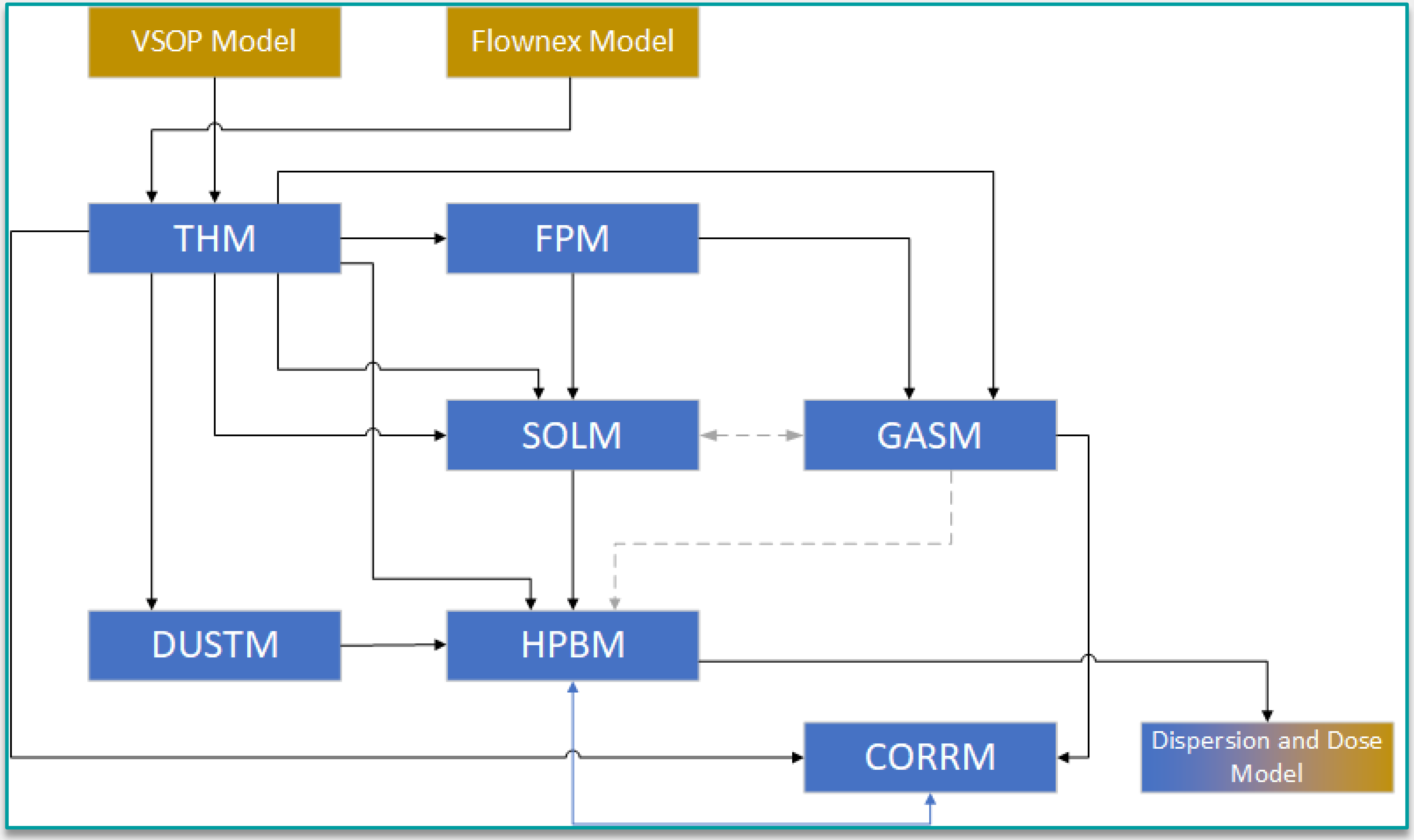
Overall Mechanistic Source Term Calculation



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Q & A

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List of Acronyms

CORRM	Corrosion model	**PyC**	Pyrolytic-carbon
DLOFC	Depressurized loss of forced cooling	**Q&A**	Questions & answers
DOE	Department of Energy	**R/B**	Release to birth ratio
DUSTM	Dust production model	**RCS**	Reactivity control system
FHS	Fuel handling system	**RG**	Regulatory Guide
FP	Fission product	**RN**	Radionuclide
GASM	Gaseous FP release model	**SiC**	Silicon-Carbide
HM	Heavy metal	**SOLM**	RN diffusion and release model
HPBM	Helium pressure boundary model	**THM**	Thermo-hydraulics model
HTGR	High Temperature Gas-cooled Reactor	**TR**	Topical Report
KSIM	Neutron kinetics & plant simulation model	**TRISO**	Tristructural-Isotropic
MST	Mechanistic source term	**TRITM**	Tritium release model
NQA	Nuclear Quality Assurance	**UCO**	Uranium Oxycarbide
PIRT	Phenomena identification and ranking table	**XSTERM**	X-energy's mechanistic source term code suite

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NRC Staff Review of Topical Report (TR) 000632 “Xe-100 Licensing Topical Report Mechanistic Source Term Approach” (MST)

ACRS Full Committee Meeting
July 9, 2025

ADVANCED REACTOR READY

https://www.nrc.gov/reactors/new-reactors/advanced.html

Background

- MST TR originally submitted on May 10, 2024 (ML24131A146) with updated submittal on March 14, 2025 (ML25073A093)
  - Updated submittal includes updates identified during regulatory audit
    - Updates to MST TR sections 1.5 and 7.1 clarify that applicability is limited to preliminary analyses
    - Correction of typos
    - Updates to Appendix H showing MST model interfaces

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Background

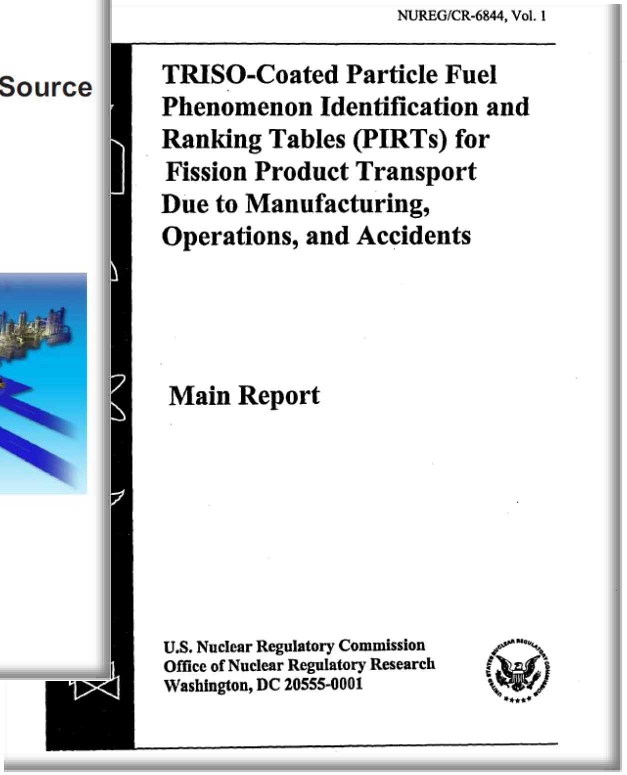

INL/EXT-10-17997

HTGR Mechanistic Source Terms White Paper

July 2010

The INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance

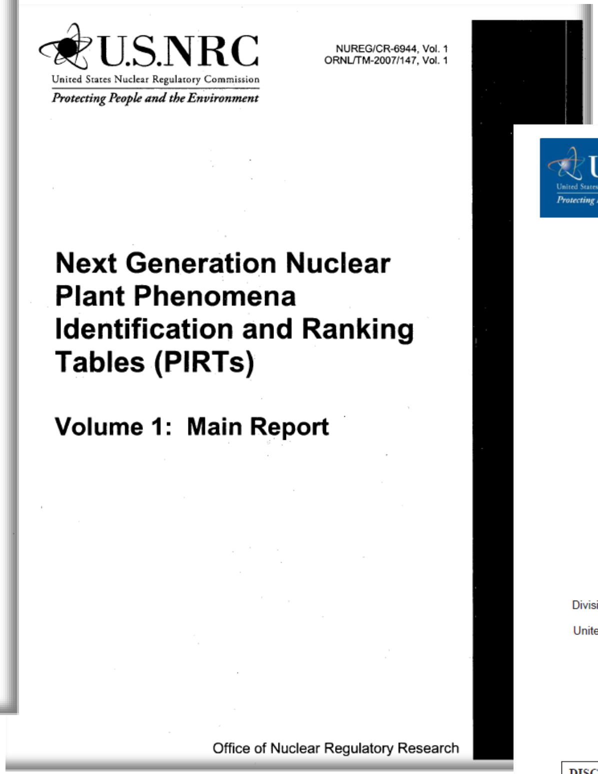
Idaho National Laboratory


NUREG/CR-6844, Vol. 1

TRISO-Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations, and Accidents

Main Report

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001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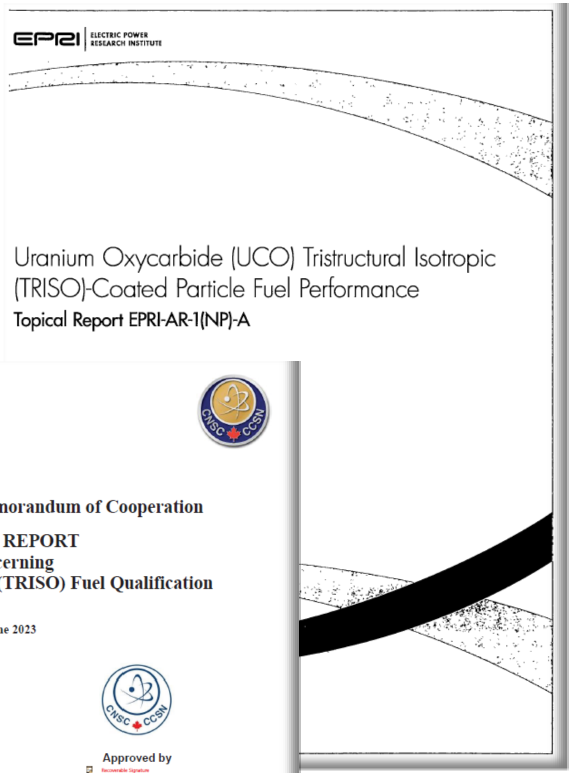
NUREG/CR-6944, Vol. 1
ORNL/TM-2007/147, Vol. 1

Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 1: Main Report

Office of Nuclear Regulatory Research


EPRI | ELECTRIC POWER RESEARCH INSTITUTE

Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO)-Coated Particle Fuel Performance

Topical Report EPRI-AR-1(NP)-A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U.S. NRC—CNSC Memorandum of Cooperation

FINAL REPORT
concerning
Tristructural Isotropic (TRISO) Fuel Qualification

June 2023

Approved by
Mohamed K. Shams

Dr. Mohammed K. Shams, Director
Division of Advanced Reactors and Non-Power Production and Utilization Facilities
United States Nuclear Regulatory Commission

Approved by
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Dr. Caroline Ducros, Director General
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Canadian Nuclear Safety Commission

Melanie Rickard

Melanie Rickard, Director General
Directorate of Assessment and Analysis
Canadian Nuclear Safety Commission

DISCLAIMER: The NRC and the CNSC have prepared this final report to inform stakeholders of the current project status for performing a generic assessment of TRISO fuel. The information contained in this document has not been subject to NRC and CNSC management and legal review, and its contents are subject to change and should not be interpreted as official agency positions.

U.S. NRC ML23172A242 Page 1 of 31 CNSC e-Docs #7055295

Regulatory Basis

- Title 10 of the *Code of Federal Regulations* (10 CFR) 50.34(a)(1)(ii)(D) requires, in part, that an applicant for a construction permit (CP) perform an evaluation and analysis of a **postulated fission product release** to evaluate the offsite radiological consequences.
- Under 10 CFR 50.34(a)(4) an applicant for a CP must perform a **preliminary analysis and evaluation of the design and performance of structures, systems, and components** with the objective of assessing the risk to public health and safety resulting from the operation of the facility and including the determination of margin of safety during normal operations and transient conditions anticipated during the life of the facility.
  - Staff identified relevant Principal Design Criteria (PDC): Xe-100 PDC 10, RFDC 16, PDC 19
- Under 10 CFR 50.34(a)(8) an applicant for a CP must identify the systems, structures or components of the facility, if any, which require research and development to confirm the adequacy of their design and describe the **research program that will be conducted to resolve any safety questions associated with such systems, structures, or components**. Such research and development may include obtaining sufficient **data regarding the safety features of the design to assess the analytical tools** used for safety analysis in accordance with 10 CFR 50.43(e)(1)(iii).

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Scope of NRC Staff Review

- MST TR section 4.2 describes that MST models, implemented in the XSTERM code, are used to calculate dose consequences for licensing basis events, including the deterministic evaluation of design basis accidents
- NRC staff reviewed MST modeling approach to address radionuclide transport phenomena to support preliminary analysis of the Xe-100
- Review is limited to and focused on high-level physical phenomena of interest and whether the analysis approach and methods can reasonably support future licensing actions
  - Design is preliminary
  - Development and assessment of methods are in progress or planned
  - Evaluation of models within XSTERM for acceptability will be conducted during the review of an application that relies on the results of XSTERM evaluations

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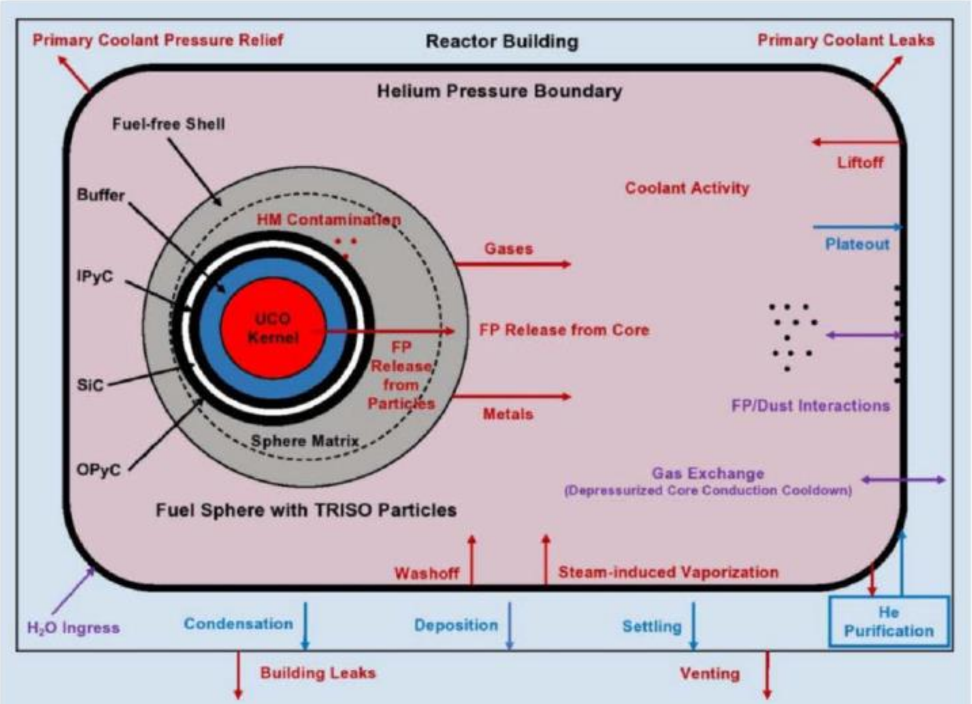
Barriers to Radionuclide Release



- Fuel
  - Fuel particle kernel (Uranium Oxycarbide (UCO)) within the TRISO fuel particles
  - Silicon Carbide and Pyrolytic Carbon coatings applied to the fuel kernel
  - Fuel matrix and fuel free zone of the fuel pebble
- Helium Pressure Boundary
- Reactor Building (Not credited)

XSTERM Models

- MST TR describes nine models in XSTERM:
  - Thermodynamics Calculation Model (THM)
    - NRC staff identifies this model to be of high importance because radionuclide release is expected to be diffusion dominant (temperature-dependent).
    - Use of THM for analyses supporting a Xe-100 licensing application requires justification by the applicant.
  - Point Kinetics Core Simulation Model (KSIM)
    - The description of point kinetics appears to be different than standard point kinetics approaches (i.e., 0D, single eigenvalue, lack diffusion coupling). Use of KSIM for analyses supporting a Xe-100 CP application requires justification by the applicant.
  - Tritium Production and Transport Model (TRITM)
    - MST TR section 5.1.8 clarifies that this model is under development.

XSTERM Models

- MST TR describes nine models in XSTERM (cont):
  - TRISO Particle Failure Probability Model (FPM)
  - Solids Product Transport Calculations Model (SOLM)
  - Steady-State Gaseous Fission Products Transport Calculations Model (GASM)
  - Dust Production Rate Calculations Model (DUSTM)
  - Helium Pressure Boundary Model (HPBM)
  - Core Corrosion Model (CORRM)
- NRC staff determined that FPM, SOLM, GASM, DUSTM, HPBM, and CORRM address phenomena needed to predict MST to support preliminary analysis:
  - Models rely on previous modeling and operational experience from gas-cooled reactors such as Arbeitsgemeinschaft Versuchs Reaktor (AVR)
  - Based on the NRC staff's experience with light water reactor (LWR) and non-LWR source term analysis, the NRC staff did not identify significant gaps in the MST models.
  - MST TR section 4.2 states that the source term modeling described may be revised
    - NRC staff did not perform a detailed technical review for the models described in MST TR
    - NRC make no conclusions regarding the acceptability of these models

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Assessment Plans (Verification and Validation (V&V))

- MST TR section 6 states that:
  1. V&V effort is underway to ensure that XSTERM is qualified to support final safety analyses
  2. Validation plans are developed to cover high and medium ranked phenomena that are identified through a Phenomena Identification and Ranking Table (PIRT) process
  3. The phenomena modeled by XSTERM were extracted from an earlier version of the PIRT
- NRC staff determined that the assessment process is acceptable because the identification of code assessment requirements through the PIRT process is an established approach (see RG 1.203)
- NRC staff are unable to assess the adequacy of the V&V plan:
  - Validation plan is not based on the latest PIRT information
  - MST TR does not contain information describing the knowledge level of the phenomena identified in the PIRT
  - The plan is preliminary and subject to change

Conclusions

- The NRC staff concludes that X-energy's TR 000632, "Xe-100 Licensing Topical Report Mechanistic Source Term Approach," Revision 3, provides a reasonable plan for the development of the MST methodology.
  - The FPM, SOLM, GASM, DUSTM, HPBM, CORRM models in XSTERM appear to cover the phenomena needed to predict the MST to support the preliminary analysis and evaluation of the Xe-100 design
  - The TR describes an acceptable approach to V&V
- NRC staff make no conclusions regarding the acceptability of the models in XSTERM for the MST analyses of the Xe-100 because:
  - Models within XSTERM are still under development
  - A detailed technical review of the individual models was not completed
  - Details regarding key phenomena identification and associated knowledge levels are not provided in MST TR
  - The models and associated validation plans are preliminary and subject to change
- The NRC staff expects that a detailed technical review of XSTERM model applicability to the Xe-100 reactor will be addressed as part of the review of a licensing application that references MST TR.

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Acronyms

AVR	Arbeitsgemeinschaft Versuchs Reaktor
CORRM	Core Corrosion Model
CP	Construction Permit
DUSTM	Dust Production Rate Calculations Model
FPM	Failure Probability Model
GASM	Steady-State Gaseous Fission Products Transport Calculations Model
HPBM	Helium Pressure Boundary Model
KSIM	Point Kinetics Core Simulation Model
LWR	Light Water Reactor
MST	Mechanistic Source Term
PDC	Principal Design Criteria
PIRT	Phenomena Identification and Ranking Table
SOLM	Solids Product Transport Calculations Model
THM	Thermodynamics Calculation Model
TR	Topical Report
TRISO	Triple Coated Isotropic Particle
TRITM	Tritium Production and Transport Model
UCO	Uranium Oxycarbide
V&V	Verification and Validation

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