東京電力福島第一原子力発電所における
事故の分析に係る検討会（第34回）
参考資料

WE START WITH YES.

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TOPIC 3 - CORE DEBRIS LOCATION EVALUATIONS

MITCH FARMER
Nuclear Science & Engineering Division
Argonne National Laboratory

Fukushima Forensics Meeting, November 17-18, 2022
Hybrid Virtual (Webex) and In-Person at NEI, 1201 F Street, NW, Suite 1100, Washington, DC

PRESENTATION OUTLINE

- Review of most recent TEPCO/IRID/NRA[1] observations/questions of ex-vessel debris characteristics for 1F1.
- High level review of past MACE and OECD/MCCI test results focused on providing potential insights to some of these questions based on test results.
- CORQUENCH scoping calculations aimed at further addressing some of these questions, but from a modeling viewpoint.
- ~~Revisiting previous idea for potential *in-situ* core-debris water ingression measurement for 1F2~~. – see backup slides

1. Masaya YASUI, "NRA's Investigation (Phase 2) of Fukushima Daiichi Nuclear Accidents (2021-2022)," Reactor Safety Technology Expert Panel Forensics Meeting, Nuclear Energy Institute, Washington, DC, 17th November 2022.

QUESTIONS RAISED[1] FROM RECENT 1F1 INVESTIGATIONS

1. Why did the debris released from the RPV not spread out?
   – *Assumption on my part*: this is based on the elevated height of the crust material in doorway opening in relation to the volume of core debris discharged.
2. How was the pedestal wall concrete damaged but not the rebar?
3. How was the “suspended crust” material formed?

- Other questions of interest:

1. What is the source of the white powder that appears to cover some surfaces?

INSIGHTS FROM MACE AND OECD/MCCI TESTS RELEVANT TO 1F1 OBSERVATIONS

- MACE tests examined debris coolability under ***early*** cavity flooding conditions.
  - All tests 1-D except the MACE Scoping Test (M0), which was 2-D.
- The OECD/MCCI (or ‘CCI’) tests were intended to provide additional data on 2-D MCCI behavior as well as debris coolability.
  - All tests flooded late except for CCI-6 that featured early flooding.
- MACE tests (with LCS and SIL concrete types) all exhibited behavior in which the upper crust formed by water cooling would ‘anchor’ to test section sidewalls.
- The ‘anchored’ crust would eventually separate from the melt due to: i) reduced gas sparging as the test progressed, causing the voided melt height to decrease, and ii) concrete densification upon melting (i.e., ‘slumping’).
  - In all tests, this led to suspended ‘bridge crusts’ anchored to test section sidewalls and separated from the underlying melt by an intervening gap (illustrations to follow).

INSIGHTS FROM MACE AND OECD/MCCI TESTS RELEVANT TO 1F1 OBSERVATIONS

- The extent that core debris will slump due to concrete densification upon melting is given by the equation:

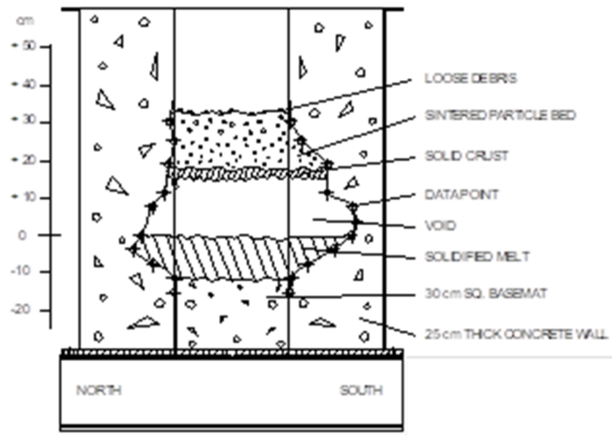
$$\frac{V_f}{V_0} = (1 - \chi_{gas})\left(\frac{\rho_{con}}{\rho_{slag}}\right)$$

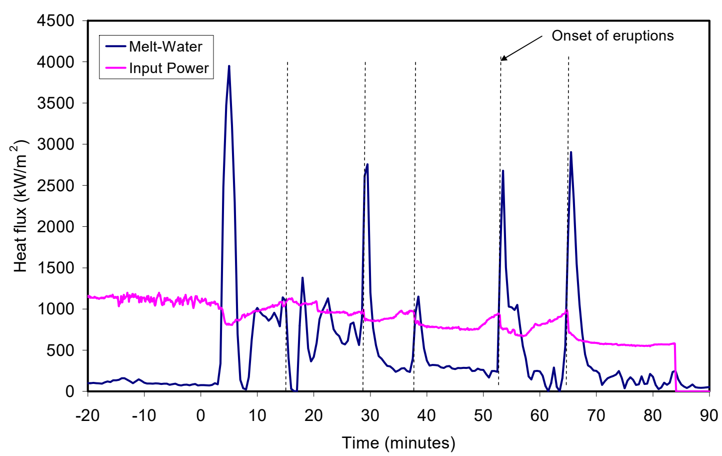
- Here, χ_{gas} is the mass fraction of decomposition gases in concrete (H_2O and CO_2), ρ_{con} is the original concrete density, and ρ_{slag} is the density of the slag produced by melting (i.e., gases leave, and $Ca(OH)_2$, $CaCO_3$, and $MgCa(CO_2)_3$ are decomposed into the simple oxides CaO and MgO).
- For CORCON default 'Basalt' concrete, χ_{gas} = 0.0708, and based on CORQUENCH thermo-physical property subroutines, ρ_{con}= 2431 kg/m^3 and ρ_{slag}= 2542 kg/m^3.
- With this information, $\frac{V_f}{V_0} = 0.889$ for Basalt concrete, implying that for every 10 cm of erosion, 1.1 cm of surface elevation reduction will occur during ablation in 1-D.
- More slump will occur in 2-D erosion cases, but volume reduction equation is more complicated as it depends on extent of lateral vs. axial ablation.

MACE SCOPING TEST[2]

LCS concrete, 30 cm x 30 cm square test section, 130 kg corium mass, high power density test

- Top crust anchored to sidewalls, and was mechanically stable for rest of test.
- Due to high power density (700-1400 W/kg fuel), relatively thin conduction-limited crust formed.
- Periods of high melt void fraction occurred in which the melt re-contacted the crust, leading to melt eruptions and particle bed formation.
- Anchored crust viewed as 'non-prototypic' and the test section design was changed to refractory sidewalls and larger scales in subsequent tests in an effort to achieve a floating crust boundary condition.



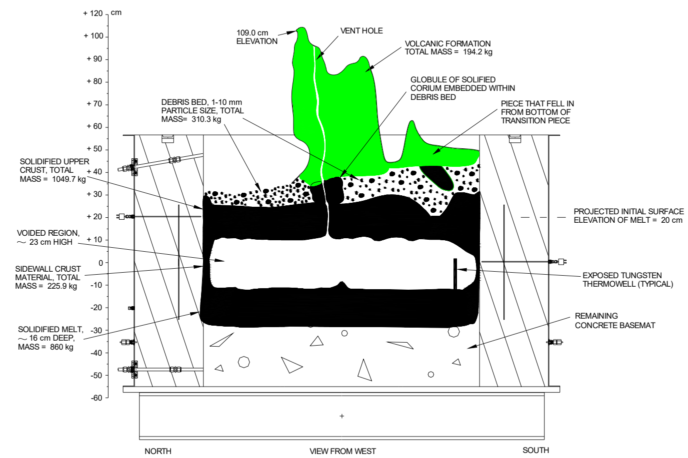


2. M. T. Farmer, D. J. Kilsdonk, and R. W. Aeschlimann, "Corium Coolability under Ex-Vessel Accident Conditions for LWRs," *Nuclear Eng. Technology*, Vol. *41*, pp. 575-602, June 2009.

MACE TEST M3B[2]

LCS concrete, 120 cm x 120 cm square test section, 1-D (refractory walls), 2000 kg corium mass, normal power density

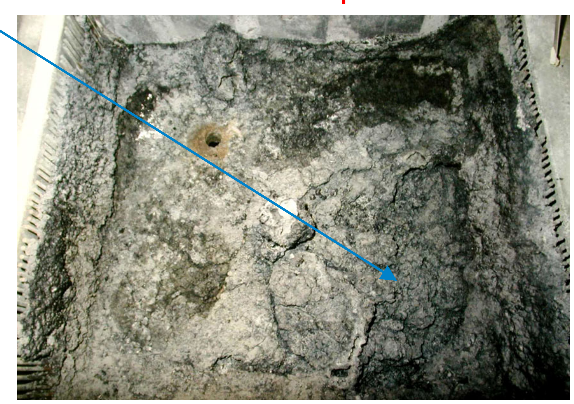
- Crust stress analyses[3,4] indicated that a test section size of 2 meters or more would be needed to achieve a floating crust boundary condition.
- Practical considerations limited the maximum test section size to 1.2 m.
- Test showed similar phenomenological behavior as M0 (anchored crust, periodic eruptions), but evidence of crust structural failure was also noted at this increased test scale.



As found

After removal of erupted material

Section of crust that structurally failed

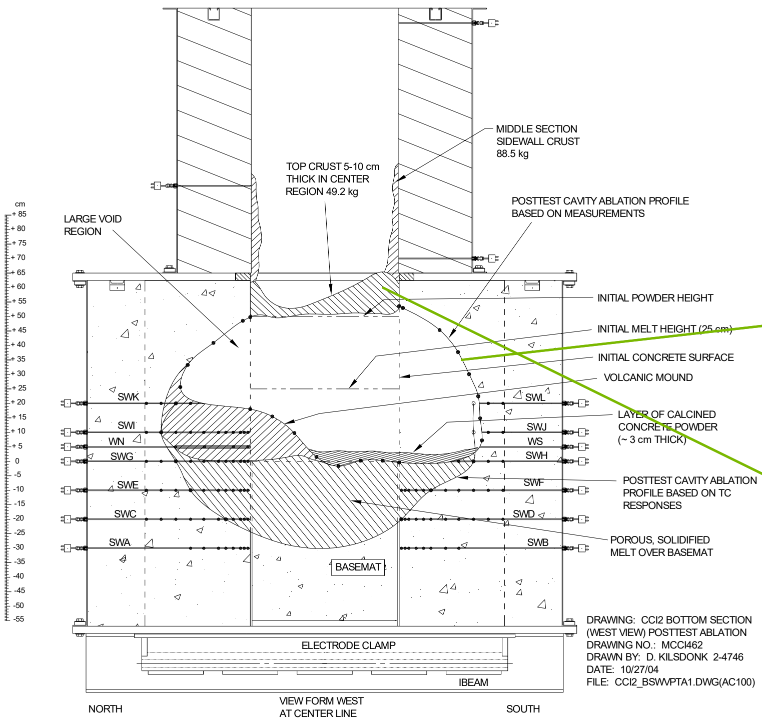


3. Z. Feng, R .L. Engelstad, E. Lovell, M .L. Corradini, “Stress Analysis and Scaling Studies of Corium Crusts,” Proceedings of the Second OECD (NEA) CSNI Specialist Meeting on Molten Core Debris-Concrete Interactions, KfK 5108 NEA/CSNI/R(92)10, April 1992.
4. J. H. Ptacek, Z. Feng, R.L. Engelstad, E.G. Lovell, M.L. Corradini, and B.R. Sehgal, “Modelling of the MCCI Phenomena with the Presence of a Water Layer,” Proceedings of the Second OECD (NEA) CSNI Specialist Meeting on Molten Core Debris-Concrete Interactions, KfK 5108 NEA/CSNI/R(92)10, April 1992.

OECD/MCCI TEST CCI-2[2]

LCS concrete, 2-D test section with 50 x 50 cm initial cavity size; 6 hours of dry cavity ablation, followed by cavity flooding

- No apparent crust anchoring, but large accumulation of core debris in upper portion of test section due to deposition from highly swelled melt pool height.
- Extensive ablation above the solidified debris over the basemat; likely due to radiation heat transfer from upper surface of melt during the test.
- Relatively thick (3 cm layer) of calcined concrete found on top of debris, supporting the idea that this material was produced by radiation heat transfer and not ablation via contact with melt.



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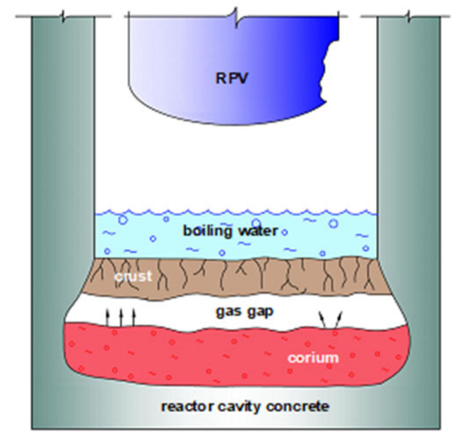
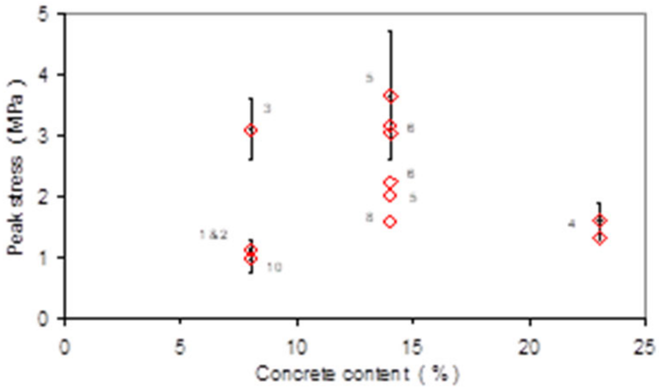
CRUST ANCHORING IN RELATION TO PLANT CONDITIONS

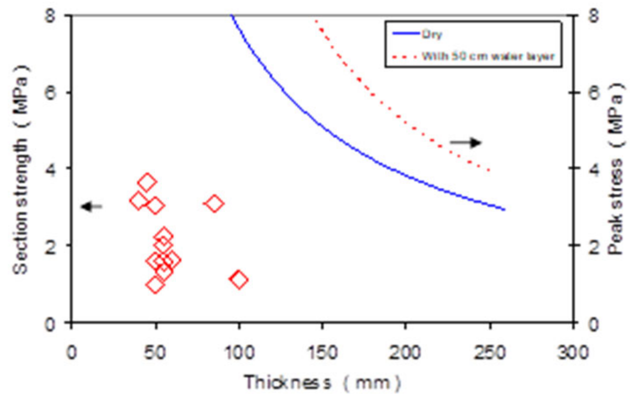
- Occurrence of anchoring in MACE tests raised concerns that if this happened at plant scale, it may prevent debris cooling by forming an insulating gap between the crust and remaining melt.
- On this basis, load tests were conducted on sectioned corium ingots from SSWICS tests to measure tensile strength of core debris containing inherent crust cracking and porosity.
- Results indicated that crusts are weak, and that sustained anchoring at plant scale is unlikely given the 6 m cavity span in many plants.
- Rather, periodic crust anchoring and 'breach' would likely occur, leading to renewed pathway(s) for water to re-contact and ingress into the debris.

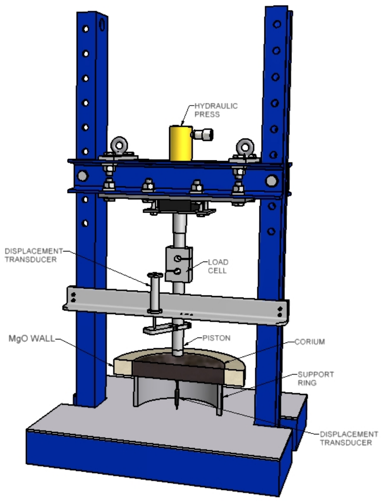


. Max centerline stress before fracture for ingot sections under point load at room temp



Measured section strength and calculated peak stress in a 6 m OD self supported crust





MAIN INSIGHTS FROM MACE AND CCI TESTS

1. In MACE tests featuring early cavity flooding, crust anchoring leaving behind a suspended bridge crust occurred in all tests.
   - Exacerbated by the fact that tests were flooded early when pool swell due to gas sparging was the highest.
   - Evidence of crust 'breach' observed in one test (M3B, largest @ 1.2 x 1.2 m).
     - *These observations seem to be consistent with 1F1 findings of suspended crust material and occurrence of crust shelves attached to structure.*
     - *Based on crust strength measurements, likely limited to doorway opening and drywell areas due to the tighter dimensions in these locations*.
2. For dry cavity tests with extensive ablation, high melt void fractions (>50%) periodically observed leading to deposition of crust material at high elevations in the test section. (Note: also occurred in ACE/MCCI Tests L1 and L5).
     - *Might partially explain elevated debris heights in 1F1; i.e., the debris did actually spread, but this is masked by elevated crusts formed by foaming and solidification behavior, as in the MACE/CCI tests.*
     - *Researchers attributed this high void fraction behavior to melt 'foaming,' and published models for this process[5].*

5. B. Tourniaire , E. Dufour, and B. Spindler, "Foam Formation in Oxidic Pool with Application to MCCI Real Material Experiments," Nuclear Engineering and Design, Vol. 239, pp. 1971-1978 (2009).

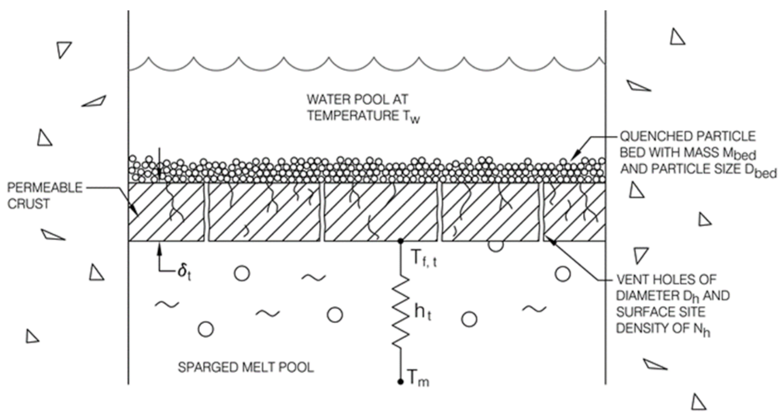
MAIN INSIGHTS FROM MACE AND CCI TESTS

3. The dry cavity tests also showed evidence of ablation above the collapsed melt height, leaving calcined powder buildup on top of the crust material. The vertical extent of this ablation was limited by bridge crust material attached to structure above the melt. The bridge crust apparently acted as an insulator preventing ablation above the crust.
   - *Consistent with observations of pedestal wall ablation below crust material attached to the pedestal walls in 1F1*.
4. The above mentioned ablation behavior also led to buildup of calcined concrete layer over the solidified debris.
   - *Could partially explain the occurrence of white powder layers covering material in various locations in 1F1.*
   - *The fact that the powder was not incorporated into the melt, but rather accumulated on top of the upper crust, indicates that this material was probably formed by radiation heat transfer from the melt as opposed to direct contact with the core debris.*

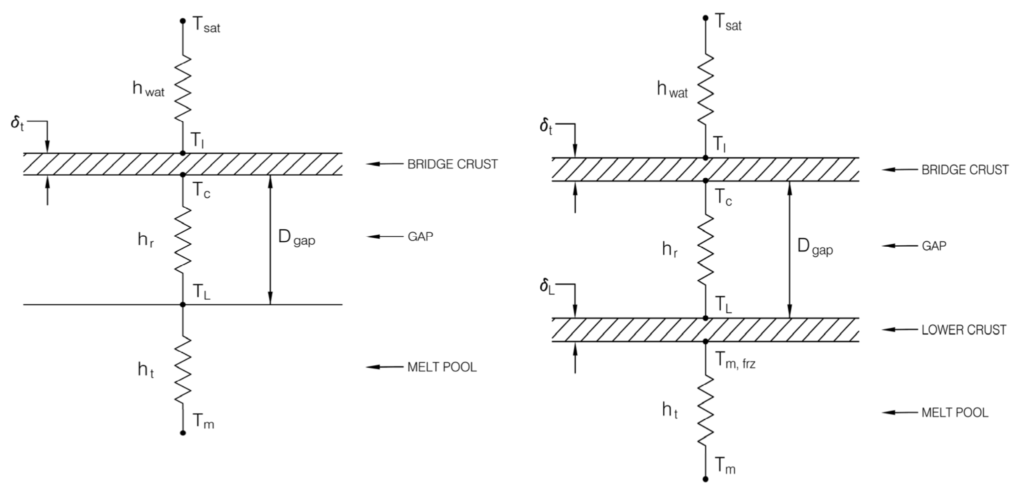
CORQUENCH SCOPING CALCULATIONS OF CRUST ANCHORING BEHAVIOR IN 1F1

- A simple crust anchoring model was integrated into CORQUENCH in the mid 90's and validated against MACE test results.
  - Motivation: need for an analysis tool to better understand crust anchoring behavior as observed in MACE tests.
- Models still present and executable in current version of CORQUENCH, but are rarely used except for code validation efforts.
- Full documentation in reference 6 if you are interested.

Floating crust boundary condition



Anchored crust boundary conditions



6. M. T. Farmer, "The CORQUENCH Code for Modeling of Ex-Vessel Corium Coolability under Top Flooding Conditions: Code Manual-Version 4.1-beta," Argonne National Laboratory, ANL-18/22, August 2018.

SCOPING CALCULATIONS CONTD.

Basic modeling assumptions:

1. The crust will continue to ‘float’ over melt as long as it’s mechanical strength is < than that which can support the combined loads of the crust and particle bed weights, as well as the weight of overlying water layer (as applicable).
2. If the crust grows to a thickness where it can support those loads, then it is assumed to anchor at it’s current position.
3. Thereafter, whether or not the melt remains in contact with the crust depends on the fixed crust elevation vs. the time-dependent voided melt height.
   – If the melt swells to maintain or re-contact the anchored crust, then normal cooling mechanisms can proceed.
   – If the voided height is < than the bottom of the fixed crust, then a radiation heat transfer resistance is introduced between the melt and crust.
4. As time progresses, the crust strength is continuously checked against the applied loads, and if the loads exceed the strength, the crust is assumed to ‘fail’ and is placed back on top the melt as a ‘floating’ crust.

SCOPING CALCULATIONS CONTD.

- Explicitly, the anchoring criterion is as follows:

$$\underbrace{g\left(m_{bed} + \rho_{t,c} A_b \delta_{t,\min} + m_{wat}\right)}_{applied\ \ load\ \ on\ \ crust} \leq \underbrace{C_{geom}\ \hat{\sigma}_{t,f}\ \delta^2_{t,\min}}_{crust\ \ mechanical\ \ strength}$$

- Once anchored, this equation is also used to determine if the crust subsequently fails; the crust is then placed back atop the melt pool.
  - Mechanisms that can lead to failure after anchoring are: i) increased crust size (by lateral ablation), and/or change of loading on top of crust (increase area via radial ablation; reduced crust thickness via re-melting while suspended; water addition…)
- Whether or not a gap forms is determined simply by tracking voided melt height relative to the anchored crust position bottom surface position; i.e.,

$$D_{gap} = \left\langle EL_{anchor} - EL_{m,v}(t) + \delta_{t,anchor} - \delta_t(t),\ 0\right\rangle$$

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SIMULATED CASES

- Two cases were executed: one to mockup up behavior in the pedestal doorway region, and a second to mock up behavior in the larger drywell annulus region. Geometry for two cases as follows:

1. *Pedestal doorway opening*: 0.851 m wide door x 1.28 m pedestal wall thickness; ablation into pedestal walls adjacent to the doorway; adiabatic on other two sides.
2. *Drywell Annulus*: 2.55 m radial slice between exterior of pedestal wall and drywell liner; width of slice assumed to be 2 m. Ablation into pedestal wall and PVC liner modeled; other two sides treated as adiabatic.

- 30 cm uniform melt depth assumed after vessel failure in pedestal/drywell regions.
  - For 140 MT pour mass, equivalent to filling the pedestal sumps with corium and spreading material out the door to cover 112 degrees of the drywell area.
  - MELCOR melt composition and initial temperature the same as in Ref. 7.
- Concrete type assumed to be CORCON Basalt.
- Based on crust strength measurements made as part of OECD/MCCI program, a tensile strength of 3 MPa is assumed (see pg. 12).
- Brockmann correlation used to predict melt void fraction; melt foaming ***is not*** modeled.
- Calculation ran out to 14 days, which includes 11.25 days of dry cavity ablation, followed by cavity flooding to a uniform depth of 2 m (current condition).

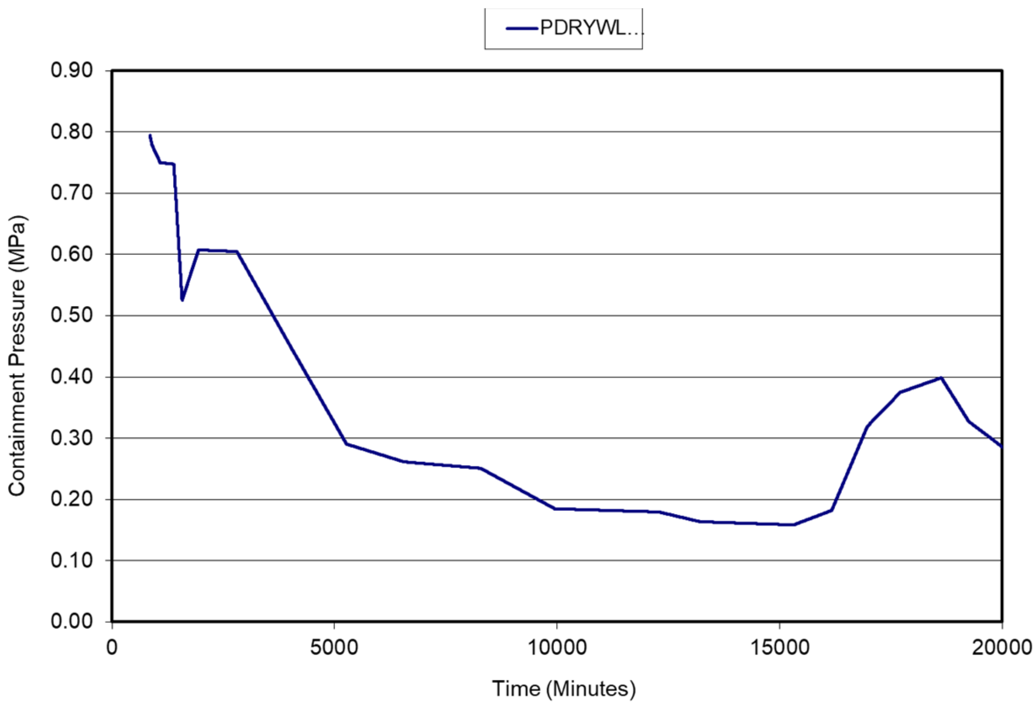
7. K. R. Robb, M. W. Francis, and M. T. Farmer, “Ex-vessel Core Melt Modeling Comparison Between MELTSPREAD-CORQUENCH and MELCOR 2.1,” Oak Ridge National Laboratory, ORNL/TM-2014/1, March 2014

ASSUMED CONTAINMENT PRESSURE

Important as this impacts superficial gas velocity from concrete decomposition and melt void fraction

- Estimated by using TEPCO data where it exists and interpolating using MELCOR results[8] in regions where data does not exist….

Interpolated Data

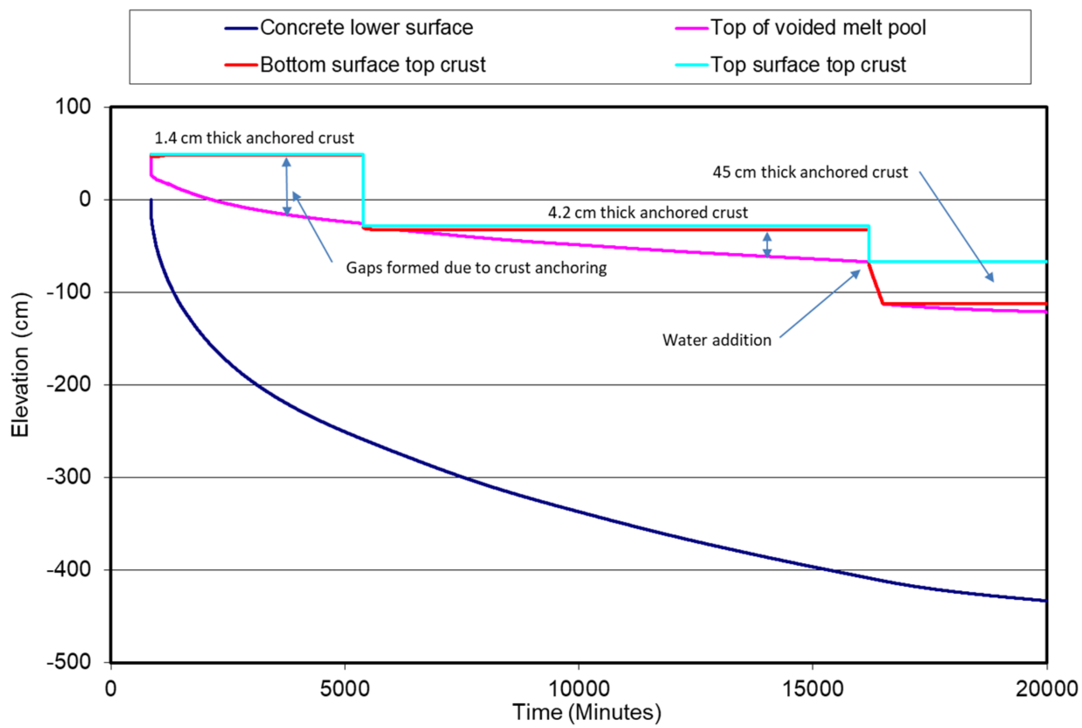


8. N. Andrews, R. Gauntt, et al., “BSAF Phase 2 Sandia National Lab Activities,” presentation SAND2017-0178PE.

DOORWAY RESULTS

Surface elevation of crust and voided melt height

- Results indicate possibility of three crust anchoring and two crust failure events in the region spanning the pedestal doorway over the calculated time interval.
- Crusts are anchored over a major fraction of the time.
- Water addition caused 2nd failure.
- Although not explicitly modeled, failure events would leave crust ledges on concrete walls (1st 1.4 cm thick, the 2nd 4.2 cm thick).
- Large time intervals during dry phase in which gaps formed would allow lateral ablation by radiation heat transfer to exposed concrete.

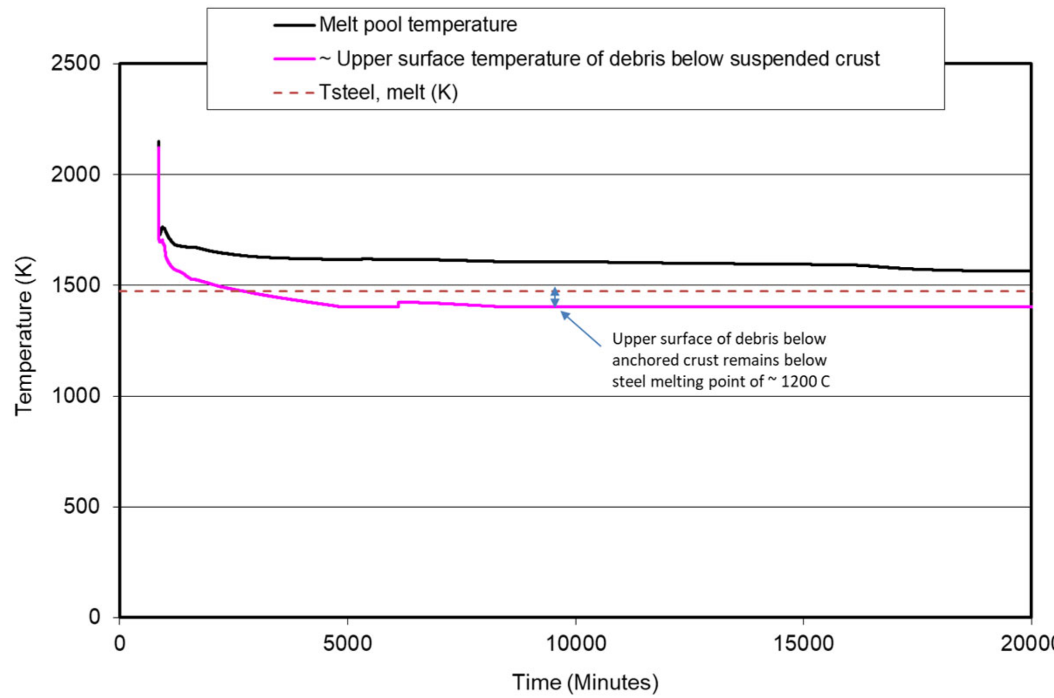


DOORWAY RESULTS

Melt and crust temperature results

- During extended periods of crust anchoring before flooding, the upper surface temperature of the debris below the bridge crust remains below steel melting temperature (assumed to be 1200 C = 1473 K here).

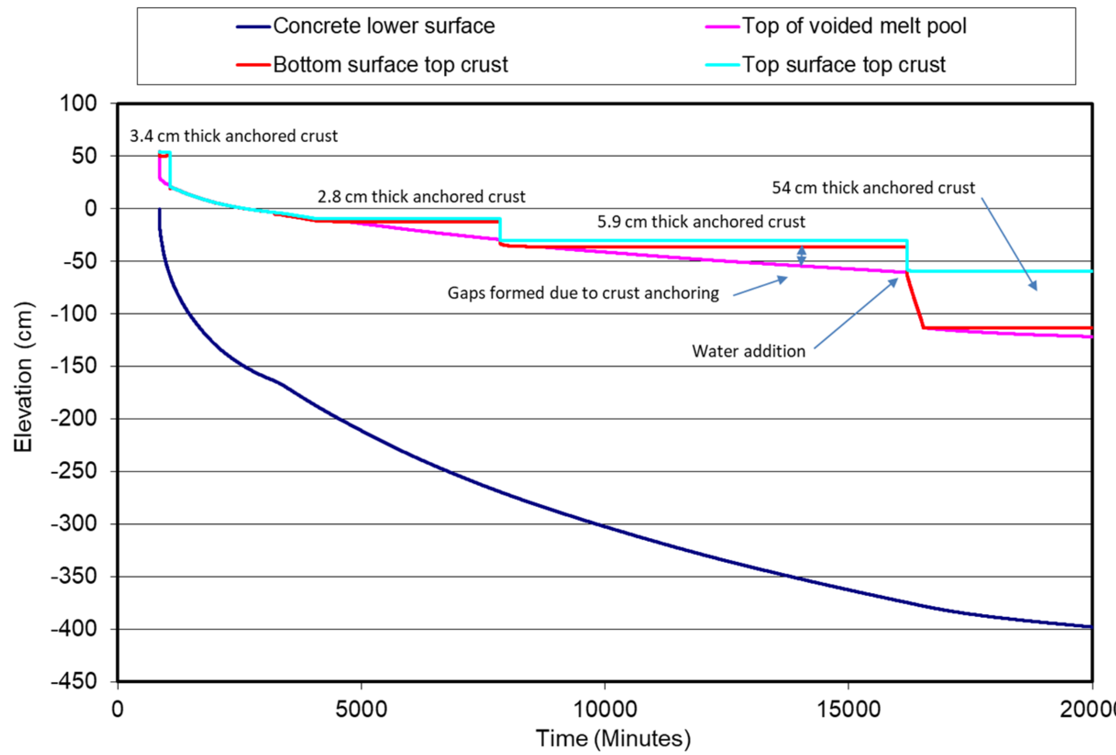
- Thus, the rebar exposed by radiation-driven concrete ablation in the doorway sidewalls would not have been ablated according to this modeling result.



DRYWELL ANNULUS RESULTS

Surface elevation of crust and voided melt height

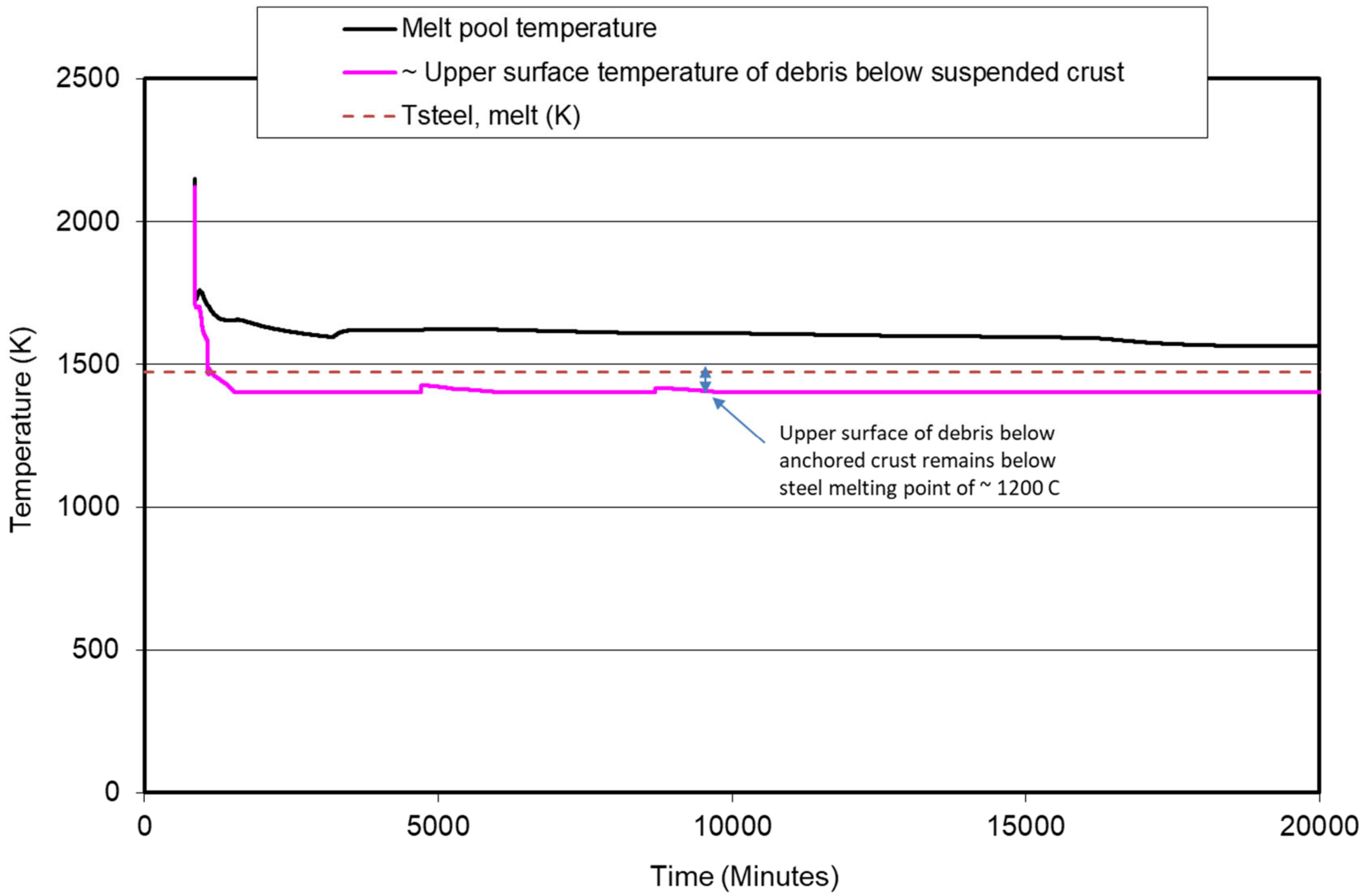
- Overall, trends and observations are similar to doorway results. However, a few differences:
- Four anchoring events as opposed to three for the doorway case.
- Early on, there was an extended period (~ 2 days) in which the upper surface was initially crust free, and then was covered with a crust that floated.



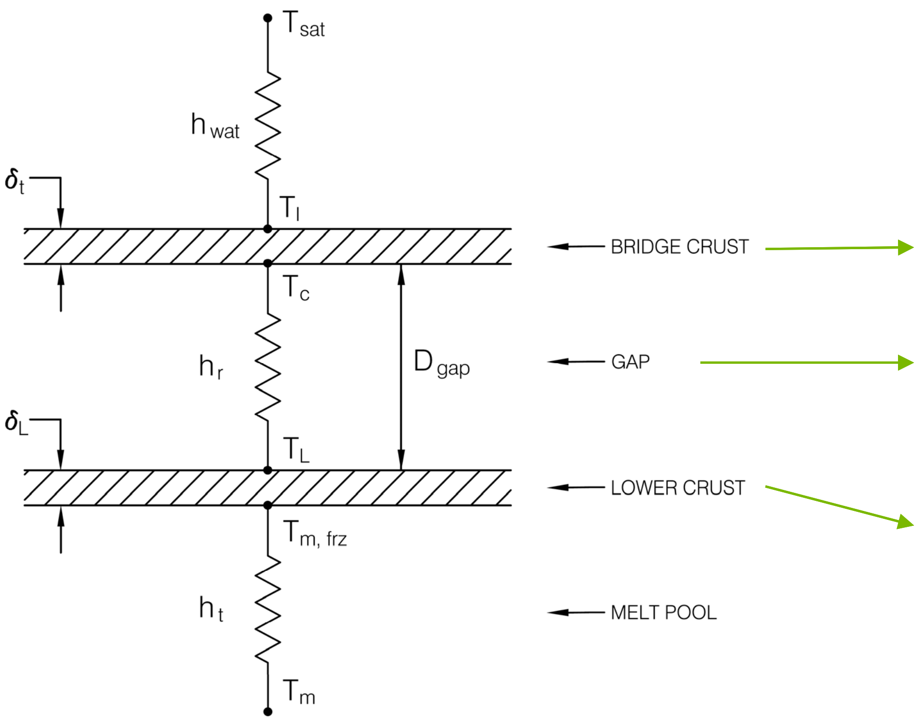
DRYWELL ANNULUS RESULTS

Melt and crust temperature results

- General trends and conclusions similar to the doorway case.



PREDICTED END STATE CONDITIONS AT 11 DAYS, JUST PRIOR TO CAVITY FLOODING



Parameter	Drywell Annulus Case	Doorway Case
Suspended Bridge Crust Thickness (cm)	5.9	4.3
Gap Thickness Between Crusts (cm)	23.0	33.6
Bottom Crust Thickness over Melt (cm)	2.9	3.8
Radiation View Factor to Sidewalls	0.10	0.20

MAIN INSIGHTS FROM CQ SIMULATIONS

1. Using crust anchoring models as currently deployed in CQ and the estimated crust tensile strength of ~ 3 MPa from previous measurements, the results indicates that crust anchoring would likely occur over the first 11 days in which the cavity remained dry.
   – *Multiple crust failure events are predicted, which would leave crust ledges in the range of 1-5 cm attached to sidewall materials*.
2. Crust ledges consistent with some of the observations reported on the basis of video data from 1F1.
3. Predictions of the occurrence of anchored crusts as well as the temperature evolutions in the gap between the anchored crust and melt were consistent with the idea that concrete around the rebar would have been ablated, but not the rebar itself.
   – *Also consistent with some of the reported observations.*

5. B. Tourniaire , E. Dufour, and B. Spindler, “Foam Formation in Oxidic Pool with Application to MCCI Real Material Experiments,” Nuclear Engineering and Design, Vol. 239, pp. 1971-1978 (2009).

CLOSING COMMENTS-CQ ANALYSES

- Note that the CQ crust anchoring calculations presented here are scoping in nature; this is first time these models have been used for a long-duration real plant accident scenario including extended dry and wet phases.
  - Note that there were a few instances (in time) for both cases where the code was not able to meet specified convergence criteria, and I did not have time to chase down the reasons why or debug.
- This work also revealed some modeling shortcomings.
  - Crust strength calculation based on a simple plate (i.e., MCCI surface area) model. For places like the annulus, a beam strength model would be more appropriate because the behavior is essentially 1-D in the radial direction.
  - The model does not leave crust ledges when the crust fails, as observed in 1F1.
  - The code also pessimistically assumes that once the crust anchors, water is not able to flood below the crust to continue cooling. In essence, ‘crust breach’ is not modeled.

CLOSING COMMENT-GENERAL

- Much work was done in the MACE and OECD/MCCI programs addressing the issue of crust anchoring and whether or not this type of behavior would be applicable to plant sequences.
  - Concerns of whether anchored crust(s) would inhibit debris coolability.
- The results (both analytical and experimental) indicated that for tight cavity regions (a few meters) this may occur, but it was argued that even if the crusts did anchor, they would not be completely stable. In particular, ‘crust breach’ would occur, allowing water to flood below the anchored crust and thereby maintain debris cooling.
- The results from 1F1 seem to support this vision of crust anchoring and breach behavior, thereby allowing the debris to cool. This is a beneficial confirmatory observation from the viewpoint of reactor safety!!

ACKNOWLEDGEMENTS

- Thanks to all organizations within Japan for ongoing interactions on this project.
  - Findings from Daiichi have provided many insights into severe accident progression and management, and considerably reduced knowledge gaps in this area.
- Thanks to DOE and Program Manager Mr. Damian Peko for continued support; US national lab involvement would not be possible without it.
- Thanks to Dr. Rempe for leading these efforts and providing the information in a format that we can access, analyze, and assess.

BACKUP SLIDES

REVISITING THE POTENTIAL FOR *IN-SITU* CORE DEBRIS WATER INGRESSION MEASUREMENT FOR 1F2

- 1F2 examinations have revealed extraordinary information on ex-vessel core debris distribution within the pedestal, including data on water injection characteristics.
- Specifically, video indicates that injected water penetrates the core debris (50-70 cm in depth) and passes through that material during passage to drywell annulus where water level is constant at ~30 cm. This is clear evidence of water ingression.
- ***If conditions allow***, it would be advantageous to obtain video footage while injection flowrate is increased in a step-wise manner until water begins to accumulate on the surface and spill over directly into the annulus through the pedestal doorway.
- This information could be used to estimate debris permeability and dryout limit for an actual prototypic core debris accumulation, which is valuable for safety evaluations.
- A white paper was prepared describing this procedure.

1F2 in-pedestal debris distribution

OVERVIEW OF METHOD

- Water injection flowrate would be gradually increased until it pools above the debris and begins to flow out the doorway, this would be flooding limit, $\dot{Q}_{limit}$.
  – Camera footage would be needed to determine when this point is reached.

- With flooding limit known, debris permeability can be estimated using the equation (based on Darcy's law):

$$\kappa = \frac{\mu L \dot{Q}_{limit}}{\rho g \Delta H A}$$

- The debris dryout limit can then be estimated from:

$$q'' = \frac{\kappa \, \rho_g h_{fg} \left(\rho_f - \rho_g\right) g}{2\mu_g}$$