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UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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ADVISORY COMMITTEE ON REACTOR SAFEGUARDS

(ACRS)

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SUBCOMMITTEES ON METALLURGY & REACTOR FUELS

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TUESDAY

OCTOBER 5, 2021

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The Subcommittee met via Video
Teleconference, at 9:00 a.m. EDT, David Petti,
Subcommittee Chair, presiding.

COMMITTEE MEMBERS:

- DAVID A. PETTI, Chair
- RONALD G. BALLINGER, Member
- CHARLES H. BROWN, JR. Member
- GREGORY H. HALNON, Member
- JOSE MARCH-LEUBA, Member
- JOY L. REMPE, Member
- MATTHEW W. SUNSERI, Member

ACRS CONSULTANT:

STEPHEN SCHULTZ

1 DESIGNATED FEDERAL OFFICIAL:

2 CHRISTOPHER BROWN

3 ALSO PRESENT:

4 ZENA ABDULLAHI

5 LARRY BURKHART

6 ALEXANDER CHERESKIN

7 DAVID HOLCOMB

8 STEWART MAGRUDER

9 SCOTT MOORE

10 HOSSEIN NOURBAKHS

11 MICHAEL ORENAK

12 WENDY REED

13 JANET RINER

14 RICHARD RIVERA

15 MOHAMED SHAMS

16 TAMMY SKOV

17 CHRISTOPHER VAN WERT

18 SHANDETH WALTON

19 WEIDONG WANG

20 DEREK WIDMAYER

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P R O C E E D I N G S

9:00 a.m.

CHAIR PETTI: This is a meeting of the Metallurgy and Reactor Fuels Subcommittee of the Advisory Committee on Reactor Safeguards. I'm Dave Petti, chairman of today's subcommittee meeting.

ACRS members in attendance are Ron Ballinger, Charles Brown, Joy Rempe, Jose March-Leuba, Greg Halnon, Matt Sunseri, and our consultant, Steve Schultz, is also with us. Christopher Brown of the ACRS staff is the Designated Federal Official for this meeting.

During today's meeting, the subcommittee is going to hear about the Draft NUREG report entitled ORNL Molten Salt Reactor Fuel Qualification. The subcommittee will hear presentations by and hold discussions with the NRC staff, staff from ORNL, and other interested persons regarding this matter.

The rules for participation in all ACRS meetings, including today, were announced in the Federal Register on June 13th, 2019. The ACRS section of the U.S. NRC public website provides our charter, bylaws, agendas, letter reports, and full transcripts of all full and subcommittee meetings including slides presented there.

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1 The meeting notice and agenda for this
2 meeting were posted there. We received no written
3 statements or requests to make an oral statement from
4 the public.

5 The subcommittee will gather information,
6 analyze relevant issues and facts, and formulate
7 proposed positions and actions as appropriate for
8 deliberations by the full committee anticipated in
9 November.

10 The rules for participation in today's
11 meeting have been announced as part of this meeting
12 previously published in the Federal Register.

13 A transcript of the meeting is being kept
14 and will be made available as stated in the Federal
15 Register notice.

16 Due to the COVID pandemic, today's meeting
17 is being held over Microsoft Teams for ACRS and NRC
18 staff. There's also a call-in number with a pass code
19 to allow participation of the public over the phone
20 using Microsoft Teams. Refer to the bottom of the
21 published agenda for this number.

22 When addressing the subcommittee, the
23 participants should first identify themselves and
24 speak with sufficient clarity and volume so that they
25 may be readily heard. When not speaking, we request

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1 the participants mute your computer, microphone, or
2 phone.

3 We will now proceed with the meeting and I'd
4 like to start by calling on Mohamed Shams, Division
5 Director of NRR, Division of Advanced Reactors and
6 NPUF for opening remarks.

7 Mohamed.

8 MR. VAN WERT: I believe Mohamed is actually
9 on travel right now. So I will be giving the opening
10 remarks.

11 CHAIR PETTI: Okay, so ahead, sir.

12 MR. VAN WERT: This is Chris Van Wert and I
13 am Acting Branch Chief for the Technical Branch No. 2
14 in the Division of Advanced Reactors and Non-Power
15 Utilization Facilities.

16 So just a couple of opening remarks here to
17 give you an idea of the framework in which we're going
18 to be hearing this presentation.

19 So first of all, thank you very much for
20 having us today and the kind of setting for this
21 presentation is that we've had these on-going efforts
22 related to fuel qualification guidance. This is in
23 support of NEIMA. And you recently heard a
24 presentation by Tim Gestwicki regarding NUREG-2246
25 which was the staff's fuel qualification guidance.

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1 This was, in general, a technology neutral approach to
2 fuel qualification, although it was noted at the time
3 that certain aspects of molten salt fuel reactors make
4 it a little bit difficult to apply the guidance to it.
5 So with that in mind, we have been in the middle of
6 ongoing efforts with Oak Ridge to develop guidance a
7 little bit more specific for molten salt
8 qualification.

9 And so we still are using a similar
10 framework, as you heard before with NUREG-2246, in
11 that we're trying to focus on fundamental safety
12 functions, but we recognize that there are differences
13 between manufactured fuel, solid fuel that we're more
14 familiar with, as compared with synthesized molten
15 salt fuel.

16 So this is also an ongoing effort with the
17 molten salt reactor fuel qualification. We have had
18 previous efforts with Oak Ridge and documents have
19 been presented related to this topic, but this has
20 culminated in this draft NUREG that we'll be
21 presenting today.

22 This is also something that will be
23 continuing after we complete this NUREG. There is on-
24 going talks of a Reg. Guide that the staff will
25 develop in coordination with or with assistance from

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1 Oak Ridge to endorse this NUREG. At this point, as
2 I'm clear, we will do a single new, single Reg. Guide
3 to endorse both NUREG-2246, as well as this NUREG, or
4 if we will use separate Reg. Guides to endorse these
5 documents.

6 And also, just to give you an idea of the
7 time line, this NUREG has gone out for public comments
8 and so we are expecting to get comments and hoping to
9 get comments, as well as incorporating any internal
10 generated comments here. And we will come back with
11 a final version of this report at that point.

12 So with that in mind, I just want to thank
13 you again and I will leave it up to Dave Holcomb from
14 Oak Ridge to present the technical meat of his
15 presentation, but if you have any questions for me,
16 I'd be more than happy to answer as well. Thank you
17 very much.

18 CHAIR PETTI: Thanks, Chris.

19 MEMBER REMPE: Dave, this is Joy. Just so
20 I'm on the right page, you've stated in your opening
21 remarks that you're planning to have a letter in
22 November, but yet, they're going to be coming back
23 with comments later.

24 Is it appropriate to have a letter now or is
25 staff requesting a letter now? Or why are we thinking

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1 about a letter now versus after they come back with
2 the updated document? And I was just wondering about
3 that.

4 CHAIR PETTI: We had a meeting with staff
5 and felt that there probably would not be a lot of
6 significant comments that will come back from the
7 public and so we just decided that we would go ahead
8 with these comments because we've these comments, real
9 important for them to look at.

10 MEMBER REMPE: Okay.

11 CHAIR PETTI: David.

12 DR. HOLCOMB: So good morning, folks. My
13 name is David Holcomb. I work for Oak Ridge National
14 Laboratory. As Chris has indicated, we've been
15 supporting the NRC for the past few years looking at
16 what it would mean to qualify or develop qualification
17 guidance. And that's the purpose of the presentation
18 here. This is intended as a summary of the Draft
19 NUREG CR that has been shared with you and so I'm
20 trying to provide highlights from that. If you have
21 detailed questions on a specific text on there, please
22 feel free to raise those as well.

23 I'm representing here my colleagues, George
24 Flanagan and Mike Poore, as well, as we worked as a
25 team on developing this.

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1 Please, next slide.

2 MEMBER MARCH-LEUBA: Dave, this is Jose.
3 Before you move forward, just so I can focus on what
4 you are saying. In my mind there are two types of
5 molten salt reactors, two big pluses. One is where
6 the fuel or some material is dissolved in the coolant
7 and it moves freely through the reactor; another one
8 where you segregate the fuel into some, what do you
9 call it, cladding of some type.

10 We are going to talk only about the first
11 class today?

12 DR. HOLCOMB: We are talking about reactors
13 in which the fuel is a salt. In some cases, that
14 would be where fuel is in bins and then the salt
15 circulates in the bins. And those are small natural
16 circulation loops. They do not require to be pumped.

17 On the other hand, we are not talking about
18 reactors for which the fuel is not a salt. For
19 example, if it is a TRISO which is cooled by a salt
20 that would be a solid fuel. So this is intended to be
21 a generic capability of looking at fuel salt. And so
22 it is not that if it's segregated by cladding, if it's
23 still in a circulating form and natural circulation in
24 the fuel bins does indeed qualify as that.

25 MEMBER MARCH-LEUBA: Okay. Thank you.

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1 DR. HOLCOMB: I've got somebody waiting in
2 the lobby. I'm going to admit them.

3 Okay, well, we're starting as you've seen in
4 2246 they have a definition for fuel qualification
5 which involving behaving according to a manufacturing
6 spec. Well, as fuel salt is not a manufactured
7 product, it's a synthesized product, we are relying
8 upon a different definition that we're supporting.
9 And this comes from an NRC presentation from a few
10 years ago by Joe Williams.

11 This is about indicating that fuel
12 qualifications is a process that provides high
13 confidence. The physical and chemical behavior of
14 fuel is sufficiently understood that can be adequately
15 modeled in both normal and accident conditions,
16 reflecting the role of the fuel design and the overall
17 safety of the facility.

18 Uncertainties are defined so that the
19 calculated fission product releases include
20 appropriate margins to ensure conservative
21 calculations of the radiological dose consequences.
22 We'll keep coming back to this as this is our touch
23 point of what we're trying to mean -- to show that the
24 fuel is -- what it takes to be a qualified fuel. Sort
25 of pictorially on this is that fuel qualification

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1 allows you to do the fuel performance measurement --
2 to do the calculations of fuel performance under
3 accident scenarios, under normal and AOO conditions.

4 We really upon the traditional functional
5 containment, defense-in-depth, and the barriers to
6 prevent the generation of the source term and provide
7 reasonable assurance of adequate protection.

8 Next slide, please.

9 Say fuel -- qualification we're building
10 from the NUREG-2246. We've got a slightly different
11 take on things because of the different
12 characteristics of liquids as compared to solids, but
13 it is still looking at the goal decomposition process
14 where you start at top level goal of the fuel is
15 qualified and break it down into individual sub-goals.
16 And we're really focusing heavily on the fundamental
17 safety functions as to determine what are the success
18 criteria for whether you have -- you do have
19 adequately performing fuel.

20 Well, part of the reason we have to do this
21 right now is that there are literally dozens of MSR
22 design variants under consideration and nearly all of
23 them have been developed in the past decade. And
24 they're emerging, I mean within the past month or two
25 we've had another U.S. company finally put out

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1 publicly what its design is going to look like. Even
2 though they're not yet credibly going to be going to
3 the Commission I would not be surprised if Alpha Tech
4 Research at some point in the future says that a U.S.
5 company presents its innovative design for regulation
6 and it's very different from other designs. So which
7 designs are going to be presented for regulatory
8 adequately safety review, it remains uncertain.

9 So we're really looking at the process based
10 on the salt chemistry and physics which really is
11 largely independent of the reactor designer's
12 configuration.

13 Next slide, please.

14 So the fuel qualification, when you're
15 looking at the fundamental safety function, a function
16 that really is independent. You can support a
17 performance-based or prescriptive process. So
18 understanding how the fuel salt property support
19 achievement of fundamental safety function is truly a
20 performance-based evaluation. We evaluate the
21 acceptable range of fuel salt properties to maintain
22 appropriate margin from design limits under normal and
23 AOO conditions and limit the damage to safety-related
24 SSCs to ensure proper functioning during accidents.

25 Essentially, the fuel salt can't result in

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1 so much damage that safety-related SSC ceases to
2 perform their functions. And the fuel salt is a
3 safety-related SSC, so it in part performs -- it
4 performs its safety-related functions, but it is not
5 the only safety-related SSC.

6 And also, the prescriptive -- we determine
7 the range of fuel salt properties that result in
8 compliance with specific requirements, both fuel and
9 coolant requirements. And that's really the major
10 difference with the solid is that you also have to be
11 in compliance with the coolant requirements.

12 Next slide, please.

13 So liquid fuel really does have substantial
14 fundamental differences from solid fuel. It is both
15 the nuclear fuel and the primary heat transfer media
16 and it must meet the requirements of both processes.
17 So liquid fuel is chemically damageable, but the
18 chemistry can be -- may be repaired during use. It
19 depends upon whether there's access to the salt.

20 For example, in a bin-type fuel, it's not
21 really accessible, but in a circulating loop there may
22 be accessibility to add or remove components during
23 use. Solid fuel is mechanically damageable. The
24 composition of liquid fuel again may be adjustable
25 during use, but solid fuel is not adjustable. It's

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1 set prior to use.

2 The properties of liquid fuel depend upon
3 its composition and state. The properties of solid
4 fuel depend upon its fabrication processes as well as,
5 of course, its composition which is part of the
6 fabrication spec.

7 And another thing is because the fuel is a
8 liquid, fluids are formed to fit their container. If
9 you poke a hole in one container, the next container
10 becomes its container, and it could release nearly all
11 of the radionuclides from a breach. Unlike a solid
12 which doesn't form to fit its containers, so if you
13 crack a fuel bin all of the fuel comes out. You have
14 to really, massively rupture to cause a true loss of
15 all solid fuel.

16 Next slide, please.

17 Fuel salt qualification applies while it's
18 a regulated product at the reactor site. So from
19 receipt of regulated material until transfer to
20 independent storage. However, the properties that
21 you're concerned about depend upon where in the fuel
22 salt life cycle. For example, if you're fueling a
23 reactor for the first time, for example, if you've
24 transported a reactor with the 99 percent of the fuel
25 component in a transportable reactor, but it doesn't

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1 have any of the fissile material and you're adding
2 fuel salt concentrate on that, you're certainly going
3 to be interested in the reactivity impact of the fuel
4 salt concentrate.

5 The fluid properties, on the other hand, are
6 largely immaterial once it's frozen as it's a used
7 fuel, once it's in a long-term storage. Materials
8 that leave the fuel salt and lack a reasonable means
9 cease to be part of the fuel salt and have to meet
10 other safety regulations. Things like insoluble
11 materials, fission gases, vapors, and aerosols because
12 part of the radioactive waste stream, once they no
13 longer have the ability returning to the bulk of the
14 fuel salt. On the other hand, plated-out materials
15 that couldn't re-dissolve or re-suspend in the liquid
16 remain part of the fuel salt.

17 Next slide, please.

18 So this means as one of the key issues is
19 what is fuel salt? What is and what isn't? Because
20 in solid fuel, we've traditionally cladding and fuel
21 assemblies are qualified as part of the solid fuel.
22 Other liquid fuel doesn't come in discrete elements.
23 It may be provided in barrels. It may be provided
24 where you get all of the non-fissile parts and then
25 you add fissile material slowly to it or you take

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1 things out of it during service. So it doesn't really
2 come in rods or assemblies. And also it moves
3 independently of its container during normal
4 operations. And the container could even be replaced
5 as part of normal operations. You could drain it
6 into a drain tank with a new heat exchanger or a new
7 reactor vessel in and then return the fuel salt to
8 use. So it doesn't really -- it's not really an
9 integral system.

10 So fuel salt therefore includes all the
11 materials containing fissionable materials or
12 radionuclides that remain in hydraulic communication,
13 but does not include the surrounding systems,
14 structures, or components. Salt vapors and aerosols
15 remain part of the fuel salt system until they become
16 adequately trapped in which case -- until then they
17 become part of the radioactive waste stream.

18 The container corrosion products, however,
19 become part of the fuel salt. Fresh and used fuel
20 salt in on-site storage is within the scope of this
21 qualification process.

22 Next slide, please.

23 The common properties and the common plant
24 functions enable a general fuel salt evaluation
25 method. Although the specifics are very different

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1 depending on the plant design and the specific
2 accident sequences are very much design dependent, the
3 basic operational and safety functions are common to
4 any nuclear power plant. That's -- the fundamental
5 safety functions pertain to all plants.

6 And the halide salt characteristics are
7 common to any MSR. They all have high boiling points
8 which result in low operating pressures. It's low
9 Gibbs free energy in the salt. Basically, it's a low
10 chemical potential energy. You're not going to get
11 vigorous chemical reactions with anything.

12 Natural circulation heat transfer properties
13 are also part -- they're just an inherent part of the
14 fuel salt. It's not a really good high thermal
15 conductivity material. In many ways, it's useful to
16 think of the heat transfer properties of liquid water,
17 water are very similar to those of -- with salt, just
18 at much higher temperatures.

19 The fuel salt interacts with its containers
20 by a common chemical and physical mechanism. For
21 example, by a thermal energy transfer, chemical
22 reactions, and mechanical processes, just the
23 hydraulic load, for example.

24 Next slide, please.

25 MEMBER REMPE: David, this is Joy. I should

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1 have jumped in, I guess, on the prior slide, but this
2 is more relevant to the report than what's in your
3 slides.

4 Your report emphasizes the difference
5 between used and spent fuel because I guess with the
6 molten salt you'll be processing the molten salt and
7 then sticking it back in the reactor in some of these
8 designs. And if that -- first of all, it's kind of
9 interesting because for years -- we tried to
10 distinguish between spent and used fuel to say oh, we
11 just have used fuel and that didn't go very well as
12 emphasized by a recent GAO report.

13 But my question is more in how you're going
14 to have to pick an EPC for these reactors because
15 you're going to have to consider all the sources of
16 radionuclides on a site which means as you accumulate
17 the used fuel and you're processing it, you need to
18 consider that as a potential source for radionuclide
19 release as well as the spent fuel when you just can't
20 use it any more, right?

21 And that's something that the -- maybe this
22 is a question for the staff more than you, but it just
23 seems like that's something we're going to have to
24 think about, right?

25 DR. HOLCOMB: Well, it's certainly true that

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1 all radionuclides on site are of interest. And it may
2 be during the processing that you have the highest
3 potential for release because once you're no longer
4 processing and it's been used for a while, the natural
5 circulation heat transfer on there will go to decay
6 heat. So it's not a really exciting system once it's
7 been out of core for quite a while.

8 And it's a good question as to what choices
9 the designers are going to make because there are a
10 number of options about how much processing to do.
11 Some of the processing is just inherent. I mean
12 things that are insoluble are going to plate out or
13 you're going to filter them out. The melt of the
14 fission gases have really low solubility in the
15 materials and particularly in the fast spectrum
16 systems where they won't even go into -- they don't
17 have anything like graphite to go into. They
18 essentially all come out.

19 And yes, that rad waste stream is a
20 substantial source of the radionuclides there and that
21 may be stored on site. That may not be stored on site
22 and that has to be considered in the safety analysis.

23 MEMBER REMPE: So are the designers aware of
24 this because until there's a place -- again, this is
25 all design, conceptual design work, I suppose at this

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1 time. But as the design developers are coming up with
2 their design, is this being emphasized to them that
3 they can't go around claiming that they can survive
4 with a low ECP until they actually figure out what
5 they're going to do with either shipping it off site
6 or accumulating it on site. These are big questions
7 in order to work with NEIMA which requires the whole
8 fuel cycle to be developed. And as we think about how
9 to pick a site boundary, those kind of issues need to
10 be really emphasized with the design developers,
11 right?

12 DR. HOLCOMB: Yes, certainly Terrestrial is
13 the furthest along on this and they are leading
14 through the Canadian process. But the announced
15 Terrestrial plans about going ahead and having seven
16 sets of cores on site is indicating they are thinking
17 about how they are going to be storing multiple
18 generations of the cores and indicating that
19 currently, they're planning on the once through fuel
20 cycle because it is a much simpler system, but they
21 are very amenable to if they can get both the
22 technical and the regulatory processes, essentially
23 continuously reusing the fuel is an option to them.

24 But their announced plans were seven cores
25 on site and they will have a net life time storage of

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1 their fuel for the entire life of the plants and
2 that's what they have indicated. Those are in public
3 statements. They're not in regulatory filings, at
4 least not public regulatory filings and you can see
5 where they are with the Canadian process, but they are
6 not nearly as advanced in the U.S. yet, but I'll let
7 Chris if he wants to comment further on that.

8 MR. VAN WERT: I don't have too much more on
9 that, in general, other than I want to point out that
10 that's kind of separate from the fuel qualification
11 NUREG that we're developing here. The intent of this
12 is to lead them down the path such that when they go
13 through their fuel qualification process they will
14 understand their fuel well enough to understand their
15 source term and be able to calculate the subsequent
16 analyses.

17 But yes, you are absolutely correct that
18 they do need to consider how they operate in the plant
19 in its entirety, whether or not they're reprocessing
20 on site, or just storing it, and then shipping it off.

21 I believe we have some efforts and one that
22 I'm thinking right now Oak Ridge has been developing
23 some considerations as well, and as I recall
24 correctly, some of the environmental concerns are
25 brought up in there and -- but as far as how far along

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1 we are in communicating regulatory concerns, I think
2 the fuel qualification is the furthest along we are in
3 any of these topics, but yes, we do need to do more
4 regarding EPC and other topics as well.

5 MEMBER REMPE: I understand separate from
6 what the fuel qualification is, but on the other hand,
7 we are also considering emergency planning right now
8 and the Agency needs to make sure that we consider all
9 of these aspects as we move forward in Part 53 and
10 other types of activities. So thank you.

11 MR. VAN WERT: Agreed. Thanks.

12 DR. HOLCOMB: Okay. I think we've finished
13 with this slide.

14 Again, the method tailors the solid fuel
15 qualification process to the characteristics and
16 functions of liquid salt fuel. Modifications, both
17 add and remove issues from the solid fuel
18 qualification process. So we've got an example here.
19 Fuel salt is not a manufactured process in the sense
20 that NUREG-226 describes the solid fuel as
21 biomanufacturing specifications.

22 Liquids can't be mechanically damaged, just
23 a basic function of liquids. And fuel salt also
24 serves as the primary reactor coolant. So the fuel
25 salt properties determine its capability to adequately

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1 support achievement to the fundamental safety
2 functions. And the fuel salt regulatory basis derives
3 from the role of fuel salt in establishing compliance
4 with existing regulations.

5 Next slide, please.

6 Liquid fuel salt does not have a
7 mechanically determined life time. The identification
8 of life-limiting failure and property degradation
9 mechanisms that occur as a result of the radiation
10 during reactor operation remains a key focus. We
11 don't really care that it's a radiation, so you can
12 say core's operations of fuel salt circulation, if
13 corrosion happens for the temperature differences and
14 stuff with use in core.

15 The fuel salt lifetime is the period during
16 which it contains an adequate quantity of fissile
17 material so it still works as fuel. Does not include
18 too many neutron absorbers. Again, still works as
19 fuel. And maintains acceptable thermophysical and
20 thermochemical properties.

21 The composition of the fuel salt may be
22 adjustable during operations to correct degrading
23 conditions. Again, it depends upon the design.

24 Next slide, please.

25 MEMBER REMPE: David, this is Joy again.

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1 Okay, so this slide in your report implies that there
2 is some sort of degradation associated with fluence,
3 then I thought some of your words on this slide
4 indicate well, there isn't any degradation associated
5 with fluence. Is there or isn't there?

6 And then what data do we have to say that
7 there isn't some sort of degradation with fluence? I
8 mean how far out? How many gigawatt days of burnup
9 have you ever seen with this molten salt?

10 DR. HOLCOMB: I'm trying to see --
11 radiation, of course, causes some degradation, burn
12 out to fissile materials. That is a degradation
13 process on this.

14 You also change the redox condition.
15 Fission is an oxidative process and that changes.
16 Redox makes the salt more corrosive on this.

17 As you add more materials to compensate for
18 burnup, you may reach a solubility limit on there and
19 then begin to plate out materials. Some of those
20 could be fissile materials that were played at places
21 you don't want them to. So there are a number of
22 adverse things that happen as a result of operation,
23 but as far as ionic liquid and the characteristics of
24 ionic liquids, they've had enormous amounts of
25 radiation applied to them. We've put them in beam

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1 lines before at very high powered densities and you
2 realistically don't see anything because ionic liquids
3 are the recombination rates are multiple orders of
4 magnitude greater than anything on radiolytic damage.

5 It's just not -- there's not true radiolysis
6 that's going in these types of temperature range where
7 you're forming things, but on the other hand you're
8 getting a number of things which cause property
9 degradation over time which -- and that has things
10 like where you're accumulating fission products in the
11 salt. Or the fission products can form solids. These
12 are insoluble. They might form larger solids in
13 there. They agglomerate.

14 There just are things that happen, but it's
15 not to the basic salt. It is there are other things
16 that are accumulate. Again, we put those in,
17 quantities of fissile materials, amounts of neutron
18 absorbers, and some are physical and some are chemical
19 properties.

20 MEMBER REMPE: Has there much fluence --
21 what's the -- how much operating experience do you
22 have other than the MSRE and how long did it operate?
23 How much fluence did they see?

24 DR. HOLCOMB: Well, that's not where we got
25 -- tried to maximize fluence on there. If you wanted

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1 to see, there were capsule tests done on an MTR, but
2 mostly if you were looking at peak things, that was
3 done to the Aircraft Reactor Experiment where they
4 were putting things into beam lines where things are
5 -- where you -- and most of those were like high-
6 energy proton or radiations and they were putting peak
7 flux. And they were mostly looking at peak fluxes to
8 see whether you could do anything, rather than looking
9 at fluence.

10 And it's tough to say when you're taking
11 things out of the salt and putting more things back
12 into the salt, what the total fluence is on any
13 particular part of the salt.

14 CHAIR PETTI: David, just a question on --
15 you said that on these ionic liquids that
16 recombination is very quick and I certainly knew that
17 for the fluoride system, but there was some discussion
18 I knew among some salt researchers that that wasn't
19 necessarily known for all the different salts that
20 were under consideration, that the chloride system had
21 not experimentally established that. Is that true or
22 do we now believe that, you know, it's sort of like
23 the --

24 DR. HOLCOMB: Halide salt, is it -- we are
25 orders of magnitude from where you would be of concern

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1 because people have used them where you put high
2 fluxes of other things like electrons or other things
3 into there.

4 You are correct that no one has run
5 experimentally -- them in a reactor. We have enough
6 analogies on there that recombination is not what
7 we're expecting to be a problem. That is just -- it's
8 such a fundamental property of ionic liquids, liquids
9 that if you arc and spark and you put protein beams
10 and electron beams and the like in them and you get
11 recombination. It is very much energetically
12 favorable.

13 CHAIR PETTI: Okay.

14 DR. HOLCOMB: But you're right, has anybody
15 run this in a reactor before? No, there's been very
16 little done in chloride salts.

17 CHAIR PETTI: Right.

18 MEMBER HALNON: David, one question from me,
19 Greg Halnon. I'm not super familiar with molten salt,
20 but are voids of concern during operation at all?
21 Does that change the composition?

22 DR. HOLCOMB: Bubbles matter, but it depends
23 upon how much your power density is on this or whether
24 your pump has done something like entrained bubbles on
25 there. And so it does things like well, gee, the

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1 reactivity, the -- other -- the reactivity
2 coefficients for the bubbles also changes things like
3 reactivity feedback because some of the expansion of
4 this is limited by if it's a bubbly material, so it is
5 of interest and it's something you have to be able to
6 model, but we're not expecting to have any real damage
7 as a result of this.

8 So you'll be getting things like fission gas
9 bubbles will be forming in this. Certainly, the MSREs
10 saw little burps in reactivity because at one point
11 they were ingesting gases which were part of their gas
12 drippings where fission gas dripping system and
13 pumping it through the core and they saw little
14 reactivity burps.

15 And so yes, that is indeed something which
16 does impact reactivity. Do we think it has any safety
17 significance? Probably not, not unless you've got
18 enough that you really are exhibiting adequate
19 negative reactivity feedback from the formal
20 expansion.

21 MEMBER HALNON: I guess in the morning I
22 made an analogy to the mechanical deformation of the
23 fuel pin and I guess when you mention there's no
24 mechanical deformation or effect on the fuel because
25 it's liquid, I guess that's where my head went. I

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1 assume that that's all taken into consideration during
2 the fuel qualification process then?

3 DR. HOLCOMB: Yes, certainly, bubbles form
4 on this and one of the reasons no one is considering
5 hydrocarbons and lubricants on there, as it turns out
6 hydrocarbons, when they break down and go to the
7 surface of this there are fun surfactants (phonetic)
8 and it results in foam. And foam is not -- then foam
9 overflows and it does a number of things that he would
10 prefer it not to do. They don't seem to be really
11 substantial issues, but it's still having a foaming
12 system, I don't think is in anybody's desirable
13 design.

14 Otherwise, bubbles, you just have to have
15 enough free space up above it so that the gas can
16 escape and then -- in a sense, there's a lot of energy
17 in the fission gases. You have to adequately cool the
18 fission gases and all the bubbles coming off of the
19 system. But bubbles just reach the surface and
20 collapse and they inherently just migrate out to the
21 density difference in buoyancy.

22 MEMBER HALNON: Okay. Thanks.

23 DR. HOLCOMB: Any more questions on this
24 slide? Comments? We'll go on to the next one.

25 Functional containment is really important

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1 to how MSRs provide adequately radionuclide retention.
2 The barrier performance must be degraded to release
3 the radionuclides to the environment and performance
4 degradation can occur through failure or for bypass.
5 Bypass is very important on MSRs. Anything from yes,
6 it's a low-pressure system, somebody accidentally
7 leaving a hatch open, to the fact that you have to
8 reject the decay heat out to the environment and
9 you've got lines that therefore go through the
10 containment. And you have to make sure that you don't
11 have rupture on any of the lines.

12 And fuel salt properties that stress
13 barriers cause them to be -- are more likely to
14 release radionuclides. For example, you increase the
15 temperature, be it higher vapor pressure in the cover
16 gas and you decrease the strength of the container and
17 we're operating much closer to the formal stress
18 limits because of we're at higher temperatures and you
19 get more money, you get the higher temperatures you
20 can operate it at. That's just higher thermal
21 efficiency.

22 And the performance requirements for
23 materials normally in contact with the salt versus
24 those that only need to withstand accidents are
25 different. For example, if you are not crediting the

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1 normally salt-wetted layer for accident performance on
2 there is only your guard vessel. Then that really
3 needs to withstand the salt -- the safety-related
4 component and you might get -- and that's for a
5 limited duration.

6 Next slide, please.

7 Fuel salt properties have substantial impact
8 on containment performance. Normal operation, the
9 salt-seeking radionuclides are chemically retained.
10 Most of the cesium, strontium, the traditional things
11 that you worry about in light water reactors really
12 tend to go ahead and stay in salt because they form
13 very high -- low vapor pressure, high boiling point,
14 fluorides or chlorides.

15 The fission gases, those with more than a
16 few seconds of half-life (audio interference). The
17 noble -- our definition of noble means not soluble in
18 the salt. Largely, they plate out or escape into the
19 vapor because they form nanoparticles and they're
20 salt-wetted so they're not in equilibrium there, so
21 they can just migrate out into the cover gas.

22 The fuel salt causes stress on potentially
23 resulting in damage to container materials, core
24 erosion, erosion, creep. The tritium behavior depends
25 upon operations, composition, and redox state. The

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1 redox, if it actually is oxidated, we tend to
2 chemically bind the tritium and it doesn't tend to go
3 out. If you are in a reducing state which is good for
4 the corrosion, the tritium tends to free and then it
5 tends to go -- diffuse out through where it's got
6 large surface areas and thin walls.

7 MEMBER MARCH-LEUBA: Hey, Dave, this is
8 Jose.

9 MR. HOLCOMB: Yes.

10 MEMBER MARCH-LEUBA: When you say fission
11 gasses largely escape, you mean they escape the salt
12 --

13 MR. HOLCOMB: Yes.

14 MEMBER MARCH-LEUBA: -- they're still
15 retained by the vessel and containment, right?

16 MR. HOLCOMB: Yeah, yes. You have -- you're
17 required to have a containment around the fission
18 gasses. And you would have multiple layers of
19 containment around the fission gasses.

20 MEMBER MARCH-LEUBA: And in some reactors,
21 you may have a significant production of tritium. So
22 that's a concern?

23 MR. HOLCOMB: Yes. Tritium, tritium
24 probably isn't -- most of it is probably not going to
25 come out in that manner because the diffusion

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1 coefficients of tritium are really small. So what you
2 tend to have is tritium is probably going to come out
3 through the power cycle mostly.

4 And that is a very significant concern
5 because it could be, you know, during normal
6 operations is when you have your largest potential for
7 radioactive material release into the power cycle.

8 And most of the designers so far have just
9 accepted the fact that we're going to have to have a
10 chemical trap in the coolant -- in the secondary
11 coolant. And that was indeed what the molten salt
12 breeder reactor program in the 1970s had intended.

13 And so the nitrate salts are very good
14 chemical traps for the tritium. And, but that is very
15 much a concern, mostly through the power cycle.
16 Though you're correct that there will be amounts that
17 (audio interference), there will be amounts that go
18 through the reactor vessel.

19 And then so you have to have a cleanup of
20 the tritium out of the containment gas base, if indeed
21 we're using a containment (audio interference),
22 because a number of people are keeping the fuels, the
23 entire vessel and cover gas system immersed in a
24 secondary coolant salt, so it's a liquid containment.

25 MEMBER MARCH-LEUBA: So there is very little

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1 --

2 MEMBER BLEY: This is --

3 MEMBER MARCH-LEUBA: There is very little
4 hydrogen? Go ahead, Ron.

5 MEMBER BLEY: This is especially true for
6 FLiBe, right?

7 MR. HOLCOMB: FLiBe is worst, yep. Anything
8 which -- with lots of lithium or lots of beryllium.
9 You essentially think of it as quantities very similar
10 to what a heavy water reactor produces, except for the
11 fact that because the structural boundaries are above
12 300 C, and that's rough -- and it goes exponentially
13 above that. It's -- there-- it penetrates through.

14 But where the thin walls and high surface
15 area are, the heat exchanger tubes. And they have to
16 be thin to function, so most of it goes through the
17 power cycle.

18 MEMBER MARCH-LEUBA: But what I hear -- what
19 I hear you say -- what I hear you say is that there is
20 very little hydrogen in the system, so you can afford
21 to trap the tritium chemically.

22 MR. HOLCOMB: Oh, yeah, there is. Yeah, no
23 one wants to have water anywhere near these reactors.
24 Because water gives you the possibility of steam
25 explosions, gives you the possibilities of getting

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1 high pressurization.

2 So even things like pump cooling and stuff
3 is probably going to be done by refrigerating the
4 atmosphere, you know, something other that -- or using
5 a liquid metal. Some other coolant that does not have
6 a phase change. We really will not be using --

7 MEMBER MARCH-LEUBA: Yeah, so --

8 MR. HOLCOMB: And it's just a -- and that is
9 one of the learning things out of MSRE is there, you
10 know, most, you know, their maximum credible accident
11 was leaking there -- they actually their shielding was
12 a pebble structure of -- that used water cooling.

13 And that intermixing with the fuel salt in
14 a double spill was their maximum credible accident.
15 So I don't think anybody that I've seen in any of the
16 designs has water near the system. So --

17 MEMBER MARCH-LEUBA: In my mind -- in my
18 mind tritium is a problem, you know, tritium reactors
19 because it hides in the tons and tons of water that
20 are there.

21 MR. HOLCOMB: Yep, and we really do not have
22 water. It's a bad idea to have water near an MSR.

23 MEMBER MARCH-LEUBA: So it's really
24 conceivable to have a very good hydrogen filter
25 chemically which will grab -- 90% of what it will grab

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1 will be tritium. Okay, thank you.

2 MR. HOLCOMB: Yes.

3 MEMBER BLEY: But it's, in the case of
4 FLiBe, the thing is it's very -- the diffusivity's a
5 very strong function of temperature. Ten degrees C
6 it'll go by a factor of 2. So if you have temperature
7 gradients in the system in the interface between the
8 -- well, primary and secondary, whatever you want to
9 call the secondary, you could have big differences in
10 migration rate of tritium depending on the
11 temperature.

12 MR. HOLCOMB: Yes. The tritium -- and T
13 hot, they'll be more mobile at the upper end of the --
14 in the heat exchanger. Again, it's the heat exchanger
15 tubing where more of the stuff will go through.

16 I think one of the leading techniques that
17 people are -- other folks are considering is to
18 saturate the secondary (audio interference) side with
19 hydrogen and then back -- then try to back-diffuse the
20 hydrogen into the primary system and essentially try
21 to block a diffusion out of the system by overwhelming
22 it within diffusion.

23 MEMBER BLEY: Yeah, that runs a little bit
24 counter to potential control, but anyway.

25 MEMBER REMPE: So what kind of

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1 instrumentation is used to monitor these devices?
2 What was used at MSRE and what's being proposed?

3 MR. HOLCOMB: Do you mean -- what aspects of
4 these devices? I mean, thermocouples work at
5 temperature on air. And you know, PWRs traditionally
6 don't -- you know, do the heat balance on the
7 secondary side. And so you can do heat balance on
8 these things on the secondary side, much like you
9 would in other reactors.

10 You know, flow monitors on here, you have
11 differential pressure gauges on there, they are
12 traditionally used. They had not used any flow
13 monitoring on the fuel salt at MSRE because you shift
14 the redox -- because essentially the liquid in the
15 impulse lines was, traditionally is NaK.

16 And if you broke the -- had a leak of the
17 NaK into the fuel salt, you make it much more
18 reducing. And it turns out the uranium would then
19 attack the carbon and form uranium carbide in core.
20 And so they just didn't monitor it, monitor the flow.

21 There are a lot of different ways that you
22 might do this. On their activation flow meters,
23 certainly you can watch things going around. On their
24 -- probably, again, I think most of the measurements
25 are going to be made on the secondary side, on --

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1 MEMBER REMPE: What about flux? And again,
2 what about the interactions of the fuel salt with any
3 sort of sheath on these, on the instrumentation? And
4 again, you know, flux impurities, are they just
5 sampling to make sure their cleanup's working, or do
6 they actually monitor anything real time?

7 MR. HOLCOMB: Well, some of the things
8 people talk about are looking at the cover gas on the
9 -- here. But again, if you're saying what instruments
10 are they using to look at cleanup, generally there's
11 a filter line.

12 And so they grab what's on the filters, and
13 the filters are being replaced. If it's, you know,
14 and those are things like metal mesh filters, nickel.
15 Or they're, you know, you can grab sample in the
16 salts, and that's just a sort of bucket and well
17 that's, and then, you know, offline sampling.

18 You know, it depends. There are people who
19 look at using probes on this for electrochemical
20 probes here. But things like uranium concentration,
21 it turns out it's much more sensitive to look at its
22 impact on reactivity than anything else. And
23 reactivity you monitor with neutron measurements,
24 which don't touch the salt.

25 There are very few things that you actually

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1 need to touch the salt to measure.

2 MEMBER REMPE: Okay, thanks.

3 CHAIR PETTI: But there probably will be
4 active redox measurements in most of these systems,
5 David, you think?

6 MR. HOLCOMB: I'm not sure, because you
7 could look at U3, U4 grab samples. What we did at
8 MSRE was look at it every few days. Because it's not
9 something we're expecting to evolve very fast. And we
10 expect it to evolve under a normal process. It's kind
11 of like confirming that your models are working.

12 So I'm not really expecting very much active
13 instrumentation on this. You know, it's -- the
14 chemical processes, we know sort of what's being
15 generated when fission happens. And okay, it's
16 oxidative. And then sometimes when the decay process
17 can't be reducing on there. Some of the chloride
18 salts will actually become more reducing over time
19 during the decay.

20 And but we have models of this. And what
21 you'll be doing is confirming that your models are
22 working. And none of these things, the reason you
23 care about them is the damage to the materials. Most
24 of those things are corrosion and those are long --
25 those are longer time period things.

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1 And you're not expecting, you know, sort of
2 these cliff edge, anything where I've got to know this
3 this minute. If I know it tomorrow or next week,
4 generally that's pretty good.

5 So as I say, most of the operational stuff
6 I expect to be done on the secondary side, just as
7 traditional reactor -- you know, PWRs are, just
8 because it's easier. And you get good information
9 there.

10 Again, there are high potential consequences
11 for large -- a large early gas releases. We're
12 pointing out that mechanistic analysis of radioactive
13 material depends upon the fuel salt properties.

14 One of the things you'll note is that
15 there's an awful of the energy, you know, like 40% of
16 the fission products have a noble gas someplace in
17 their decay chain. And if that noble gas has more
18 than a few seconds of lifetime, they will then, you
19 know, that'll escape. And so a fair amount of the
20 cesium-137 production comes out of the xenon-137
21 production.

22 And so you get a lot of cesium-137
23 production in the cover gas because it's got a 3.8
24 minute half-life. And sort of exactly where that's
25 produced depends upon what your design is.

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1 Are you trying to keep all the -- this in
2 your reactor vessel, or do you want to actively purge
3 this and put that into a different location so it's
4 not available for an accident later. Or it's gone
5 into some rad waste protection system as opposed to
6 there. And so there's a lot of design variance on
7 this.

8 CHAIR PETTI: So David, what about iodine
9 and tellurium? I've seen --

10 MR. HOLCOMB: Iodine, they -- a lot of these
11 things depend upon the redox on there. The tellurium,
12 for example, is, well if it goes onto -- if you keep
13 it reducing, the tellurium largely stays in the fluid
14 and then doesn't do very much.

15 On the other hand, if you let the things
16 become oxidative, in the nickel -- in the nickel
17 alloys that we have experience with, the tellurium
18 then plates onto the surface and goes into this --
19 goes into the grain boundaries and tends to form
20 surface cracks.

21 That could become important on things that
22 are thin, particularly things like heat exchanger
23 tubing over time. So that becomes why redox control
24 is so important, because we run enough experiments to
25 know well, if you keep the tellurium in solution, it

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1 doesn't do that. It's got to get played out.

2 Iodine, there will be some iodine that will
3 come into the cover gas -- gas space, much like the --
4 cesium and such. And you may be an iodine and
5 fluoride things. And so that amount of stuff which is
6 in the cover gas either needs to be trapped or well-
7 confined. There's no question about that.

8 You also have real problems with things like
9 if you end up with the zirc fluoride on there.
10 Because the zirconium fluoride might plug the cover
11 gas line on there because it's higher vapor pressure,
12 and then tends to solidify.

13 And then it doesn't have a nice, low melting
14 point. So you'd have to use something like a screw
15 augur in your cover gas line to send it back into the
16 fuel salt or send it for treatment.

17 Same thing with uranium tetrachloride.
18 Chloride. So there are a number of things that go on
19 there. Exactly where the iodine goes, it depends upon
20 the redox, depends upon the operations. And we don't
21 have a -- that's one of the ones that we don't have a
22 perfect map of where things are. And so we need to
23 get more information if we want to have detailed this
24 is where this radionuclide goes.

25 DOE is currently engaged in a number of salt

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1 spill evaluation programs. On the other hand, we're
2 quite confident it doesn't generate things like
3 pressure waves. So your major issue is is just making
4 sure that you have a sealed containment or multiple
5 layers of sealed containment so that -- because
6 basically you cannot -- a large, early cover gas
7 release would be a catastrophic event.

8 So these things have to be designed so that
9 essentially you cannot go ahead and release all the
10 cover gas immediately. And so shearing off the whole
11 reactor vessel or some method for releasing most of
12 the cover gas early would -- you just -- that's --
13 that's must be a beyond-design-basis event well beyond
14 credible probably.

15 And we'll also pointing out, the MSBR, if
16 you're not familiar with that, was the eventual
17 project for, in the 1970s, for developing breeder
18 reactors in the large one. And they just had done
19 most of the calculations. And realistically the --
20 you know, 99.9% reduction in the radiotoxicity in the
21 cover gas in 48 hours.

22 So really, it's dropping very fast initially
23 on this. And so it is that early release has got the
24 most significance on there. It is not to say that
25 remaining parts, which are largely krypton and xenon,

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1 xenon, are not important to contain. But they're not
2 the same large land denial accidents after that 48
3 hours. Next slide please.

4 Fuel salt boundary breach accident
5 progression is part of performance-based and
6 deterministic fuel qualification. You know, multiple
7 locates in 10 CFR require evaluations of a possible,
8 postulated fission product release in core into
9 containments. So essentially, salt spill accidents.

10 Fuel salt or cover gas can't directly
11 express exterior containment layers without first
12 breaching the inner containment layer. So a lot of
13 the evaluation is how do you breach the inner
14 containment layer.

15 So high radiation and high temperatures
16 immediately outside of the fuel salt boundaries
17 substantially circumscribe the characteristics and the
18 materials adjacent to the fuel salt container.

19 So that's a lot of those instrument issues
20 and wiring issues and the like. You can't really have
21 electronics or, you know, or organic materials right,
22 even right outside the reactor vessel. The
23 temperature and the radiation environment is simply
24 too harsh.

25 The focus is on the fuel salt properties

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1 that must be known to adequately model accident
2 progression interaction characteristic with materials
3 and containment. So you have to look at okay, what
4 might be in containment and what could you spill the
5 salt on, on what's credible about that. Next slide
6 please.

7 The fuel-related advanced reactor
8 requirements and similar for liquid and solid fuel
9 because both of them are fuel. So, and there's the 10
10 CFR 50.43(e)(1)(i) recommends that performance of each
11 safety feature -- requires that the performance safety
12 feature of the design has been demonstrated either
13 through analysis, appropriate test programs,
14 experience, or a combination thereof.

15 Fuel salt thermochemical and thermophysical
16 properties provide the information necessary to model
17 its role in the plant safety features and when
18 performing their plant safety functions. The fuel
19 salt properties vary with composition and temperature.

20
21 So we need to determine the fuel salt
22 properties across the range in temperatures and
23 composition that span the potential operational and
24 accident conditions. And the quality of the
25 measurements need to be sufficient to enable modeling

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1 the role of fuel salt in achieving the plant
2 fundamental safety functions.

3 So if you've got a variation with viscosity
4 with composition, well, we need to know the
5 composition well enough. Because some things don't
6 vary a great deal with composition. Some things vary
7 a great deal. Things like the reactivity. If you
8 change the amount of uranium in the salt, well, you
9 get a fair amount of reactivity change.

10 On the other hand, even with lots of fission
11 product buildup, there really wasn't much viscosity
12 change at MSRE. Next slide, please.

13 And the liquid fuel salt must meet the
14 safety intents of the coolant-related GDCs or ARDCs as
15 appropriate. So if we look at the Reg Guide 1.232
16 approach to this and we're saying well, that's, you
17 know, in Part 50 that's how you establish the minimum
18 principal design criteria. There is compliance with
19 the appropriate set of design criteria.

20 So GDC 15 requires the coolant system be
21 designed so the design conditions -- the reactor
22 coolant pressure boundary are not exceeded during
23 normal operations or AOO. ARDC just removes the
24 pressure from the -- from the coolant boundary
25 functioning.

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1 So the key choice of MSRs that employ
2 functional containment is which set of layers comprise
3 the reactor coolant boundary. And the layers that are
4 credited to achieve the safety function must meet the
5 requirements. So if a normally salt-wetted layer,
6 such as the reactor coolant boundary, is credited, the
7 fuel salt conditions that would damage the layer must
8 be tested and corrected before causing significant
9 damage.

10 So this is a real challenge, and that's what
11 Joy may have been getting to in the instrumentation.
12 Because it is not easy to check on the thin wall
13 materials in the heat exchanger tubes, for example.
14 And this is why I think a number of companies are
15 likely not to credit the normally salt-wetted layer.

16 It may be possible on something like the
17 reactor vessel, where you've got -- or you just make
18 it thick enough that you watch the chromium
19 concentration build up over time -- time. And then
20 you just sample and watch for the chromium, you know,
21 and say that if you don't have enough chromium I
22 haven't gotten deep enough into my system.

23 However, if I'm concerned about something
24 like getting a hole in my heat exchanger tubing, and
25 that's accredited safety function on there, then

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1 you're going to have to be able to detect that under
2 normal operating conditions. And we don't really have
3 the technology to show small leaks in the heat
4 exchanger tubes on there.

5 Normally, you're going to be looking at
6 things like, well, you'll run the reactor, the fuel
7 salt at a lower pressure and your secondary coolant
8 would then be at a higher pressure. And so you'd look
9 at things like, well, what's the volume in my
10 secondary coolant. So I know I've got inflow into my
11 -- into the primary coolant, into the fuel salt.

12 And I think that generally you'll often be
13 moving the accredited boundary to the next layer,
14 which isn't nearly as radioactive on there, to be able
15 to monitor for damage under normal operating
16 conditions.

17 So watching things like degradation of the
18 heat exchanger tube boundary is a fairly, you know,
19 it's technically difficult.

20 MEMBER BROWN: It's Charlie Brown, can I ask
21 you a question?

22 MR. HOLCOMB: Sure.

23 MEMBER BROWN: The Naval Nuclear Program had
24 a substantial amount of experience with sodium-cooled
25 reactor in the early days, the Sea Wolf and its

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1 prototype in West Milton. And the corrosion and the
2 leaks in the steam generator tubes was a very
3 significant issue, very difficult, and that's why the
4 whole project was scrapped and rebuilt.

5 It seems -- you're saying it's tough.

6 MR. HOLCOMB: I'm saying detecting it is
7 difficult. We have a number of materials which turn
8 out if you keep the salt in a reducing it condition,
9 and so you keep the redox there. Well, the materials
10 are in the alloy are in the most reduced stated. And
11 you can drive the corrosion down very effectively by
12 keeping the redox where it should be.

13 If you let the redox go, you're having --
14 you will have problems on this. But the monitoring of
15 this, and then because Joy was asking about
16 instruments that you would put in to do this, you are
17 not expecting it to actually damage.

18 However, having an instrument to check
19 whether it has, is -- because it is a very harsh
20 environment. And trying to get an instrument that'll
21 look at tube wall thinning in, you know, right next to
22 the fuel, that's not something we can really do well.

23 But we do expect to be able to -- I mean by
24 far, the dominant corrosion mechanism in a halide salt
25 is oxidative damage. And so you just drive it into a

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1 reducing condition so it won't -- so that -- so you
2 can make that very small. There were a number of test
3 loops run for up to a decade on there, and they look
4 pristine.

5 That is not to say that other modes of
6 corrosion do not occur. However, they're either
7 really fast, where you've done something like you put
8 a dissimilar material into this and then, well, you
9 find out that's not a good idea. In 100 hours you've
10 corroded through a stainless steel part when you put
11 it into a nickel alloy loop. Or they're very slow,
12 non-oxidative corrosion.

13 So yes, these things do exist, but if you --
14 so we are very interested in maintaining the proper
15 chemistry in the fuel salt loop. Much like water
16 reactors, maintaining the proper chemistry is very
17 important.

18 MEMBER BROWN: Okay, how do you keep this
19 stuff liquid all the time, as opposed to going solid?

20 MR. HOLCOMB: Well, normally --

21 MEMBER BROWN: I haven't seen a reactor like
22 this --

23 (Simultaneous speaking.)

24 MR. HOLCOMB: Your challenge is after it's
25 been run for a while is removing -- is continuing to

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1 cool it on there, because you've got buildup of
2 fission products within it. And so it naturally would
3 tend to overheat as opposed to cool.

4 Initially, before it's built that up, you're
5 going to need heaters. Heaters, you know, when you
6 put in fresh salt, you're going to have to keep it
7 hot. And so you'll have either external heaters, or
8 you may put in gas heaters for the cover gas. It's a
9 number of different ways.

10 But you know, initially until you build up
11 the fission -- enough fission products. After that,
12 it's used fuel. Used fuel overheats rather than
13 underheats.

14 MEMBER BROWN: Okay, thank you.

15 MR. HOLCOMB: Next slide, please. So the
16 liquid fuel salt assessment frame where it follows the
17 template developed for the solid fuel advanced
18 reactors, where we would take the top-down approach,
19 decomposing the top-level goal of the fuel is
20 qualified to lower-level supporting goals.

21 You know, qualifying fuel develops
22 confidence the fuel will adequately perform its role
23 in enabling the safety -- the facility to achieve its
24 safety objectives. Lower level supporting goals are
25 further decomposed until the clear objective goals are

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1 identified that can be satisfied with direct evidence.

2 So if you look at this, that's a goal is the
3 fuel is qualified for use. That's a sub -- that's the
4 top goal in the solid fuel. And the safety criteria
5 can be satisfied with high confidence. Margin to
6 design limits during normal operations in AOO would be
7 met with high confidence.

8 The margin rating applied to release limits
9 under accent conditions, and the ability to achieve
10 and maintain safe shutdown can be assured. So it is
11 breaking things down into pieces. Next slide, please.

12 However, one of the (audio interference) you
13 know, liquid fuel is not a -- is a synthesized not a
14 fabricated process. So one of the major branches in
15 the solid fuel goal decomposition simply does not
16 apply to liquid fuel -- fuel. You know, both
17 properties can be determined by measuring, you know,
18 properties of product samples.

19 So if we just grab a sample of this, and
20 fortunately it's flowing well, so you just -- you get
21 a pretty homogenized system by grabbing. So neither
22 the fabrication-based definition of fuel qualification
23 nor a manufacturing specification branch is -- applies
24 to liquid fuel. So essentially truncate much of the
25 solid fuel program. Next slide, please.

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1 Qualifications based upon understanding the
2 chemical and physical properties of representative
3 fuel samples. A liquid state significantly changes
4 the behavior of fuel. They don't accumulate internal
5 stresses, so we don't have history-dependent
6 properties. So I don't need to have accumulated a
7 particular stress state.

8 The flow homogenizes the fluid properties,
9 so you don't get position-dependent property or size-
10 dependent properties. So I don't have the major
11 issues about leak test assemblies and bowing and such
12 that are all inherent characteristics of things being
13 solids.

14 The chemical and physical properties are set
15 by the elemental composition in temperature. This is
16 actually quite important because that means I don't
17 care about the isotopic content for the chemical and
18 physical properties, which means that I can take -- so
19 one I have determined what the elemental composition
20 is, I can use small, minimally radioactive liquid fuel
21 salt samples to get representative physical and
22 chemical properties.

23 I don't need to use cesium-137 in my salt to
24 determine its thermal conductivity. I can get that
25 from, you know, a stable cesium on this. And that

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1 really is quite helpful that it's an elemental
2 property, not an isotopic property for the
3 thermophysical and thermochemical. Not of course the
4 reactivity. Next slide, please.

5 Liquid fuel salt qualification establishes
6 acceptable salt composition ranges that maintain the
7 safety functions. Liquid fuel salt's a Newtonian
8 fluid. Classic fluid that's not thixotropic or
9 anything exotic.

10 The heat transfer and flow behave in well-
11 known manners, their continuous variation in the
12 physical properties with composition. Yet reasonable
13 assurance of adequate protection derived from a
14 combination of measured composition and knowledge of
15 the resulting chemical and physical properties.

16 A liquid fuel salt property database would
17 capture the relationship between fuel salt composition
18 and properties. Fortunately, the major properties on
19 there are not strongly impacted by things which are
20 very small fractions of it, things that are 0.01% of
21 things are not dominant issues in this. And it's
22 just, it's a nice feature of ionic liquids. Next
23 slide, please.

24 CHAIR PETTI: So David, just a question. I
25 agree with this, you know, the statements for the,

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1 let's call them the heat transfer normal operation and
2 accident properties. But solubilities, how close do
3 you get to solubility limits for some of the fission
4 products on these -- in these systems?

5 MR. HOLCOMB: Largely it depends. And
6 unfortunately that's the answer on there. For
7 example, the thermal, the -- if you're using a
8 fluoride salt and it's more complex because the
9 solubility of the fission products are, you know,
10 impacts the solubility of the fissile materials. So
11 they compete for solubility.

12 So if I get a lot of lanthanides in there,
13 I can plate out my actinides. And so you really do
14 need to have a map of where you are. The nice thing
15 is if it's just this fission product and it becomes
16 insoluble, initially it comes out as a particle, and
17 you filter on this.

18 So the things that are -- we call them the
19 noble fission products, well, some of them have very
20 low solubilities, approximately none on there. It's,
21 the real issue on this is that when I get something
22 like a, you know, where I've not caused my plutonium
23 to plate out at my low temperature because I've got so
24 much lanthanide buildup. But in reality, things like
25 cesium, strontium, most of these things form really

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1 good fluorides.

2 And what you do is as a whole you adjust
3 things like what's the melting point. And they're not
4 -- they're really -- they're well mistable (phonetic).
5 So you're not -- yes, phase separation on particularly
6 on the fast spectrum reactors where you've got very
7 large fractions of fissile materials, phase separation
8 is a possibility of something which can happen.

9 And you will need to have a map of where you
10 are and where you're headed. That's why that property
11 database is important. And part of this is how fast
12 do you get there and what type of a margin do I need
13 to have from these types of phase separation problems.

14 CHAIR PETTI: So, but the chemistry here
15 sounds somewhat complex in the liquid phase. So you
16 have some, hopefully some pretty good models to help.

17 MR. HOLCOMB: Yes, fortunately ionic
18 liquids, halite salts are some of the best, well-
19 studies types of materials that -- in existence. I
20 think we provided the roadmap prior to this that the
21 Campaign and NEAMS -- combination Campaign and the
22 NEAMS program have generated about how we're going to
23 get the thermophysical and thermochemical properties,
24 you know, adequately measured. Or -- and adequately
25 modeled.

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1 But some of the relationships are
2 complicated, but mostly we're not -- in most instances
3 we're not near the boundaries. But that is not a
4 universal statement. In some instances people are
5 running much closer to the boundaries, and that will
6 be a design concern. And it will certainly be
7 something that they will need to be able to
8 demonstrate that we have adequate knowledge of.

9 And fortunately because we have continuous
10 variations in the properties, what they're probably
11 going to do is take extremal points and say well,
12 we're not going to get further than this in
13 composition and show that we still haven't had a phase
14 separation.

15 CHAIR PETTI: So are these salts ideal, or
16 do they also exhibit some non-ideal behavior in a
17 chemical sense?

18 MR. HOLCOMB: Halite salts are pretty, you
19 know, are -- are very distinctive ionic liquids. They
20 have very normal, you know, Newtonian heat transfer.
21 You know, very well-known. But things like phase
22 separation, well, that is certainly a non-ideal
23 property. And phase separation is a possibility. You
24 can get solids that form in this with composition
25 changes.

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1 So in most instances and in most respects,
2 if you are well away from boundaries, when you are
3 well away from boundaries, they look pretty ideal.

4 But if you get near composition boundaries
5 where you're -- where gee, you add a little bit more
6 to this, and I would then get a phase separation where
7 I might get a solidification out of something, then I
8 worry about my accidents. Where, gee, I get an
9 overcooling transient, and now I'm plating out my
10 fissile material at the lower end of my heat
11 exchanger.

12 CHAIR PETTI: Right, right.

13 MR. HOLCOMB: So.

14 CHAIR PETTI: This is just a comment that
15 some of this discussion is really good, and it didn't
16 jump out to me in the report itself, the chemical
17 ideality and non-ideality and how important that is in
18 some of the defense, like you're talking about, so.

19 MR. HOLCOMB: We'll take comments on the
20 report, certainly. I would appreciate if we can add
21 things which will add clarity to that. We are trying
22 to make this a useful document, not just a regulatory
23 limits thing, so that we can both help the designers
24 and the regulators. So if you've got suggestions on
25 how to improve, we're -- I'm interested, my ears are

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1 open.

2 CHAIR PETTI: Yeah, no, we've got -- those
3 are -- my comments are things like that, this needs a
4 little more here a little more there sort of, to help.

5 MR. HOLCOMB: Because unfortunately I'm
6 awful close to this.

7 CHAIR PETTI: Right.

8 MR. HOLCOMB: And so my presumption of
9 knowledge on things is probably different than most
10 others. And so I need extra eyes. Okay.

11 CHAIR PETTI: Keep going.

12 MR. HOLCOMB: Next slide, please. So a
13 liquid fuel property database relates composition to
14 physical and chemical properties to add developers.
15 The database development is currently underway,
16 sponsored by DOE-NE.

17 It's also, it turns out that folks like the
18 Europeans through the Joint Research Centre,
19 Karlsruhe, have created another -- the database. And
20 they -- we've finally been working through the GIF to
21 get them to use the appropriate IEC quality standards
22 to give an equivalent data.

23 And so people can contribute data on the
24 phases, on the properties of the -- of salts. Because
25 there's a fair amount of complexity in the number of

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1 potential compositions that are there. And we -- and
2 the database is becoming more and more populated, but
3 it's got a few years.

4 And so what I expect is that individual
5 vendors will pay for data on their particular salt and
6 may or may not then elect to add it to the database.
7 So we may end up not being very efficient and having
8 to do things several times.

9 But for example, I was quite pleased to hear
10 that TerraPower in their work with Los Alamos on
11 sodium chloride-plutonium chloride data are agreeing
12 to take that data, which they own through -- and add
13 it to the common database. And so we just are adding
14 more information to the database over time.

15 Eventually, you just going to have salt
16 composition and just look up what the salt composition
17 temperature in this, look up the properties in the
18 database. Chances are, you know, it depends upon how
19 much an applicant is willing to do beforehand to say
20 do I have to do more thermophysical and thermochemical
21 property measurements to know where do I have to
22 maneuver things to set my boundaries.

23 But if I, you know, and but again, this is
24 one of the largest efforts that is under -- currently
25 underway, supported jointly by DOE, the Europeans, and

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1 the -- and DOE both through its MSR Campaign and
2 through NEAMS. Because largely they're using some
3 fairly fancy modeling tools to give predictions of
4 what the properties are.

5 And then they're measuring them at select
6 points and using the combination of modeling and
7 simulation and validation of the models -- models to
8 get the overall database. Next slide, please.

9 MEMBER REMPE: Does the database also
10 consider materials interactions?

11 MR. HOLCOMB: Yes, you have to -- there are
12 a couple of other programs that are just being
13 published now that NEAMS is doing on a significant
14 amount of interactions with the material. We do not
15 have truly first principle understanding of some of
16 the corrosion processes and we're doing engineering --
17 engineering scale approximations to number of things.

18 But as far as the salt composition, yeah, or
19 we stick more chromium in this because we corroded it.
20 That is one of the composition elements in the -- in
21 the salt, as far as the salt properties. Now, as far
22 as the accident progression modeling, we are having to
23 do things like well, except -- well, gee if it leaks
24 or if it does break, what happens.

25 Not -- and we are using some of the

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1 engineering development tools to try to say, well,
2 let's select these conditions or these things to make
3 that less likely. But we don't have a full first
4 principles understanding of everything which is going
5 on in, particularly in some of the corrosion parts on
6 here, because that would certainly help us to design
7 new alloys.

8 And so we're looking at developing,
9 continuously improving the development of the -- of
10 the -- of our understanding on there. But what we're
11 having to do is, currently, is mitigate the impacts of
12 if something does fail, can we still prevent, you
13 know, a large accident, accidents?

14 And that's kind of why we have the advantage
15 that the salt's only touching that first layer. And
16 CFR already tells us we have to accommodate an
17 accident where that first layer fails.

18 And things like if you have, say for example
19 you have a 304 stainless guard vessel around this
20 thing, and even if your vessel ruptures, well, the 304
21 stainless is going to last for indefinitely, a long
22 time. It's really radiation-damage tolerant and under
23 the condition that we're getting, so the neutrons
24 aren't going to have to done very much to it.

25 So you've got a pretty good secondary

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1 containment around this, even though you didn't have
2 very good evidence, perhaps, that your first -- that
3 you have a fundamental understanding of your -- of the
4 damage to your first material.

5 MEMBER REMPE: So your response -- thank you
6 for it, but your response emphasizes this first
7 principles, which now I'm starting to wonder about
8 your earlier discussion of the other data that's being
9 put into this database.

10 I understand that data are limited and it's
11 nice to have some sort of tool that shows the curve
12 that best matches the data. But hopefully it will be
13 obvious to the regulator where the data stop and where
14 those tools are used to extrapolate the data.

15 Is the data going to be presented in a way
16 that's easy for the regulatory to say, okay, we have
17 -- we understand based on data points between X1 and
18 X2, but any data beyond X2 is just some model
19 someone's created and extrapolated?

20 MR. HOLCOMB: Typically we tend to take the
21 data at the boundary points on here, and then not have
22 to do extrapolation and just doing interpolations.
23 And so we take it at a higher temperature than would
24 be acceptable and at maximum, you know, accident
25 conditions. So we don't try to do extrapolations

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1 because we don't really have good abilities of doing
2 that.

3 And so that means that what you're doing is
4 interpolating the data and relying upon the fact that
5 the fuel salt is generally well-behaved with
6 continuous property variations. And yes, we're using
7 models to say well, we don't have a really dense data
8 field. And so it might be a bit off.

9 But most of the -- but the ways that they're
10 trying to accommodate this is by taking data that it
11 would -- beyond the acceptable range. Taking data
12 where gee, this is at hotter than, well, we know that
13 this nickel-based alloy is going to turn butter by
14 these temperatures.

15 And we take the data at these temperatures
16 because we don't have to use a nickel-based alloy when
17 I'm doing this. It's probably in some refractory
18 material when I'm taking the original data set.

19 MEMBER REMPE: Thank you, that's what I
20 wanted to hear. Years ago there was this idea that
21 the DOE codes could be used to extrapolate because we
22 had first principles knowledge, and I'd still like to
23 be interpolating rather than extrapolating.

24 MR. HOLCOMB: Yeah, we don't really -- we
25 don't have -- we haven't validated that we have the

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1 knowledge on there. And until we do, we can't really
2 use them that way.

3 I see Stephen Schultz has got his hand up.

4 DR. SCHULTZ: Hi, Dave, thank you. A
5 question on the previous slide you mention that
6 appropriate quality assurance needs to be applied in
7 the database development. Is there sufficient
8 guidance and programmatic information that assures
9 that in terms of quality assurance?

10 MR. HOLCOMB: They are doing, in terms of
11 setting the boundaries of the properties. So we'll
12 know, gee, is the heat capacity off ten percent or
13 something. And that is being done by following good
14 scientific methods.

15 On the other hand, the implications of being
16 off on that are different because that involves you
17 having adequate models of the accident progression
18 sequences. And so you have both a concern about how
19 good do you need the data to be. And we can do a
20 number of things to say this is how well we know the
21 data and what the boundaries are.

22 But the question about how good do we know
23 -- need to know -- to really need to know the data is
24 also going to be very design-dependent. Some designs
25 may have a great deal more margin in certain

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1 properties than others will. And that's going to mean
2 that, well, we wouldn't need to get it down to a, you
3 know, a five percent knowledge, but maybe I could have
4 -- take a factor of 2 on this.

5 So we've got the scientific basis for
6 saying, well, what's my uncertainty in the
7 measurement. But what's my -- but what's the
8 implications of that uncertainty is going to be very
9 design-dependent.

10 DR. SCHULTZ: Thank you, that helps. And
11 retrospectively, the database as it has been developed
12 in the past, do you have a sufficient quality
13 assurance capability identified in that past data that
14 --

15 MR. HOLCOMB: We are unfortunately having to
16 regenerate on there. There is not an -- now, the
17 things that have been done since 2002 by the JRC,
18 because they did not initially -- it was -- that's one
19 of the advantages of working together in the GIF
20 program, is I'm the US GIF representative and we
21 really worked with the JRC to make sure they
22 understood people were going to make design and safety
23 decisions based upon this.

24 And they have fully implemented an
25 equivalent to, you know, an ASME NQA-1 type thing,

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1 quality assurance. But largely this has been, you
2 know, the database has been originally developed with
3 this as its purpose, with the understanding that we
4 need to know this adequately.

5 On the other hand, the database has not yet
6 been publicly released. It is DOE continues to
7 consider the export control implications of releasing
8 the data. However, right now I believe the decision
9 is this is fundamental scientific data, which by US
10 policy must be in the public domain. But we're --
11 we'll see what we get, you know, is the basic message.

12 But it is in the original, you know, design,
13 the original goals that this is to be a -- acquired
14 under an NQA-1 type approach.

15 (Simultaneous speaking.)

16 MR. HOLCOMB: And so I don't have a real
17 answer for you because the database isn't out there
18 yet.

19 DR. SCHULTZ: Understood.

20 MR. HOLCOMB: On there. But every piece
21 that we've seen so far, you know, that is all the way
22 through the acquisition program, round robin testing
23 is there -- is to apply an NQA-1 type mindset from day
24 one.

25 DR. SCHULTZ: Thank you.

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1 MR. HOLCOMB: So the fuel properties support
2 modeling the reactor performance under normal and the
3 accident condition. So the heat transfer of Newtonian
4 fluid is primarily determined by classics, density,
5 viscosity, heat capacity.

6 So thermal conductivity and radiative heat
7 transfer parameters can become important and
8 specialized situations, things like narrow tube walls
9 or very high temperatures or stagnant conditions. But
10 mostly it's density -- it's largely (audio
11 interference).

12 Fuel, you know, fuel salt database then has
13 the fuel salt composition, which gives you the fuel
14 salt properties. That is a function of temperatures,
15 which then tells you the fuel performance. Then you
16 take normal conditions and accident scenarios and you
17 determine whether you achieved the fundamental safety
18 functions.

19 And so there's a lot of work that's
20 currently going on to sticking the fuel salt
21 properties and the scenarios and the capabilities into
22 MELCOR and the accident progression codes, as well as
23 things like SAM to go ahead and say where are the
24 radionuclides to start with.

25 Because that's one of our biggest challenges

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1 is if you have your accidents is where is everything
2 when the accident starts. And that is -- it's not
3 necessarily so much fuel qualification, but it is
4 certainly part of the DOE-NE program to develop tools
5 that support the NRC so people can at least validate
6 the predictions that the designers are making.

7 CHAIR PETTI: David, I didn't see any
8 discussion of surface tension. I would think that if
9 you're going to do melt spreading, that you might want
10 to know what the surface tension of these salts are.

11 MR. HOLCOMB: It is indeed correct. It
12 turns out that the gravity -- there have been a couple
13 of reports recently, and it is the -- you know, it's
14 a gravity type, you know, that's the leading type of
15 things. And the amount of wetting is not the biggest,
16 you know, impact on there. But you're correct,
17 surface tension is one of the properties.

18 If you look in the details of the report,
19 particularly the one before, and one are the things
20 that are in there, surface tension is one of the
21 columns, columns.

22 And it turns out most people on the -- when
23 it flows, you've channelized it. You've put a sloped
24 pan so it flows down into a tank. And it flows pretty
25 well like water, you know, water.

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1 And so yes, that is one of the things we'll
2 need to have. No, we don't think it's one of the
3 things that's really a dominant issue. But it is one
4 of the columns -- columns that's listed as yeah, you
5 need to know that. Next slide please.

6 So, periodic fuel salt property assessment
7 will be an element of reactor operations. You know,
8 I sort of think of this as analogous to materials
9 surveillance coupons. You pull the coupons
10 periodically, look at gee, are the -- is -- are the
11 properties evolving according to you models.

12 If they're according to your models, you go
13 forward. If not, you got to update your models or
14 show that you maintain -- your continuing to be within
15 acceptable boundaries.

16 You'll see the frequency of how often you
17 measure it, depends upon the rate of change and how
18 close you are to an allowable limit. That was part of
19 the questions about the phase change there is if
20 you're close, you're going to have to measure more
21 frequently and have a better model of how your
22 composition is changing.

23 So for example on here, when we were at the
24 MSRE, they measure the chromium composition weekly on
25 there. And largely that was because they were

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1 concerned about oxygen ingress.

2 Any time you open things, you always get a
3 little bit of oxygen, and that made it more oxidative,
4 which would get the chromium out. And you'd see it
5 and you'd keep adding beryllium to it in small
6 quantities until you stopped seeing the chromium
7 content go up.

8 The uranium content was inferred from the
9 reactivity impact. They tried to measure it, but they
10 found it was a thousand times more sensitive to look
11 at the reactivity impact because they just kept adding
12 small amounts of uranium to keep the reactivity where
13 they wanted it to be.

14 But the MSRE really didn't accumulate
15 sufficient fission products to require reassessing
16 most properties, things like density, viscosity, etc.
17 After years, they really didn't have enough to do very
18 much.

19 (Simultaneous speaking.)

20 MR. HOLCOMB: Go ahead.

21 CHAIR PETTI: Just to clarify, I hear people
22 talk about the, you know, MSRE operated for years, but
23 I also understand it was really only one effective
24 full power year of operation. Is that --

25 MR. HOLCOMB: Pretty close to two, but yeah,

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1 to 13,000 hours. But yeah, but yes, the -- yeah,
2 there is a limited duration experience, you are
3 correct.

4 CHAIR PETTI: Yeah.

5 MR. HOLCOMB: Next slide, please. Fuel salt
6 supports plant SSCs in achieving the fundamental
7 safety functions and regulatory requirements. So the
8 qualification focuses on identification and
9 understanding of fuel salt property degradation
10 mechanisms that occur as a result of irradiation
11 during reactor operations.

12 So property repair, composition adjustment
13 may be incorporated into normal operation so that
14 things like, you know, filtering out the solids is
15 just, I envision most people are going to want to
16 filter out the solids.

17 But again, in something like a Moltex design
18 where the fuel is in a pin, well, you can't do that.
19 So you're going to run it until you've got -- you go
20 outside of the range of acceptable properties. During
21 normal operations, an AOO fuel salt properties must
22 not result in sufficient damage -- must result in
23 sufficient margin from damage to safety-related SSCs.

24 Essentially, if you said something like your
25 heat exchanger tubes are safety-related, you have to

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1 have some evidence that you don't -- you got
2 sufficient margin from damage. Which is why I think
3 that in most cases people are probably going to say
4 those are not safety-related and my -- it's going to
5 be my next boundary that I'm going to credit.

6 Under accident condition, the fuel salt
7 properties must not result in sufficient damage to
8 safety-related SSCs to prevent them from achieving
9 their function. So it's not required if other things
10 are happening during the accident to prevent the other
11 things, but they -- but it cannot itself cause, you
12 know, damage to other safety-related SSCs. Next
13 slide, please.

14 So our fuel qualification draft's available
15 for review and comment, there's the ML number. You
16 know, we're certainly welcome for suggestions for
17 improvements. The approach, you know, send it to Stu
18 while he's still employed there or to Chris or to me,
19 it will certainly be welcome. Welcome this, we're
20 hoping to, you know, accept comments, comments from
21 the ACRS and get a draft, you know, get a candidate
22 draft as soon, you know, in a timely manner.

23 I think the next one's just the last slide
24 then.

25 CHAIR PETTI: Okay, so David, you didn't go

1 into some of the issues. I do have one important
2 issue I wanted to raise with you in the reactivity
3 control. What's there is good, but I'm worried about
4 actual reactor control. Not so much in thermal
5 systems and fluoride salts, but in fast systems.

6 There's the effective delayed neutron
7 fraction in a FAS system where some of the fuel is
8 leaving. So the delayed neutron fraction keeps
9 getting small. You know, it's smaller in a FAS system
10 than a thermal system. Then I'm moving some of the
11 fuel so it's smaller still.

12 Some designs that might let the actinides in
13 the FAC system sit there for a long time and fission
14 them as an in situ actinide burner brings more
15 uncertainty.

16 I think an experimental assessment is needed
17 that you know what that delayed neutron fraction is.
18 I thinking particularly of the chloride FAS systems
19 where, if you're going to use them for a long times,
20 they have a lot of buildup of material. You're
21 fissioning the higher order actinides. I think life
22 gets really complicated.

23 MR. HOLCOMB: You got a really robust set of
24 reactivity feedback mechanisms on this. Unlike, you
25 know, a sodium reactors or anything like this is that

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1 that Doppler feedback is really quite strong on this.

2 And you're yanking out the things, you know,
3 when you're removing the delayed, that are more
4 effective because they're -- some of them are born at
5 a lower energy. So you are getting rid of some of
6 those neutrons that have more reactivity impact on
7 this.

8 But the Doppler broadening in the FAS
9 systems, because the problem on some of the thermal
10 systems is the potential for a positive reactivity
11 from the competition between the U233 and the thorium
12 because of the -- so you can get some warnings.

13 But in a FAS system, you got -- you have two
14 very strong negative reactivity impacts, one of which
15 being the Doppler broadening. The other one is just
16 the volumetric expansion that you've got a critical
17 geometry on this. And you are at the speed of sound
18 driving fuel out of the reactor.

19 And recall that your reactivity limit is not
20 even necessarily prompt criticality. It is so far
21 into prompt criticality that you caused a pressure
22 wave that damages the reactor vessel.

23 Because recall one of the original designs,
24 and they were trying to do this as a competition to
25 the TRIGA initially, was to use MSRs as prompt first

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1 reactors. Because they've got such really good,
2 negative fuel-based reactivity characteristics.

3 And so yeah, you might be able to drive, it
4 could be conceivable to get these very, you know, some
5 form of a prompt first. But if you -- if you've got
6 adequate evidence of the very strong negative
7 reactivity feedbacks, okay, you're designing a new
8 TRIGA. So I'm not --

9 MEMBER BLEY: This is Ron again. Most of
10 these designs have more -- have some form of
11 continuous purification, am I correct?

12 MR. HOLCOMB: Well, some of it's inherent,
13 you don't have a choice. The fission gasses are
14 coming out.

15 MEMBER BLEY: Right.

16 MR. HOLCOMB: And the solids, you probably
17 got a -- you're going to probably have to filter them.
18 I don't know whether I'd say anything beyond most on
19 those. But the ones that you have to do, yeah,
20 everybody's going to do the ones you have to.

21 MEMBER BLEY: Yeah. And you can --

22 MR. HOLCOMB: Whether they're going to be
23 other ones, look at Moltex, they're not doing it. But
24 Terrestrial probably will.

25 MEMBER BLEY: And you can more or less treat

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1 this as a homogenous system, am I right also there?

2 MR. HOLCOMB: Yeah, it's pretty close to
3 that. There's temperature driven, so you have to be
4 concerned about composition, you know, from the top to
5 the bottom because of thermally driven things. But
6 basically it, the fluid has to flow very rapidly to
7 transfer the heat so it's well mixed.

8 MEMBER BLEY: So this can be treated, and
9 Dave can correct me if I'm wrong, more or less as a
10 computational, what do you want to call it, easy
11 system?

12 MR. HOLCOMB: It's got a lot of inherent,
13 you know, as a pretty ideal system on many ways. But
14 again, what you have to be concerned with is that you
15 know the reactivity impacts on this and that you have
16 adequate confidence that you have strong and timely
17 negative reactivity feedback coefficients.

18 So that if you do get something which is --
19 then you get a reactivity transient, that it does not
20 rupture the system. And I think where we will have
21 pretty darn good confidence that we've got strong and
22 effective negative reactivity coefficients on there.
23 Thermal expansion is a pretty well-known property, and
24 so you're -- it's -- I'm not that concerned about the
25 controllability --

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1 CHAIR PETTI: Dave, I talked to some folks
2 interested in the chloride system and I've raised this
3 issue. Because you know, I mean, in the early days of
4 nuclear there were concerns about controllability of
5 FAS systems, that it could be -- I mean, right, if
6 there's no delayed neutrons, you can't have a reactor,
7 right. We know that boundary, right?

8 MR. HOLCOMB: Yep.

9 CHAIR PETTI: And so in talking to some of
10 the chloride guys, again, this is not my area of
11 expertise, but they thought it was worth them looking
12 at, you know, a small, very small system to
13 demonstrate it before jumping to something big.

14 MR. HOLCOMB: Well, I think there's a whole
15 bunch of things. That molten chloride reactor
16 experiment is really important. I think there's a
17 whole bunch of stuff you're going to get with that,
18 and I would not be supportive, and I don't think
19 anybody is supportive, of going beyond the small scale
20 reactor experiment. And they will do reactor physics
21 right at the beginning of that reactor.

22 CHAIR PETTI: Right.

23 MR. HOLCOMB: That's not going to be a big
24 system on there. For much like the same reason, you
25 know, you started MSRE as a small system in this. It

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1 is just no question there's a lot to learn about this.
2 I am concerned about things like the phase separations
3 and such and really understanding that well,
4 understanding the corrosion.

5 There are a lot of things that you will
6 learn from that first test reactor. And going to a
7 power reactor with a fast chloride salt system, I just
8 don't see anybody doing that. It seems to be
9 extremely risky on our level of knowledge, knowledge
10 we don't have the MSRE to provide us real confidence
11 that yeah, we built this, it runs this way.

12 So I don't think anybody's going to present
13 that as the, well, let's go do this. I do, you know,
14 certainly you will have startup reactor physics
15 experiments that are going to be very important on the
16 MCRE. And you know, that's the first one. You know,
17 DOE and you know, Southern Services, you know, with
18 TerraPower are going to be doing as a test -- as a
19 test scale reactor, as a non-power reactor.

20 You are going to be doing zero power
21 criticals. I think that's important. And then
22 they'll do (audio interference) to criticals and the
23 full set of reactivity experiments. I don't disagree
24 that you, you know, that that is the correct thing to
25 do and it should be done.

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1 CHAIR PETTI: Right. Any other comments,
2 members? Okay, I'll guess we'll turn to public
3 comment then. Can we open the public line?

4 MR. BROWN: Dave, we don't use the public
5 phone line, we use the Microsoft calling line.

6 CHAIR PETTI: Okay, so yeah. So anybody
7 from the public listening in that would like to make
8 a comment, please unmute now.

9 Okay, with that, I guess we'd like to thank
10 you, David. I actually really liked the report. I
11 thought it was a very good report. You'll see in our
12 letter just some minor things. You wanted some
13 feedback, you'll get those in our letter.

14 But I thought it was a good report. I
15 really liked the approach, starting with the safety
16 functions, exactly how I would have approached it. So
17 it was well done and well-reasoned, so.

18 So members, I do recommend that we write a
19 letter, just given the importance of the topic. The
20 fact that next month we're also going to be briefed on
21 the more generic framework in NUREG 2246. Getting
22 them both out I think will just help the staff as they
23 move forward here.

24 Any other comments from anybody?

25 MEMBER SUNSERI: This is just Matt, Dave.

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1 I do appreciate you pulling this together, and
2 presentation. I found it very informative, so thank
3 you.

4 CHAIR PETTI: Okay, so with that, then I
5 guess we adjourn the meeting, and we'll see everybody
6 at the full committee here this afternoon.

7 (Whereupon, the above-entitled matter went
8 off the record at 10:45 a.m.)

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MSR Fuel Salt Qualification Guidance Development

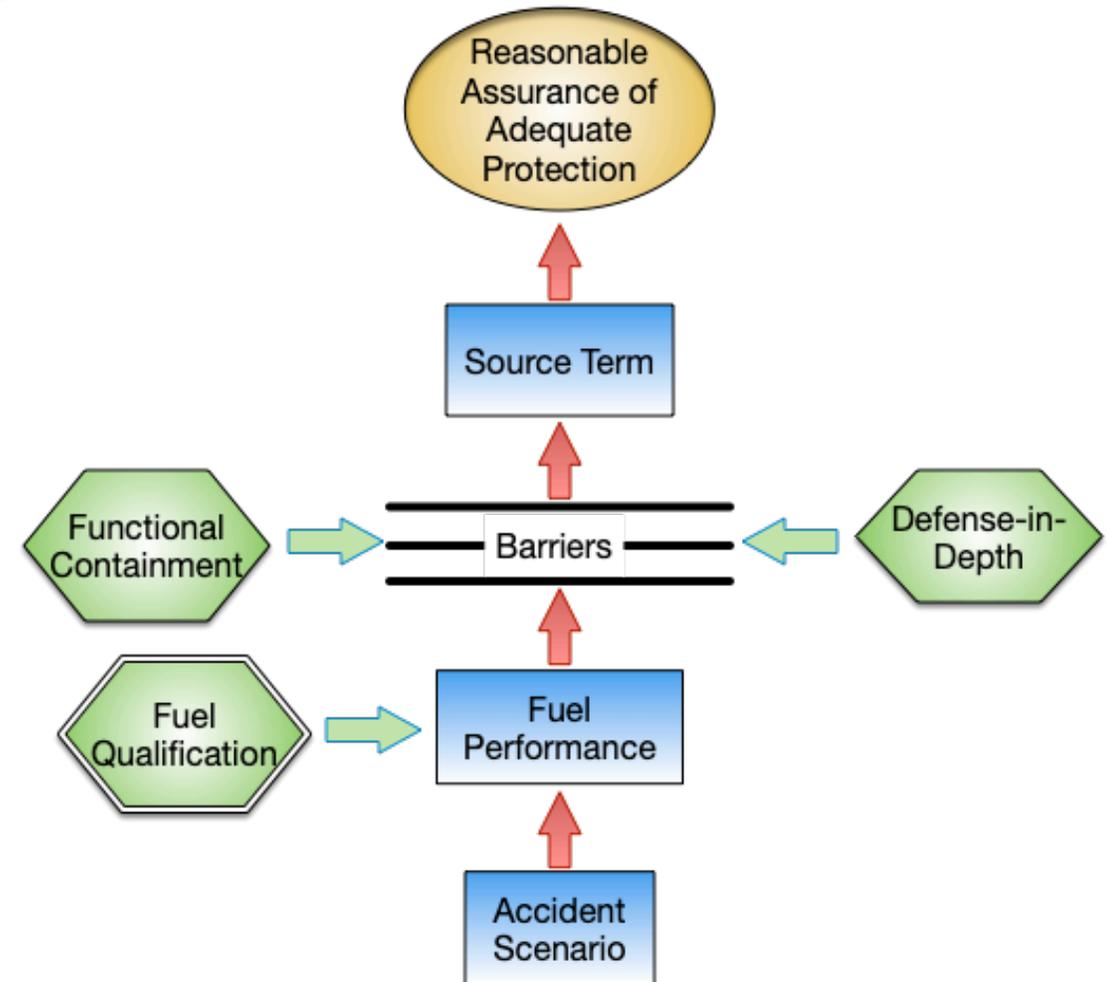
ACRS Subcommittees on Metallurgy & Reactor Fuels

David Holcomb, George Flanagan, and Mike Poore

October 5th, 2021

Fuel Qualification is an Element in Achieving Sufficient Understanding of Fuel Behavior

*“**Fuel qualification** is a process which provides high confidence that physical and chemical behavior of fuel is sufficiently understood so that it can be adequately modeled for both normal and accident conditions, reflecting the role of the fuel design in the overall safety of the facility. Uncertainties are defined so that calculated fission product releases include the appropriate margins to ensure conservative calculation of radiological dose consequences.”*



- NRC Presentation on Possible Regulatory Process Improvements for Advanced Reactor Designs, August 3rd, 2017 (ML17220A315)

Liquid Fuel Salt Qualification Builds From Advanced Reactor Assessment Framework

- Liquid salt fuel assessment framework employs goal decomposition process parallel to NUREG-2246
 - Success criteria derive from fundamental safety functions
- Dozens of MSR design variants under consideration
 - Nearly all developed over the past decade
- Which designs will be presented for regulatory safety adequacy review over the next decade is uncertain
- Fuel salt qualification process based on fuel salt chemistry and physics and is largely independent of reactor configuration

Fuel Qualification Supports Both Performance-Based and Prescriptive Safety Adequacy Evaluation Processes

Performance-Based

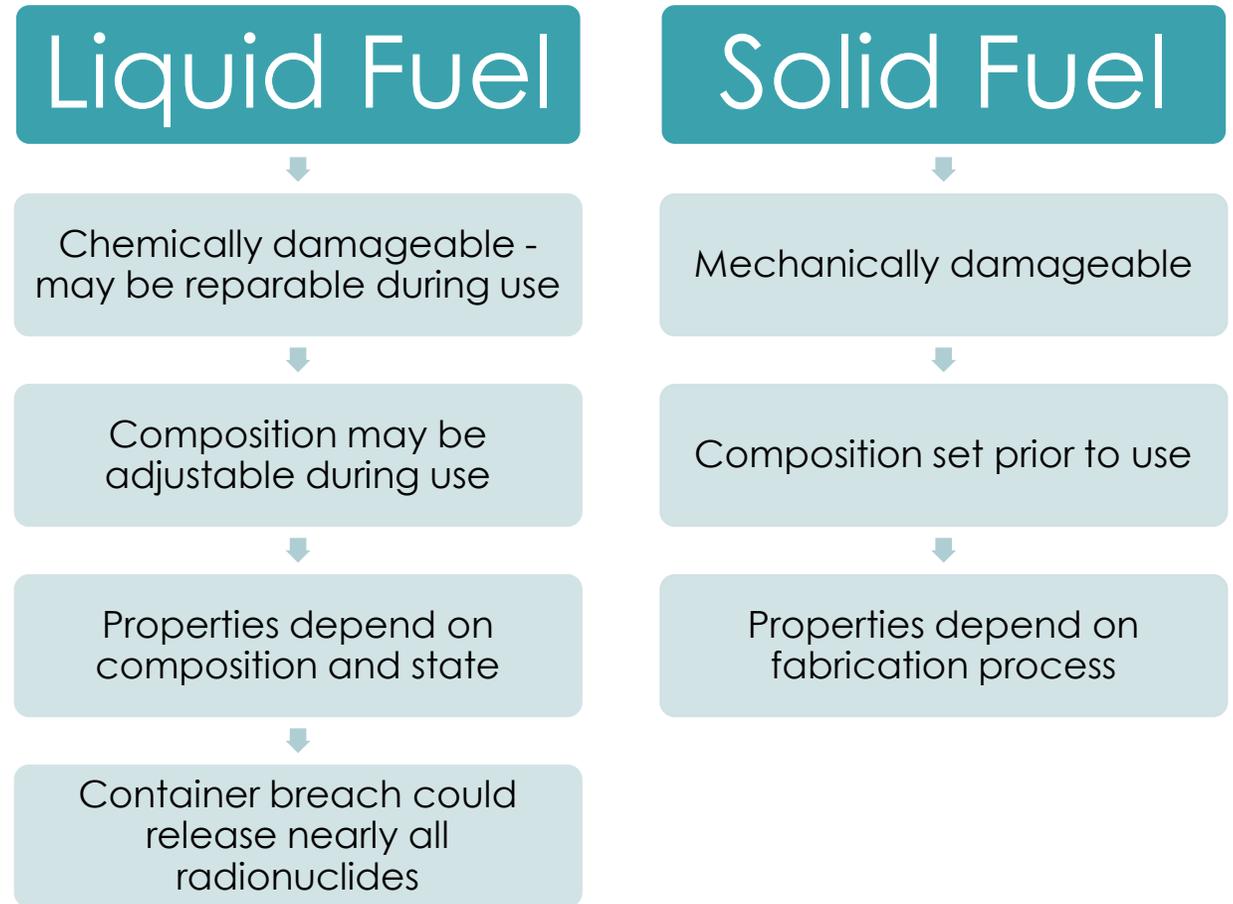
- Understand how fuel salt properties support plant achievement of fundamental safety functions
- Evaluate acceptable range of fuel salt properties to
 - Maintain appropriate margin from design limits under normal and AOO conditions
 - Limit damage to safety-related SSCs to ensure proper functioning during accidents

Prescriptive

- Determine the range of fuel salt properties that results in compliance with specific requirements
 - Both fuel and coolant requirements

Liquid Fuel Has Substantial, Fundamental Differences From Solid Fuel

- Liquid salt fuel
 - Serves as nuclear fuel and primary heat transfer media
 - Must meet requirements for both purposes



Fuel Salt Qualification Applies From Receipt of Regulated Materials Until Transfer to Independent Storage

- Properties evaluated will be different at different points of fuel salt lifecycle – for example
 - Reactivity impact of fuel salt concentrate is a concern during fueling
 - Fluid properties immaterial to frozen, used fuel salt
- Materials that leave the fuel salt and lack a reasonable means of return cease to be part of the fuel salt
 - Insoluble materials, fission gases, vapors, and aerosols become part of radioactive waste stream
 - Plated out materials that could redissolve or resuspend in the liquid remain part of fuel salt

Key Issue is “What Constitutes Fuel Salt?”

- Fuel salt does not come in discrete elements (rods or assemblies) and moves independently of its container during normal operations
 - Cladding and fuel assembly structures are qualified as part of solid fuel
- Fuel salt includes all of the material containing fissionable elements or radionuclides that remain in hydraulic communication, but does not include the surrounding systems, structures, or components
 - Salt vapors and aerosols remain part of the fuel salt system until they become adequately trapped
 - Container corrosion products become part of the fuel salt
- Fresh and used fuel salt in on-site storage are within scope

Common Salt Properties and Plant Functions Enable a General Liquid Fuel Salt Evaluation Method

- Specific accident sequences are design dependent
- Basic operational and safety functions are common to any nuclear power plant
- Halide salt characteristics are common to any MSR
 - High boiling points (low pressure)
 - Low Gibbs free energy (low chemical potential energy)
 - Natural circulation heat transfer properties
- Fuel salt interacts with its container layers via common chemical and physical mechanisms - for example via thermal energy transfer, chemical reactions, and mechanical processes

Method Tailors Solid Fuel Qualification Process To Characteristics and Functions of Liquid Salt Fuel

- Modifications both add and remove issues from solid fuel qualification process – for example
 - Fuel salt is not a manufactured product (e.g., not in the sense that NUREG-2246 describes solid fuel via a manufacturing specification)
 - Liquids cannot be mechanically damaged
 - Fuel salt also serves as the primary reactor coolant
- Fuel salt properties determine its capability to adequately support achievement of fundamental safety functions (FSFs)
- Fuel salt regulatory basis derives from the role of the fuel salt in establishing compliance with existing regulations

Liquid Fuel Salt Does Not Have a Mechanically Determined Lifetime

- Identification of life-limiting failure and property degradation mechanisms that occur as a result of irradiation during reactor operation remains key focus
- Fuel salt lifetime is the period during which it
 1. Contains adequate quantities of fissile materials,
 2. Does not include too many neutron absorbers, and
 3. Maintains acceptable thermophysical and thermochemical properties
- Composition may be adjustable during operation to correct degrading conditions

Functional Containment is Important to How MSR's Provide Adequate Radionuclide Retention

- Barrier performance must be degraded to release radionuclides into the environment
 - Performance degradation can occur through failure or bypass
- Fuel salt properties that stress barriers cause them to be more likely to release radionuclides - for example
 - Increased temperature increases radionuclide vapor pressure in cover gas and well as decreasing strength of container
- Different performance requirements for materials normally in contact with salt versus those that only need to withstand accidents

Fuel Salt Properties Have Substantial Impact on Containment Performance

- Normal operations
 - Salt seeking radionuclides are chemically retained
 - Fission gases (with half lives more than a few seconds) largely escape
 - Noble (insoluble) metals largely either plate out or escape into vapor
 - Fuel salt causes stress on, potentially resulting in damage to, container materials (e.g., via corrosion, erosion, creep, etc.)
 - Tritium behavior depends on operations and redox state
 - Chemical configuration (free or bound) depends on redox
- Accident conditions
 - Mechanistic analysis of radioactive material transport depends on fuel salt properties
 - Substantial reduction in cover gas heat content and radiotoxicity over first couple of days – MSBR predicted 99.9% reduction after 48 hours (ORNL-4396)
 - High potential consequences of large, early cover gas releases

Fuel Salt Boundary Breach Accident Progression Part of Performance Based and Deterministic Fuel Qualification

- Multiple locations in 10 CFR require evaluation of a postulated fission product release from core into containment
- Fuel salt or cover gas cannot directly stress exterior containment layers without first breaching an inner containment layer
- High radiation and high temperatures immediately outside fuel salt boundary substantially circumscribes characteristics of materials adjacent to fuel salt container
- Focus is on fuel salt properties that must be known to adequately model accident progression and interaction characteristics with materials within containment

Fuel Related Advanced Reactor Requirements Are Similar for Liquid and Solid Fuel

- Example

- 10 CFR 50.43(e)(1)(i) requires that the performance of each safety feature of the design has been demonstrated through either analysis, appropriate test programs, experience, or a combination thereof
- Fuel salt thermophysical and thermochemical properties provide the information necessary to model its role in enabling plant safety features to perform safety functions
- Fuel salt properties vary with both composition and temperature
- Fuel salt properties need to be determined across the range of temperatures and compositions that span potential operational and accident conditions
- Quality of the fuel salt property data needs to be sufficient to enable modeling the role of the fuel salt in achieving the plant FSFs

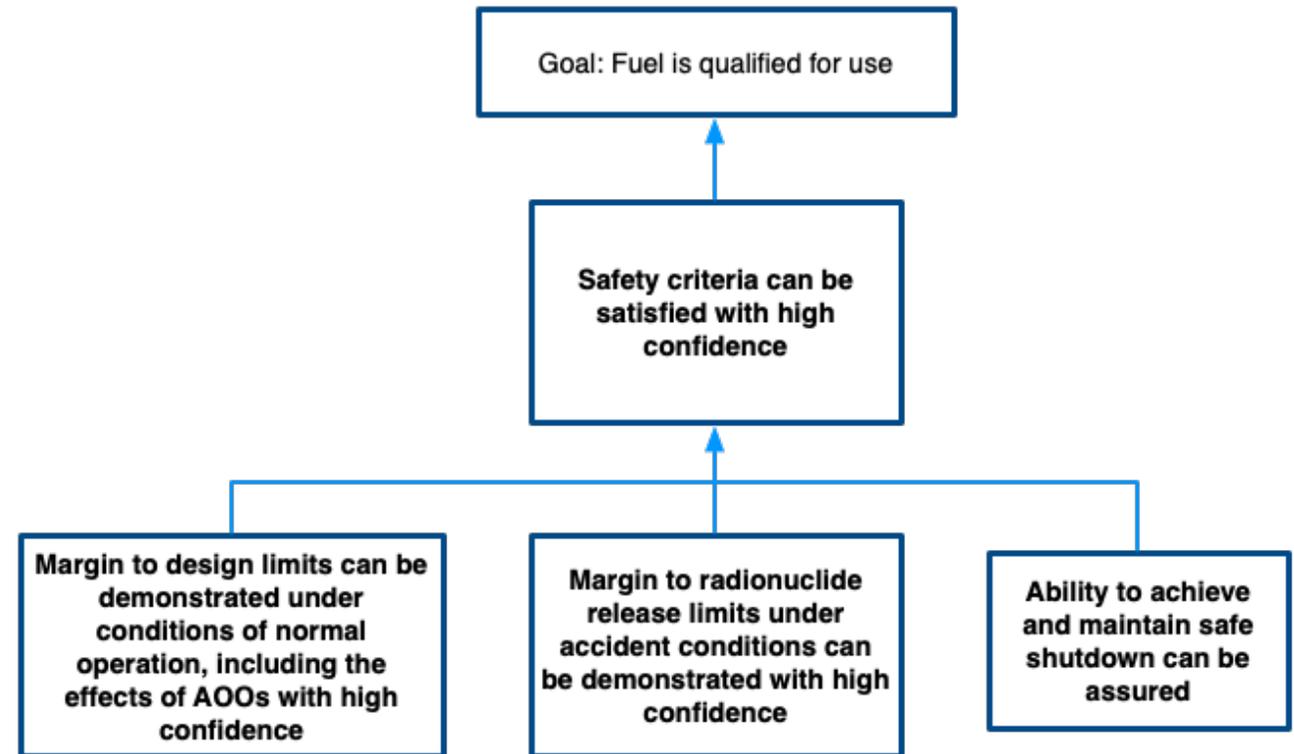
Liquid Fuel Salt Must Meet the Safety Intent of the Coolant Related GDC or ARDC (as appropriate)

- Example

- GDC 15 requires that the coolant system be designed so that the design conditions of the reactor coolant pressure boundary are not exceeded during either normal operations or AOOs
 - ARDC 15 removes pressure from the reactor coolant boundary function
- Key design choice of MSR that employ functional containment is which layer or set of layers comprise the reactor coolant boundary
 - Layer(s) credited to achieve the safety function must meet the requirement
- If a normally salt-wetted layer (e.g., reactor coolant boundary) is credited, fuel salt conditions that would damage the layer must be detected and corrected before causing significant damage

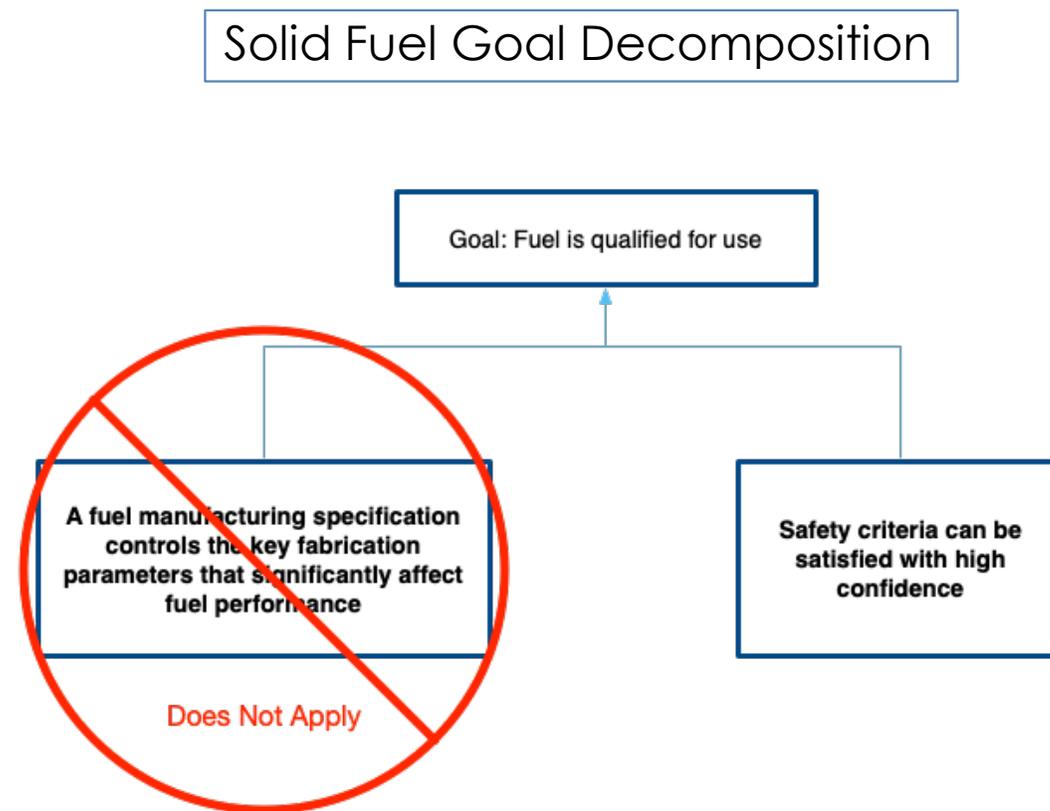
Liquid Salt Fuel Assessment Framework Follows Template Developed for Solid Fueled Advanced Reactors

- Top-down approach used to decompose top level goal of *fuel is qualified* to lower level supporting goals
 - Qualifying fuel develops high confidence that the fuel will adequately perform its role in enabling the facility to achieve its safety objectives
- Lower level supporting goals are further decomposed until clear objective goals are identified that can be satisfied with direct evidence



Liquid Fuel is a Synthesized Not a Fabricated Product

- Bulk properties can be determined by measuring properties of product samples
- Neither the fabrication based definition of fuel qualification nor manufacturing specification branch of fuel assessment employed for solid fuel advanced reactors applies to liquid fuel



Qualification is Based Upon Understanding the Chemical and Physical Properties of Representative Fuel Samples

- Liquid state significantly changes the physical behavior of fuel
 - Liquids do not accumulate internal stresses
 - No history dependent properties
 - Flow homogenizes fluid properties
 - No position dependent properties
 - No size dependent properties
- Chemical and physical properties are set by elemental composition and temperature
 - Independent of isotopic content

Small minimally-radioactive liquid fuel salt samples provide representative physical and chemical properties

Liquid Fuel Salt Qualification Establishes Acceptable Salt Composition Range That Maintains Safety Functions

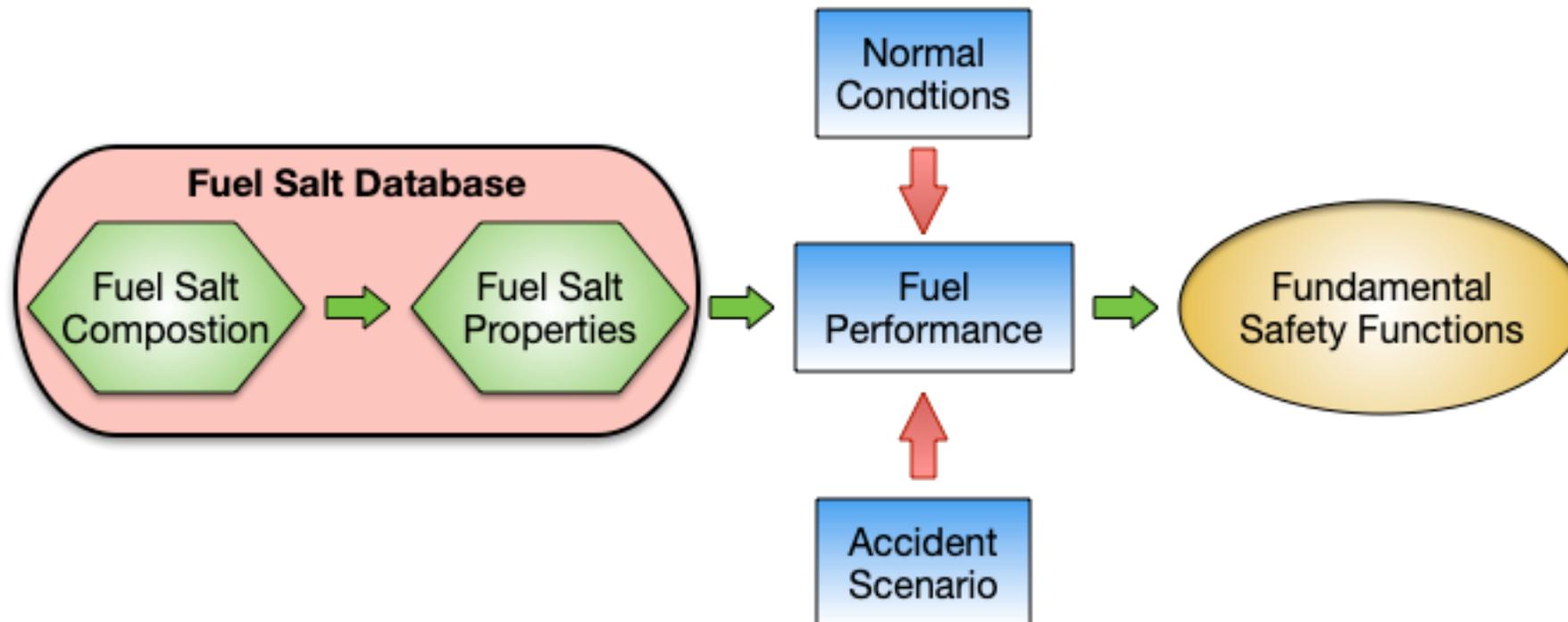
- Liquid fuel salt is a Newtonian fluid
 - Heat transfer and fluid flow behave in well known manners
 - Continuous variance in physical properties with composition
- Reasonable assurance of adequate protection derives from a combination of measured salt composition and knowledge of resulting chemical and physical properties
- A liquid fuel salt property database would capture the relationship between fuel salt composition and properties

Liquid Fuel Salt Property Database Relates Composition to Physical and Chemical Properties to Aid Developers

- Database development underway sponsored by DOE-NE
 - Salt property measurement program in progress
 - Not currently including minor constituent transuranic elements (Am, Cm)
 - Requires appropriate quality assurance for both new and existing data
- Database initially sparsely populated
 - Safety evaluations / accident models performed with bounding values to establish acceptable performance range
- Additional data added to database over time
- Goal is to eventually only require salt composition and temperature measurement at operating plants and look up properties from database

Fuel Salt Properties Support Modeling Reactor Performance Under Normal and Accident Conditions

- Heat transfer in Newtonian fluids is determined primarily by density, viscosity, and heat capacity
 - Thermal conductivity and radiative heat transfer parameters can become important in specialized situations



Periodic Fuel Salt Property Assessment Will Be an Element of Reactor Operations

- Analogous to material surveillance coupons
 - Compare measurement to prediction
- Frequency of property measurement depends on potential rate of change and how close salt composition is to allowable limits
 - Chromium composition was measured weekly at MSRE
 - Uranium content was inferred from reactivity impact
 - MSRE did not accumulate sufficient fission products to require reassessing most properties: density, viscosity, etc.

Fuel Salt Supports the Plant SSCs in Achieving the FSFs and Regulatory Requirements

- Qualification focuses on identification and understanding of fuel salt property degradation mechanisms that occur as a result of irradiation during reactor operation
 - Property repair (composition adjustment) may be incorporated into normal operation
- During normal operations and AOOs fuel salt properties must result in sufficient margin from damage to safety-related SSCs
- Under accident conditions the fuel salt properties must not result in sufficient damage to safety-related SSCs to prevent them from achieving their function

Fuel Qualification Draft NUREG/CR (ML21245A493) is Available for Review and Comment

- Suggestions for improvements to the approach can be provided at any time
- Comments and suggestions can be provided to the NRC or the authors

Discussion