Moderator Evaluation of Non-Water Hydrogenous Materials

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Questions to be Answered

- Why did we revisit the evaluation of moderating materials?
- How did we reevaluate possible moderating materials?
- What did we learn when we reevaluated those materials?
- How can we use these results in future evaluation of potential moderators?

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Background

- A common criticality control problem is the control of laboratory scale quantities of fuel
- Typically, in order to ensure criticality safety for these handling operations, a mass limit on the quantity of fuel is used
- There may also be limits on the quantity of reflector materials and moderators better than water
  - Historically, hydrogenous moderators have been compared to water based on hydrogen number density, consistent with packaging rules and past practice
  - Non-hydrogenous materials have been evaluated based on moderating ratio
  - Moderating materials less effective than water (i.e. lower hydrogen number density or moderating ratio) have no limit when water moderation is assumed

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Background

- In 2017, to improve our understanding of moderation effects, we analyzed unlimited quantities of potential moderator materials
- This evaluation found that some of the evaluated compounds with lower hydrogen number density than water were more reactive than water for a given quantity of fuel and reflector material
- This effect was found to be due to changes to the fast leakage from the system, not changes to the amount of moderation, which is primarily driven by hydrogen

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Background

- Previous evaluations have also identified the importance of elements other than hydrogen in low-mass systems
  - Rao & Srinivasan (1980), as an initial step to evaluations of BeH_2 as a moderator, evaluated the reactivity worth of “auxiliary moderator elements” such as carbon and oxygen when coupled with hydrogen
  - SAIC-1322-001 Rev. 1 (2004) commented that moderating materials “comprised of hydrogen and a good scattering material, such as carbon, beryllium, or certain metals generally make excellent moderators”, although it did not explicitly quantify the effect of the scattering material
- This study is an attempt to quantify the worth of scattering elements, and to show a possible way to evaluate potential moderating materials

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Model

- The model used for this analysis is a sphere of fissile material, surrounded by reflectors in a spherical shell
- ^{235}U metal and moderator were mixed in the central region as a uniform homogeneous slurry
- A range of fictitious moderating materials were generated
  - Evaluated hydrogen number densities were 90%, 95%, 97.5%, 100%, and 110% of water
  - Each hydrogen number density was evaluated with 17 different pairs of oxygen and carbon number density values, which were chosen to reflect plausible amounts of oxygen and carbon for organic materials with hydrogen number density in that range
- Calculations were run using MC21, a Monte Carlo transport code

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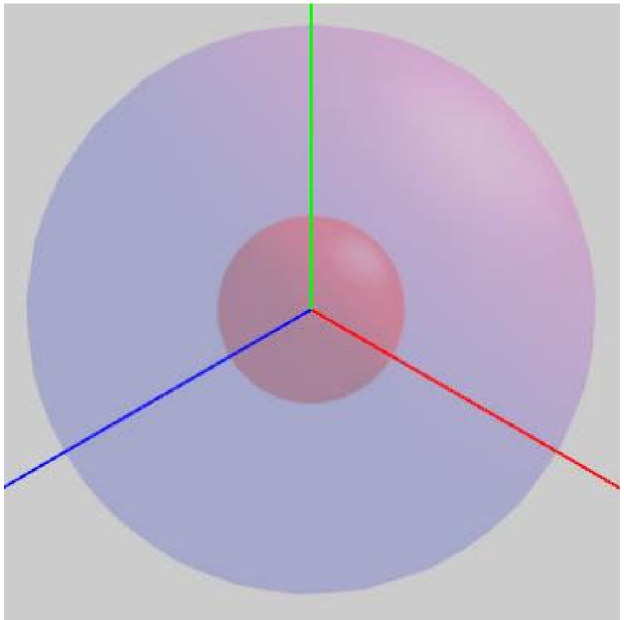
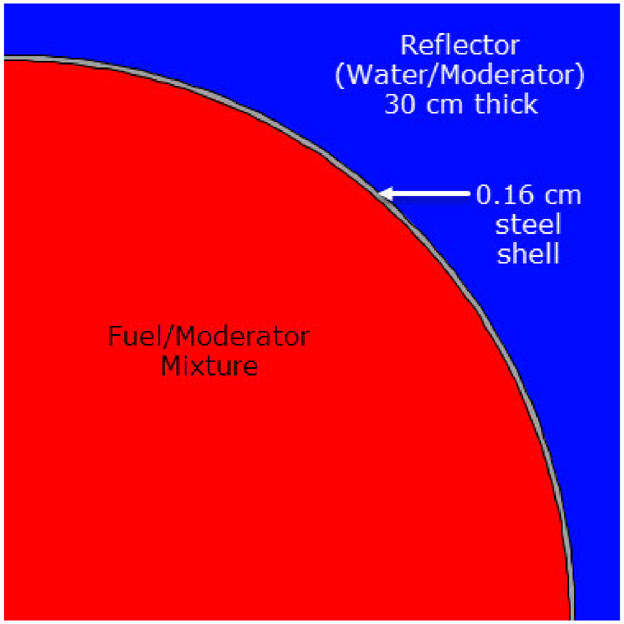
Model

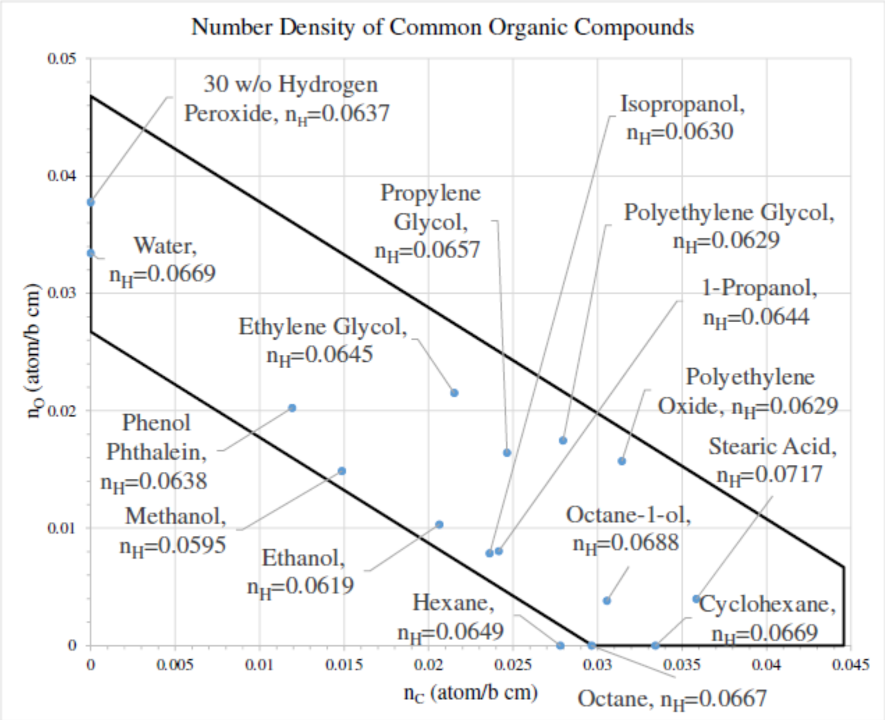
3-D Model



2-D Slice



Model



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Model

- Several reflector conditions (unreflected, water, and moderator reflected) were evaluated
- The radius of the central region was varied to identify optimal moderation
- Then, by modeling different quantities of ^{235}U with the H/U ratio held constant, the minimum critical mass (m_{crit}) can be determined
  - The critical eigenvalue of this model was determined based on a suite of international benchmarks for solutions of enriched uranium
- In addition, another sensitivity determined the maximum multiplication factor (k_{eff}) for the same moderator and a constant 500 g ^{235}U in several reflection conditions

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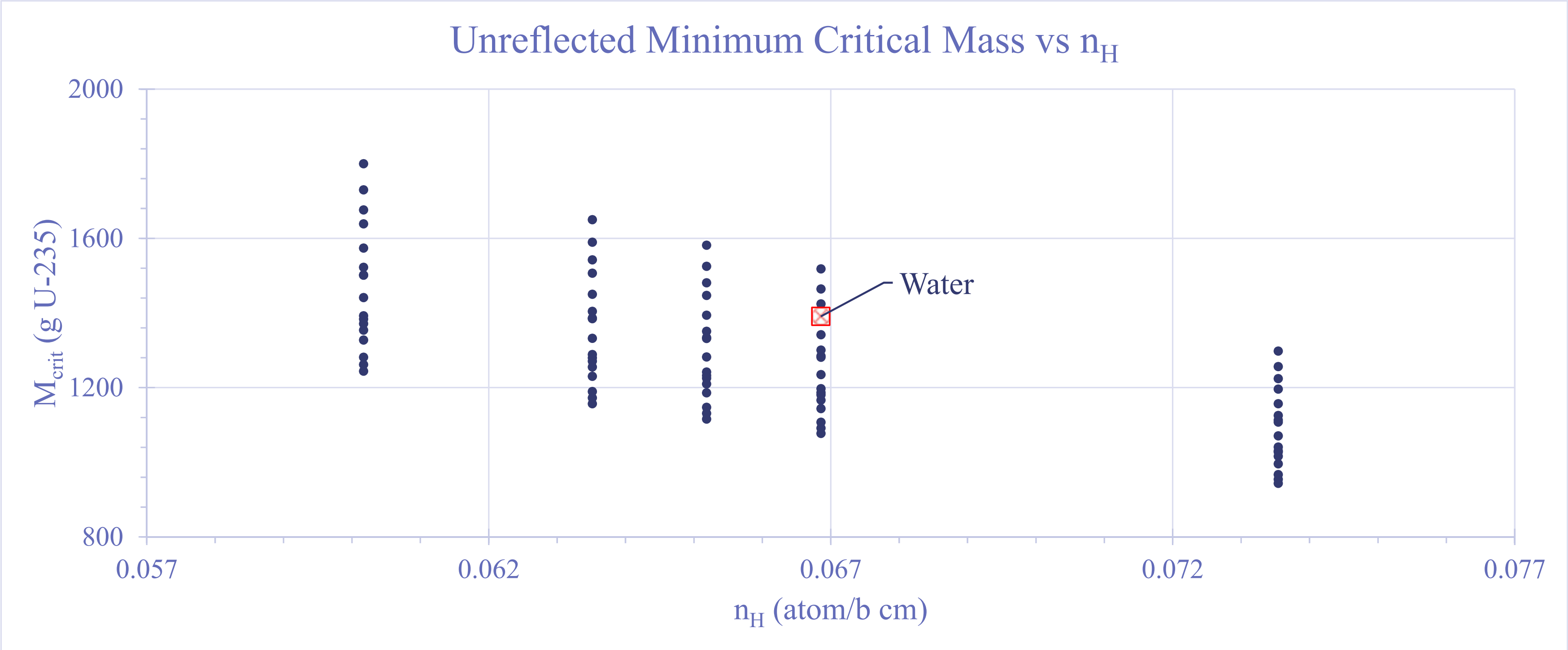
Results



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Results

- When m_{crit} is calculated in this way, there is a clear correlation with hydrogen number density
- However, the effect of carbon and oxygen is also clear from the wide ranges of m_{crit} associated with each value of hydrogen number density
- Similar results can also be seen in the multiplication factor sensitivity; for a given hydrogen number density, there is a wide range of k_{eff} values for different values of carbon and oxygen number density
- Similar patterns of results are seen for all reflector conditions evaluated

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Application

- To quantify the relative effects of hydrogen, carbon and oxygen, a multivariate linear regression against all three elements was used to calculate relative worths
  - This regression yields coefficients for all three element number densities; the oxygen and carbon coefficients can be normalized to the hydrogen coefficient

$$a_C = {}^{c_C}/_{c_H}, a_O = {}^{c_O}/_{c_H}$$

  - Then, coefficients and number densities can be combined into an "effective hydrogen number density", $n_{H,eff}$

$$n_{H,eff} = n_H + a_C n_C + a_O n_O$$

- Similar regressions were completed against both m_{crit} and k_{eff} in the evaluated reflector conditions

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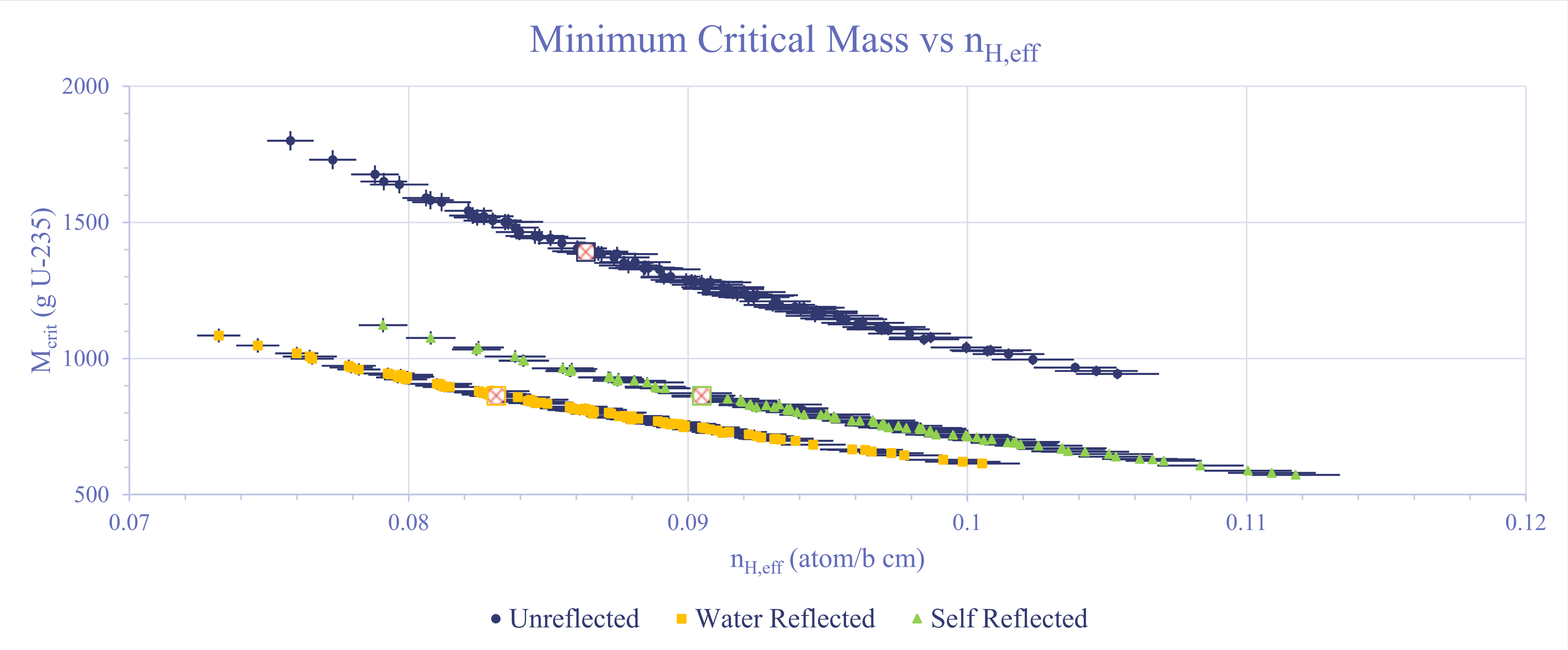
Application



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Application

Calculation Method	m_{crit}		k_{eff}	
Reflector Condition	a_O	a_C	a_O	a_C
Unreflected	0.583	0.627	0.510	0.546
Water Reflected	0.487	0.533	0.442	0.483
Moderator Reflected	0.707	0.751	0.662	0.702
^{233}U w/ BeO Reflector from Rao & Srinivasan (1980)	---	---	0.23	0.26

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Application

- The range of coefficients is related to the quantity and importance of the moderator in the different type of systems
  - Systems with more limiting reflectors, like thick BeO, have lower relative carbon and oxygen worth
  - Reflection decreases fast leakage, so the leakage change from carbon and oxygen is less important to system reactivity
  - Reflected systems are also smaller, so they have less moderator
- Since oxygen and carbon coefficients are sensitive to the reflector, recalculation of those coefficients is strongly recommended when reflector conditions change

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Application

- Neutron balances confirm that changing moderator mostly changes leakage.
- Comparing cases that are similar except for the moderator, multivariate linear regression confirms that the primary change with n_C and n_O is leakage

Calculation Method	k_∞		Leakage Probability	
Reflection Condition	a_O	a_C	a_O	a_C
Unreflected	0.032	0.009	0.340	0.357
Water Reflected	0.035	0.013	0.294	0.313
Moderator Reflected	0.034	0.011	0.448	0.467

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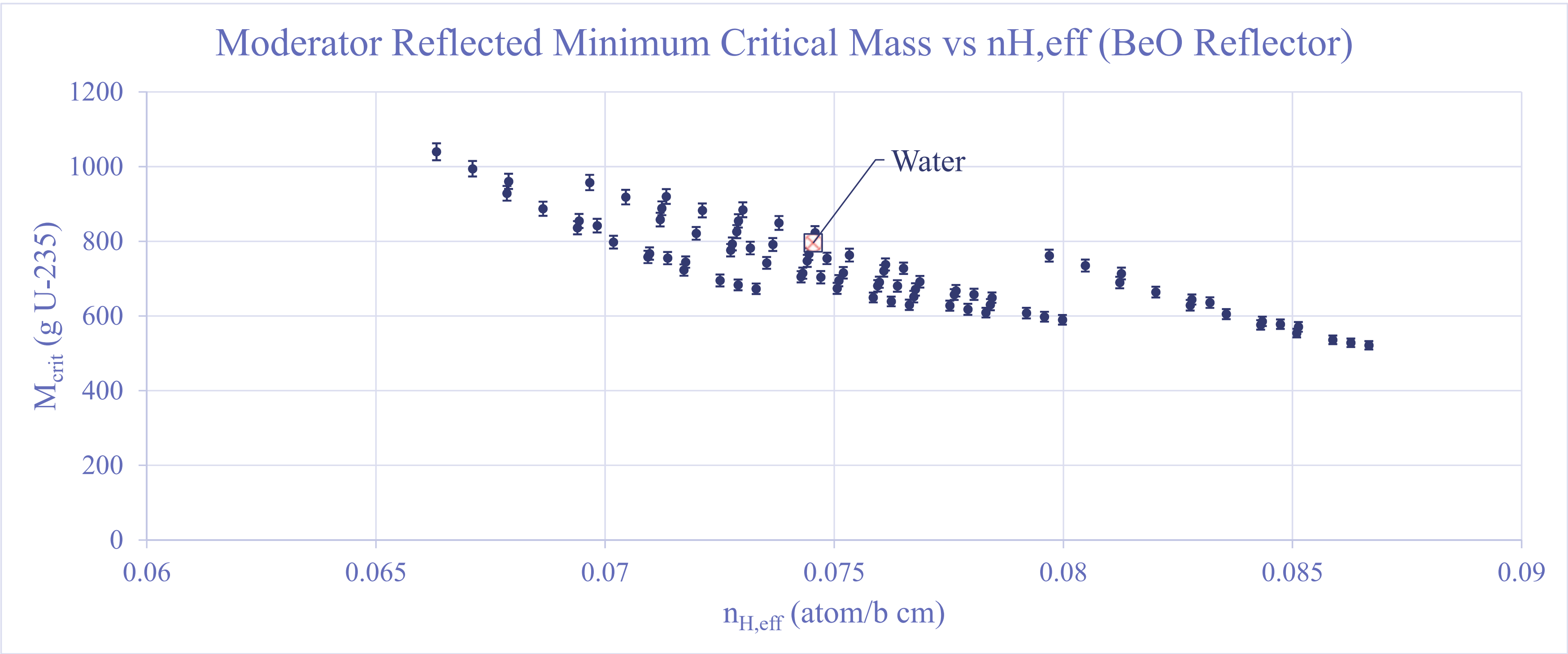
Limitations



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Limitations

- This study only considered hydrogen, carbon, and oxygen, with ^{235}U
- Based on preliminary studies, similar effects of varying magnitude are expected for aluminum, beryllium, bismuth, fluorine, lead, magnesium, phosphorus, silicon, and zirconium
  - These preliminary studies did not displace hydrogen
- Coefficients are also likely different for different fissile species, although how different is not known

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Main Takeaways

- This study presents a survey of the effects of moderator composition on the minimum critical mass of highly enriched uranium slurries
- When only using hydrogen number density to evaluate moderator effectiveness, additional conservatism or margin may be needed to account for non-hydrogen contributions
- With correction for other moderator components, moderator evaluation is feasible
  - The appropriate correction factors should be calculated with similar systems to the limiting condition

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Any Questions?

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Backup Slides

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n_H = 90% H2O

n_C	n_O	Unreflected m_{crit}	Unreflected k_{eff}	Water Reflected m_{crit}	Water Reflected k_{eff}	Moderator Reflected m_{crit}	Moderator Reflected k_{eff}
0	0.0267	1800 ± 35	0.6778	1085 ± 25	0.8231	1123 ± 26	0.8135
0	0.0334	1639 ± 32	0.6993	1008 ± 25	0.8385	1008 ± 23	0.8380
0	0.0401	1502 ± 25	0.7199	940 ± 22	0.8534	912 ± 20	0.8605
0	0.0468	1384 ± 27	0.7393	880 ± 19	0.8678	831 ± 20	0.8819
0.0149	0.0134	1730 ± 35	0.6864	1048 ± 26	0.8302	1076 ± 24	0.8229
0.0149	0.0201	1574 ± 34	0.7084	973 ± 22	0.8458	964 ± 21	0.8476
0.0149	0.0267	1442 ± 28	0.7291	907 ± 18	0.8609	873 ± 19	0.8704
0.0149	0.0334	1328 ± 28	0.7485	849 ± 21	0.8755	795 ± 18	0.8918
0.0297	0	1676 ± 33	0.6933	1019 ± 23	0.8358	1041 ± 24	0.8298
0.0297	0.0067	1523 ± 32	0.7158	945 ± 21	0.8521	931 ± 20	0.8553
0.0297	0.0134	1393 ± 28	0.7368	880 ± 19	0.8675	841 ± 18	0.8785
0.0297	0.0201	1282 ± 26	0.7568	823 ± 19	0.8824	765 ± 16	0.9004
0.0371	0	1501 ± 30	0.7189	933 ± 22	0.8547	918 ± 20	0.8582
0.0371	0.0067	1372 ± 29	0.7405	868 ± 19	0.8706	828 ± 18	0.8821
0.0371	0.0134	1262 ± 25	0.7606	812 ± 17	0.8855	753 ± 17	0.9042
0.0446	0	1354 ± 27	0.7435	858 ± 18	0.8731	817 ± 17	0.8852
0.0446	0.0067	1244 ± 25	0.7639	801 ± 18	0.8884	742 ± 16	0.9075

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$n\_H = 95\% \ H2O$

n_C	n_O	Unreflected m_{crit}	Unreflected k_{eff}	Water Reflected m_{crit}	Water Reflected k_{eff}	Moderator Reflected m_{crit}	Moderator Reflected k_{eff}
0	0.0267	1650 ± 32	0.7000	999 ± 21	0.8419	1033 ± 22	0.8329
0	0.0334	1507 ± 30	0.7210	931 ± 23	0.8569	931 ± 22	0.8566
0	0.0401	1385 ± 28	0.7408	870 ± 19	0.8716	845 ± 21	0.8786
0	0.0468	1280 ± 25	0.7599	816 ± 18	0.8854	772 ± 18	0.8990
0.0149	0.0134	1590 ± 31	0.7081	967 ± 22	0.8486	992 ± 20	0.8417
0.0149	0.0201	1450 ± 29	0.7295	900 ± 19	0.8638	893 ± 20	0.8657
0.0149	0.0267	1332 ± 27	0.7498	841 ± 19	0.8786	810 ± 19	0.8879
0.0149	0.0334	1230 ± 26	0.7689	789 ± 17	0.8929	740 ± 17	0.9088
0.0297	0	1543 ± 34	0.7148	942 ± 19	0.8541	961 ± 23	0.8485
0.0297	0.0067	1405 ± 29	0.7367	876 ± 19	0.8698	864 ± 20	0.8731
0.0297	0.0134	1289 ± 25	0.7573	817 ± 17	0.8850	782 ± 18	0.8956
0.0297	0.0201	1190 ± 24	0.7769	766 ± 18	0.8995	714 ± 15	0.9169
0.0371	0	1387 ± 27	0.7400	865 ± 20	0.8725	852 ± 20	0.8760
0.0371	0.0067	1271 ± 24	0.7607	807 ± 18	0.8877	771 ± 17	0.8989
0.0371	0.0134	1173 ± 23	0.7805	756 ± 17	0.9027	703 ± 17	0.9204
0.0446	0	1255 ± 26	0.7636	798 ± 20	0.8903	761 ± 16	0.9019
0.0446	0.0067	1157 ± 22	0.7837	747 ± 17	0.9053	693 ± 14	0.9234

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n_H = 97.5% H2O

n_C	n_O	Unreflected m_{crit}	Unreflected k_{eff}	Water Reflected m_{crit}	Water Reflected k_{eff}	Moderator Reflected m_{crit}	Moderator Reflected k_{eff}
0	0.0267	1582 ± 34	0.7108	960 ± 22	0.8509	992 ± 22	0.8424
0	0.0334	1447 ± 30	0.7314	895 ± 19	0.8657	897 ± 21	0.8657
0	0.0401	1332 ± 27	0.7511	838 ± 19	0.8802	814 ± 18	0.8872
0	0.0468	1233 ± 26	0.7699	787 ± 16	0.8940	745 ± 17	0.9075
0.0149	0.0134	1525 ± 31	0.7187	931 ± 21	0.8575	954 ± 21	0.8509
0.0149	0.0201	1394 ± 29	0.7397	867 ± 20	0.8728	860 ± 20	0.8744
0.0149	0.0267	1282 ± 24	0.7599	811 ± 20	0.8872	781 ± 17	0.8965
0.0149	0.0334	1186 ± 23	0.7788	762 ± 18	0.9012	715 ± 14	0.9168
0.0297	0	1481 ± 31	0.7253	907 ± 21	0.8629	925 ± 22	0.8575
0.0297	0.0067	1351 ± 26	0.7469	844 ± 19	0.8785	832 ± 18	0.8816
0.0297	0.0134	1242 ± 24	0.7674	788 ± 16	0.8934	755 ± 17	0.9041
0.0297	0.0201	1147 ± 23	0.7865	740 ± 16	0.9077	690 ± 15	0.9249
0.0371	0	1334 ± 26	0.7499	834 ± 20	0.8809	821 ± 18	0.8849
0.0371	0.0067	1226 ± 26	0.7706	779 ± 18	0.8960	745 ± 15	0.9072
0.0371	0.0134	1131 ± 23	0.7898	730 ± 16	0.9108	680 ± 15	0.9283
0.0446	0	1210 ± 25	0.7733	770 ± 17	0.8985	735 ± 18	0.9101
0.0446	0.0067	1116 ± 22	0.7930	722 ± 16	0.9133	670 ± 14	0.9314

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n_H = 100% H_2O

n_C	n_O	Unreflected m_{crit}	Unreflected k_{eff}	Water Reflected m_{crit}	Water Reflected k_{eff}	Moderator Reflected m_{crit}	Moderator Reflected k_{eff}
0	0.0267	1518 ± 30	0.7212	924 ± 19	0.8598	954 ± 22	0.8514
0	0.0334	1391 ± 29	0.7418	863 ± 19	0.8743	863 ± 19	0.8743
0	0.0401	1282 ± 26	0.7612	809 ± 18	0.8885	786 ± 18	0.8955
0	0.0468	1187 ± 23	0.7796	760 ± 18	0.9023	719 ± 16	0.9158
0.0149	0.0134	1465 ± 30	0.7291	896 ± 20	0.8660	918 ± 20	0.8600
0.0149	0.0201	1342 ± 29	0.7498	836 ± 18	0.8811	829 ± 18	0.8831
0.0149	0.0267	1235 ± 24	0.7697	783 ± 18	0.8956	754 ± 16	0.9047
0.0149	0.0334	1144 ± 22	0.7881	736 ± 15	0.9094	691 ± 15	0.9249
0.0297	0	1424 ± 29	0.7357	873 ± 19	0.8713	891 ± 21	0.8666
0.0297	0.0067	1301 ± 26	0.7570	814 ± 19	0.8869	803 ± 18	0.8901
0.0297	0.0134	1197 ± 24	0.7768	761 ± 17	0.9017	729 ± 17	0.9123
0.0297	0.0201	1107 ± 22	0.7959	715 ± 15	0.9156	667 ± 14	0.9326
0.0371	0	1285 ± 25	0.7599	804 ± 18	0.8894	793 ± 19	0.8933
0.0371	0.0067	1181 ± 22	0.7802	752 ± 16	0.9045	719 ± 16	0.9153
0.0371	0.0134	1092 ± 23	0.7993	706 ± 14	0.9185	658 ± 15	0.9363
0.0446	0	1167 ± 23	0.7830	744 ± 17	0.9066	710 ± 15	0.9181
0.0446	0.0067	1077 ± 20	0.8024	698 ± 16	0.9214	649 ± 14	0.9391

n_H = 110% H2O

n_C	n_O	Unreflected m_{crit}	Unreflected k_{eff}	Water Reflected m_{crit}	Water Reflected k_{eff}	Moderator Reflected m_{crit}	Moderator Reflected k_{eff}
0	0.0267	1298 ± 26	0.7613	797 ± 17	0.8931	821 ± 19	0.8865
0	0.0334	1196 ± 24	0.7806	748 ± 16	0.9071	747 ± 16	0.9078
0	0.0401	1108 ± 22	0.7991	704 ± 16	0.9206	684 ± 15	0.9279
0	0.0468	1030 ± 20	0.8165	665 ± 14	0.9337	630 ± 14	0.9468
0.0149	0.0134	1256 ± 26	0.7685	777 ± 17	0.8991	794 ± 18	0.8941
0.0149	0.0201	1157 ± 24	0.7883	727 ± 16	0.9133	721 ± 16	0.9159
0.0149	0.0267	1071 ± 21	0.8070	684 ± 15	0.9270	659 ± 15	0.9362
0.0149	0.0334	996 ± 20	0.8247	645 ± 14	0.9404	607 ± 13	0.9553
0.0297	0	1224 ± 25	0.7745	758 ± 18	0.9041	772 ± 17	0.9001
0.0297	0.0067	1126 ± 22	0.7947	710 ± 16	0.9187	700 ± 16	0.9222
0.0297	0.0134	1041 ± 21	0.8136	666 ± 15	0.9328	639 ± 14	0.9430
0.0297	0.0201	967 ± 18	0.8318	628 ± 14	0.9462	588 ± 13	0.9625
0.0371	0	1113 ± 22	0.7975	702 ± 16	0.9213	692 ± 15	0.9251
0.0371	0.0067	1028 ± 20	0.8166	659 ± 14	0.9355	631 ± 14	0.9460
0.0371	0.0134	954 ± 19	0.8348	621 ± 14	0.9489	580 ± 13	0.9655
0.0446	0	1016 ± 21	0.8192	653 ± 14	0.9376	624 ± 14	0.9485
0.0446	0.0067	944 ± 20	0.8378	614 ± 14	0.9515	573 ± 12	0.9682

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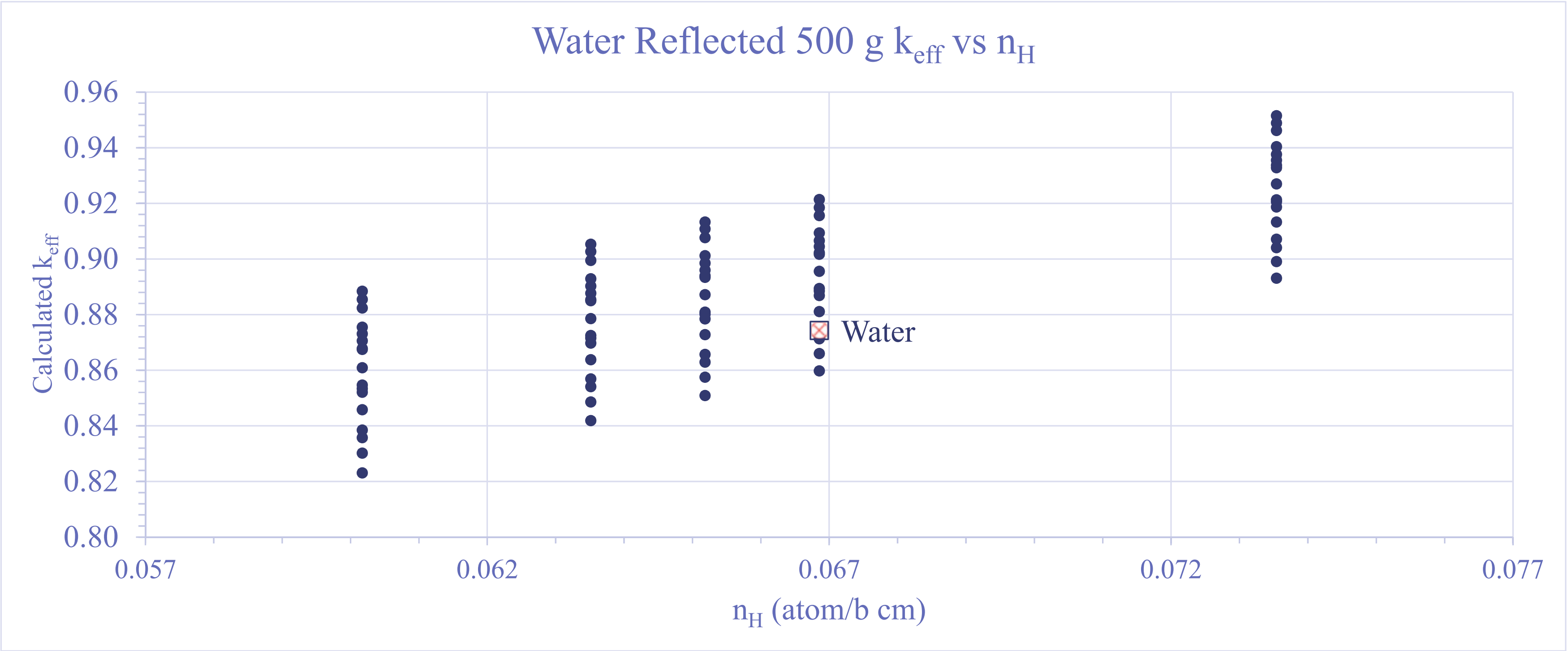
Results



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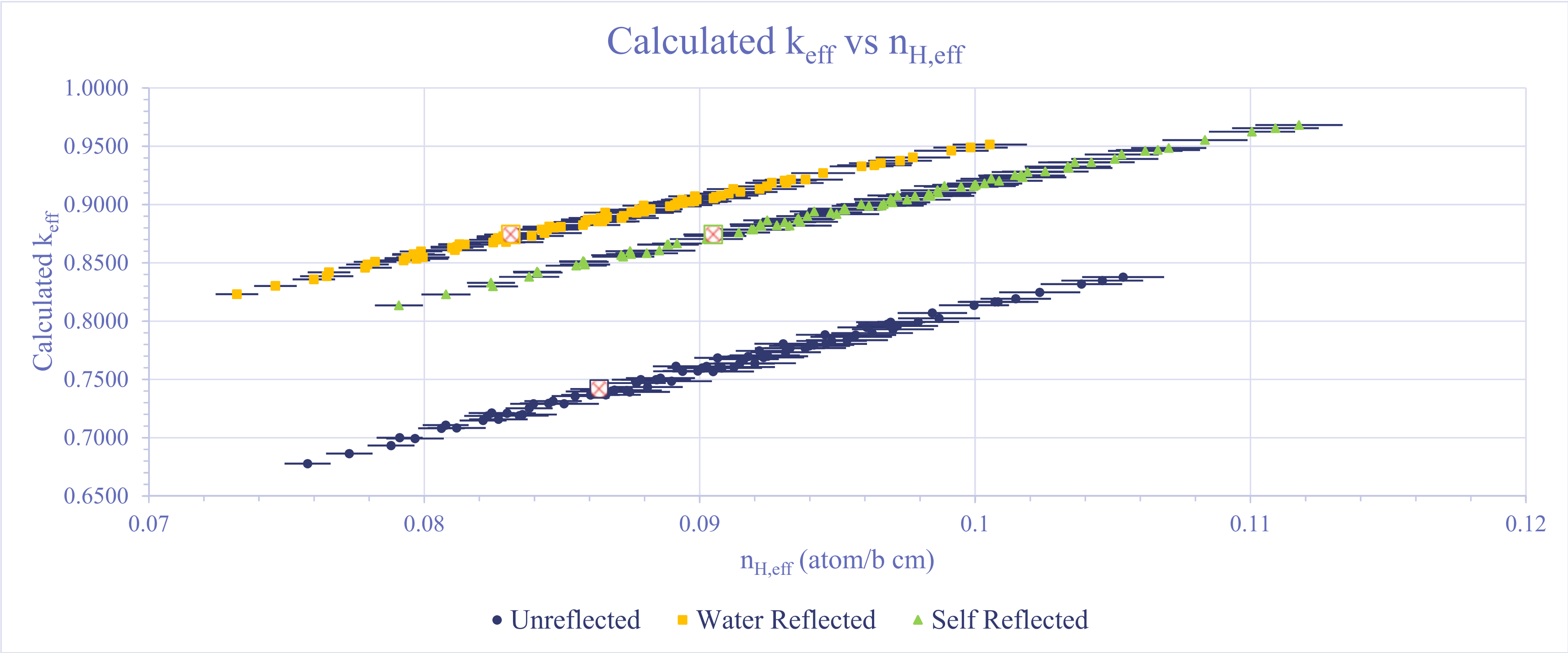
Application



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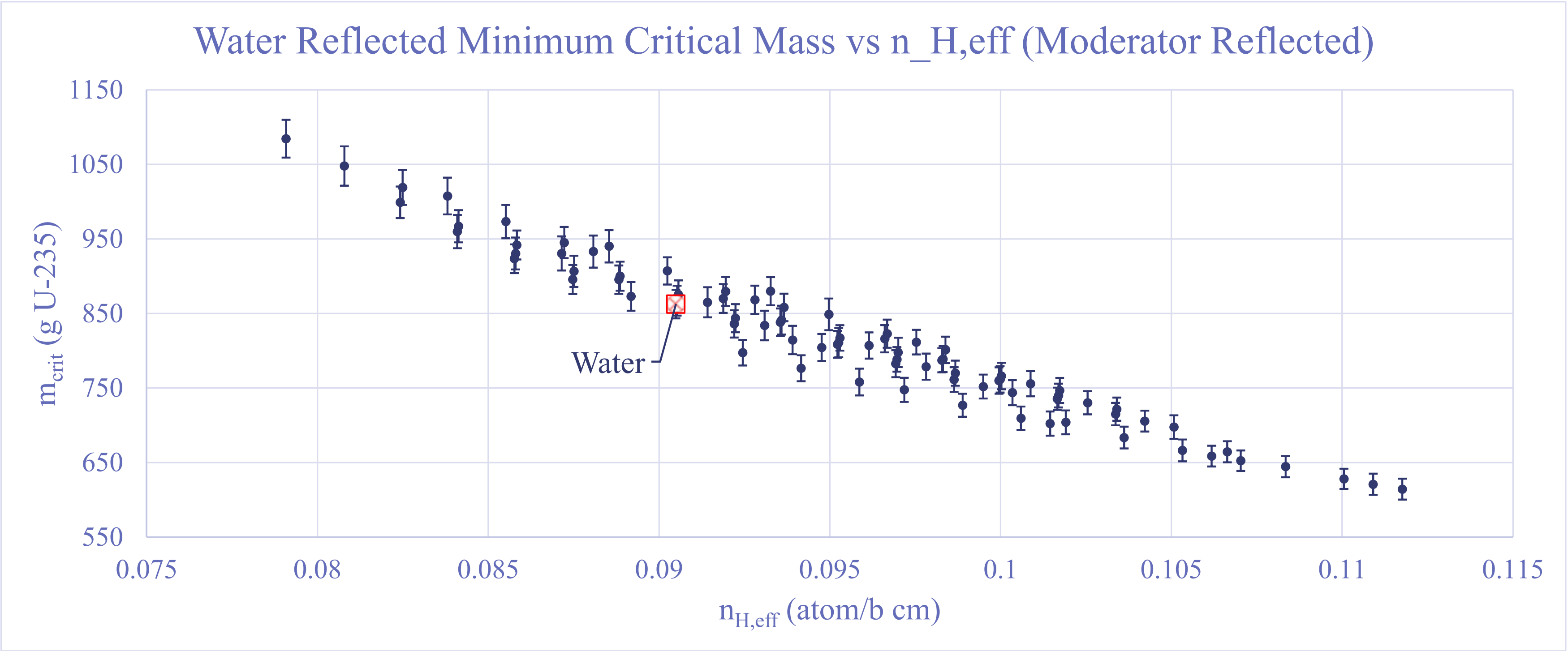
Limitations



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