

23 term of otherwise less volatile fission-products through the formation of new more
24 volatile, chloride species.

25 The literature regarding research on the chemical effects of using seawater as an
26 emergency cooling of fission-products is scarce. It is known that many chlorides of
27 different fission-products have lower boiling points than that of the pure metallic state
28 [4], thus requiring less heat before volatilizing and subsequently being released from the
29 fuel.

30 Moreover, it has been reported that unexpected behavior of a long-lived fission product
31 has been observed in the air 175 km southwest of Fukushima, at Tsukuba [5]. Instead of
32 following the modeling prediction based on expected physical decay, the long-lived
33 fission product activity has increased over time. One of the explanations proposed by the
34 author for this behavior was the formation of fission product halides [5]. This is possible,
35 as the chlorides of many fission products have a lower boiling point than the metallic
36 state. One example of the significant change in boiling points is niobium, where the
37 boiling point drops from 5031 K (metallic) to 520 K (NbCl_5) [4].

38 This could also be the case for other more volatile fission-products as well. A likely
39 candidate would be tellurium, as its halide compounds (e.g. $\text{Te}_4\text{Cl}_{16}$, 663 K [4]) have
40 lower boiling points than the metallic state (1263 K [4]). Chemically tellurium is also a
41 highly reactive element [6] and releases of different tellurium isotopes contributed
42 considerably to the total activity releases during the Fukushima Daiichi accident, as
43 reported by Le Petit et al. [7]. These arguments imply that the use of seawater as
44 emergency cooling enhanced the source term of tellurium.

45 Experiments were therefore designed and carried out to determine the interaction of
46 sodium chloride with tellurium under two atmospheres, inert and oxidizing. The initial
47 experiments were made using thermogravimetric analysis (TGA) to determine if a
48 reaction occurs between tellurium and sodium chloride. To gain a visual overview of the
49 sample at selected temperatures, heating in a furnace was carried out under oxidizing
50 conditions for one of the ratios.

51 **Tellurium chemistry**

52 An important behavior that is specific to tellurium is that tellurium is trapped by zircaloy
53 cladding [8, 9, 10]. Tellurium reacts with the zirconium present in the cladding to form
54 zirconium tellurides. Therefore, tellurium becomes trapped and releases of tellurium from
55 the core are delayed.

56 For any trapped tellurium to be released from the cladding, the cladding needs to be
57 sufficiently oxidized [9]. The oxidation occurs when the cladding no longer is covered by
58 water and exposed to steam [11], according to



60 Considering that tellurium is trapped in the cladding, a potential dryout after using
61 seawater for cooling could enable the chemical reaction between tellurium and salt on the
62 cladding surface. Moreover, ballooning and burst of the cladding when temperature rises
63 and external pressure around the cladding is lost [11], would make it possible for
64 seawater to reach the fuel pellet itself. This would enable reaction on the surface of the
65 fuel pellet.

66 **Experimental**

67 The main parts constituting the samples were metallic powder tellurium (99.8%, 200
68 mesh, Sigma Aldric) and sodium chloride (99.5%, Acros Organics). The latter was
69 ground down using a mortar and pestle to attain a finer powder. The aim was to improve
70 the mixing of tellurium and sodium chloride by having similarly sized powders.

71 Three samples (S1, S2, and S3) and two references (Ref1 and Ref2) were investigated.
72 The ratios for each sample investigated were 4:1, 1:1 and 1:4 of tellurium and sodium
73 chloride. The references were made from the same materials, but with only one of the
74 compounds used. Triplicates were made of all samples and references.

75 Every sample (7-9 mg) was placed in an alumina pan (100 μl , TA instrument), which had
76 been cleaned with 1 M HNO_3 (70%, ACS reagent, Sigma Aldrich) and MQ-water

77 (Millipore, 18 M Ω) prior to use and then left to dry in a drying cabinet overnight. After
78 adding the sample, it was then spread out in the pan by gently tapping one side of the pan
79 before placing the pan and sample inside the TGA (TGAQ500, TA instrument).

80 A gas flow of 90 ml/min was maintained throughout the whole experiment and was used
81 to establish the desired atmosphere, which for inert conditions was nitrogen (99.98 %, in-
82 house gas) and for oxidizing conditions was synthetic air (79%/21% nitrogen/oxygen,
83 AGA). A second flow of nitrogen was also used to support the pan (10 ml/min, 99.98 %,
84 in-house gas). No external monitoring of the flow was done. Instead, all gas flows were
85 monitored by the TGA-equipment itself.

86 Heating (5 K/min) was performed from ambient temperature to isothermal temperature
87 (1173 K, max temperature of the TGA) for both atmospheres. Heating was maintained
88 for 20 min at isothermal temperature, after which the system was allowed to cool to
89 ambient temperature. All temperatures were monitored by the equipment, without
90 external verification.

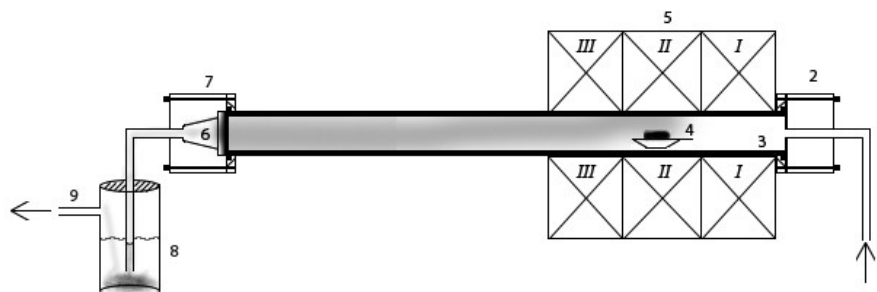
91 All outgoing pipes from the TGA were cleaned with acetone after each run. This was
92 followed by an empty run under inert conditions, and a final cleaning of the pipes with
93 acetone.

94 To attain a visual observation of the sample after heating to several different
95 temperatures, experiments were performed inside a tube furnace (ETF 30-50-18-S,
96 Entech). A 130 cm high purity alumina tube (Al₂O₃, 99.7%, Degussit AL23, Aliaxis) was
97 used inside the furnace. Connectors (stainless steel, custom made) were added to both
98 ends of the tube. To promote a smoother transition of the gas flow at the outlet, the
99 connector here was designed with an internal shape of a cone. An overview of the
100 experimental setup used can be seen in Figure 1.

101 The sample ratio investigated was 1:1 using the same supplier and quality for tellurium
102 and sodium chloride (no grinding), but with a total weight of 2 g. Each sample was
103 placed inside a crucible (Boat, Porcelain 85x13x8 mm, VWR) before being placed inside
104 the alumina tube.

105 The experiments in the furnace were performed under oxidizing conditions, where a gas
106 flow (1.5 l/min, Aalborg gas regulator) of synthetic air (compressed air) was used.
107 Moreover, to ensure oxygen in excess the gas flow was maintained throughout the whole
108 experiment.

109 Heating (10 K/min) was carried out from ambient temperature up to isothermal
110 temperature (473 K and several temperatures in the interval 573-1073 K). The isothermal
111 temperature was maintained for one hour. Following this, the system was left to cool to
112 room temperature under the gas flow (1.5 l/min) used to establish the atmosphere.



113

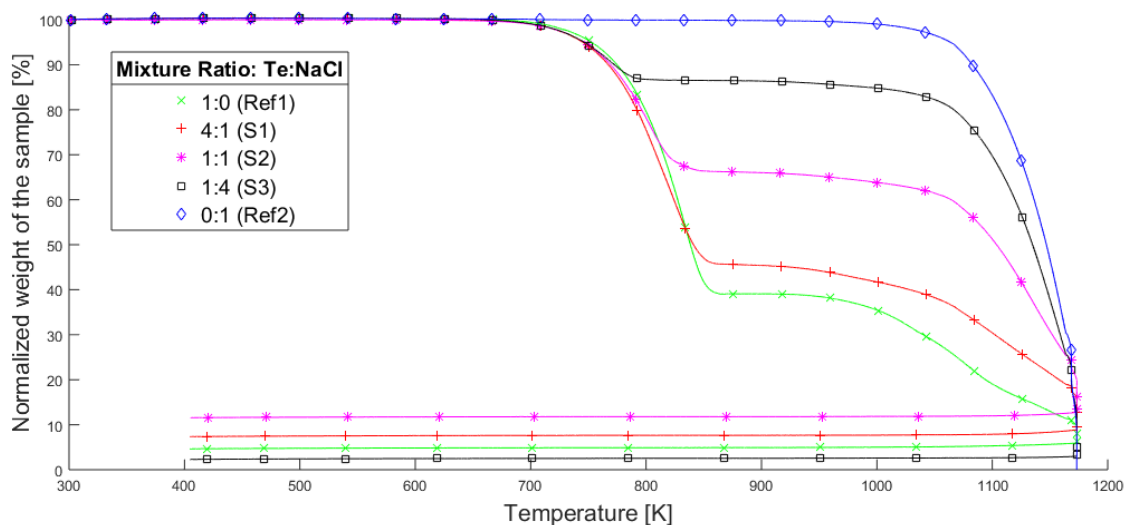
114 **Fig. 1** The experimental setup used: (1) gas flow inlet, (2) cylindrical formed inlet
115 connector made from stainless steel, (3) ceramic tube of length 130 cm, (4) the mixture of
116 compounds, (5) tubular furnace (6) a filter positioned at the end of the tube, (7) cone
117 formed outlet connector made from stainless steel, (8) cold trap used to prevent particles
118 escaping, and (9) gas flow outlet. The tubular furnace is divided into three heat zones: in
119 Heat Zone I the gas flow is heated to the programmed temperature, in Heat Zone II the gas
120 flow maintains at least the programmed temperature, and in Heat Zone III the gas flow
121 starts to cool down.

122 **Results and discussion**

123 From the TGA experiments, a normalized mass-loss as a function of temperature is
124 produced. The results can be seen in Figure 2 for inert conditions and in Figure 3 for
125 oxidizing conditions. In these two figures, five curves can be seen, each either
126 representing one of the mixture samples (S1 red, S2 pink, and S3 black), or the references
127 (Ref1 green and Ref2 blue).

128

129



130

131 **Fig. 2** The thermogravimetric analysis results for the different Te:NaCl-ratios (weight
 132 basis) heated in inert conditions. The different lines represent the average of three
 133 replicates of 0:1 (Ref1, blue diamonds), 1:4 (S1, black squares), 1:1 (S2, pink stars), 4:1
 134 (S3, red pluses), and 1:0 (Ref2, green crosses) of tellurium and sodium chloride
 135 respectively. All weights have been normalized towards the first measured weight (8-9
 136 mg) by thermogravimetric analysis.

137 Beginning with the tellurium heated alone under inert conditions in Figure 2 (Ref1,
 138 green), the mass loss remains unchanged until 692-715 K. At these temperatures a mass
 139 loss begins and continues until 855-870 K, where it stops, and the change becomes
 140 almost flat. First at 920-960 K, a new mass loss is observed. This mass loss remains until
 141 the end of the experiment, where the final normalized mass ends at 5 % of the initial
 142 value.

143 The result for when sodium chloride alone was heated under inert conditions, can be seen
 144 in Figure 2 (Ref2, blue). For sodium chloride, only one mass loss can be observed. This
 145 starts at 1000-1075 K and is maintained until the end of the experimental run. At that,
 146 point almost no mass is left.

147 The first sample (S1, red) in Figure 2 when heating under inert conditions is a mixture
 148 consisting mainly of tellurium and to a lesser extent sodium chloride. No change to the
 149 mass is observed until temperatures of 680-723 K are reached, then the first mass loss

150 begins. This mass loss remains until temperatures of 850-865 K, where the mass change
151 halts and the curve almost completely flatten out. Another mass loss does not occur until
152 925-950 K. This mass loss continues until the end of the experiments and the final mass
153 ends at 7.6 % of the original amount.

154 For the sample consisting of equal amounts of tellurium and sodium chloride, the result
155 of heating in inert conditions is shown in Figure 2 (S2, pink). The mass of the sample
156 remains unchanged until temperatures of 680-723 K are reached, where a mass loss
157 begins. This mass loss is maintained until 832-850 K, after that it is significantly reduced
158 and starts to flatten out. A significant mass loss does not occur again until the temperature
159 reaches 920-945 K. The mass loss remains until the end of the experiment, ending at a
160 normalized mass of 12 % compared to the first value.

161 The final sample heated under inert conditions is when sodium chloride constitutes the
162 major and tellurium the minor part. The result can be seen in Figure 2 (S3, black). This
163 sample remains unchanged until the temperatures reaches 670-700 K, where the first
164 mass loss occurs. The mass loss remains until the temperature reaches 785-805 K, where
165 it almost stops and remains unchanged until 921-960 K. At these temperatures, the final
166 mass loss occurs and continues until the end of the experiment. The final normalized
167 mass is 2.5 % compared to the original mass.

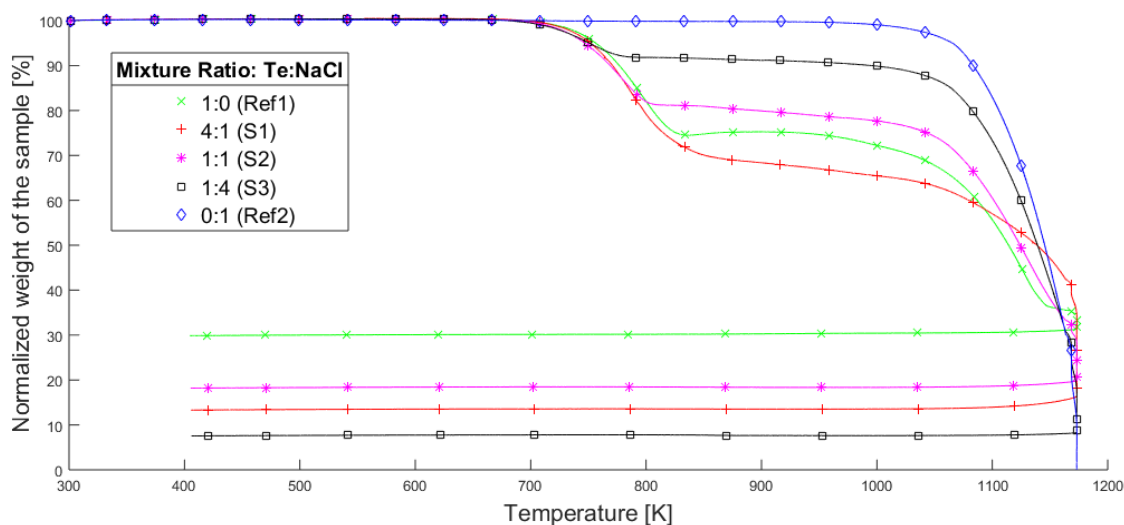
168 The first mass losses that occur for S1, S2 and S3 are most likely similar to what is
169 happening during the first mass loss of the tellurium reference (Ref1). Considering the
170 temperatures for when the mass losses occur, these are close to the melting point of
171 tellurium (725 K [4]) and, as such, a phase change from solid to liquid is most likely
172 occurring. Concurrently with the phase change of tellurium, something is also being
173 volatilized. As the reference also shows losses at these temperatures, tellurium vapor
174 would be a likely candidate. According to the literature, the volatilized species would be
175 either Te_2 or Te as these are expected to be the gaseous species of tellurium [MCF97].
176 The observed mass loss of the different samples levels out at different normalized masses
177 and is correlated to the amount of sodium chloride present in the sample (e.g. $S3 > S2 >$
178 $S1$).

179 After the initial mass loss, the change stops and becomes almost zero. This lack of
180 change occurs at different temperature intervals for all samples. This observation can be
181 attributed to the presence of sodium chloride. As the temperature needed before a mass
182 loss occurs again increases with the sodium chloride content.

183 The final mass losses that occur for the samples are all at different temperatures and ends
184 at different normalized masses. Again, the content of sodium chloride is the main
185 difference between the samples. What is happening during these mass losses would be
186 partly volatilization of tellurium (based on the tellurium reference), but also the melting
187 and phase transition of sodium chloride (melting point 1074 K [4]). The latter is also
188 being volatilized on its own, as the sodium chloride reference is also undergoing a mass
189 loss at these temperatures.

190 A general observation is that the mass loss behavior of the different samples in inert
191 conditions is dictated by the main constituting part of the sample, i.e. the amount of
192 tellurium or sodium chloride. As experiment S1 highly resembles the Ref1 case, S3 is
193 more similar to Ref2 and S2 is somewhere in between.

194 Thus, the results in Figure 2 are indicative that no reaction has occurred between
195 tellurium and sodium chloride for any of the samples. However, as tellurium has a
196 considerably lower melting point than sodium chloride there might not be enough
197 tellurium available, at the temperature for which a chemical reaction is possible. Thus, it
198 is conceivable that no reaction is observable from the result as the tellurium volatilized
199 would be almost instantly transported away by the gas flow and little to nothing would
200 remain when a potential reaction could occur. Therefore, a reaction could still occur at a
201 higher temperature if tellurium remains. A scenario when tellurium remains at a high
202 temperature at the surface of the cladding is possible as tellurium is trapped by zircaloy
203 cladding under inert conditions. Moreover, tellurium would be released only when the
204 cladding becomes sufficiently oxidized [8, 9, 10].



205

206 **Fig. 3** The thermogravimetric analysis results for the different Te:NaCl-ratios (weight
 207 basis) heated in oxidizing conditions. The different lines represent the average of three
 208 replicates of 0:1 (Ref1, blue diamonds), 1:4 (S1, black squares), 1:1 (S2, pink stars), 4:1
 209 (S3, red pluses) and 1:0 (Ref2, green crosses) of tellurium and sodium chloride
 210 respectively. All weights have been normalized towards the first measured weight (8-9
 211 mg) by thermogravimetric analysis.

212 The next set of experiments were carried out under oxidizing conditions. Starting with the
 213 references in Figure 3, the tellurium (Ref1, green) behavior is unchanged up to 700-720
 214 K. At these temperatures, a mass loss begins and goes on until 822-840 K, where the
 215 mass loss completely stops and slowly becomes a mass increase. This mass increase is
 216 maintained up to temperatures of 900-940 K. Following this increase, a rapid mass loss
 217 occurs that lasts until the end of the experiment. The final normalized mass loss is 30 %
 218 of the initial amount.

219 The sodium chloride reference heated under oxidizing conditions can be seen in Figure 3
 220 (Ref2, blue). This behaves similarly to the reference of sodium chloride seen in Figure 2
 221 (Ref2, blue) heated under inert conditions. That is, no mass loss is observable until
 222 temperatures of 1001-1047 K are reached. A rapid mass loss follows, which lasts until the
 223 end of the experiment. At the end, almost no mass remains.

224 The first sample is seen in Figure 3 (S1, red) shows the results from heating tellurium
 225 with a smaller amount of sodium chloride present in oxidizing conditions. No change to

226 the mass is observed up to temperatures of 697-721 K. The first mass loss begins at these
227 temperatures, which lasts until 845-869 K. At these temperatures, the mass loss
228 drastically slows down and remains steadily up to 1027-1057 K, where a new mass loss
229 occurs. This final mass loss lasts until the end of the experiment, with a final normalized
230 mass of 14% of the original value.

231 The second sample is seen in Figure 3 (S2, pink) is when tellurium and sodium chloride
232 are in equal amounts and are heated under oxidizing conditions. The mass remains
233 unchanged up until temperatures of 695-713 K, where a mass loss takes place. This mass
234 loss remains until temperatures of 796-815 K, as at these temperatures the rate of the
235 mass loss slows considerably. This reduced mass loss lasts until temperatures of 1020-
236 1050 K, where the mass loss drastically increases again. This final mass loss remains
237 until the end of the experiment and the final normalized mass halts at 18 % of the original
238 amount.

239 The results for the final sample heated in oxidizing conditions can be seen in Figure 3
240 (S3, black), sodium chloride is the major and tellurium the minor part of the sample. The
241 first change to the mass occurs at 677-720 K and lasts until 770-785 K. At this point, the
242 mass loss slows down and almost becomes zero. The normalized mass remains
243 unchanged up to temperatures of 1000-1030 K, where a final mass loss occurs and
244 continues until the end of the experiment, ending at a normalized mass of 8 % of the
245 initial value.

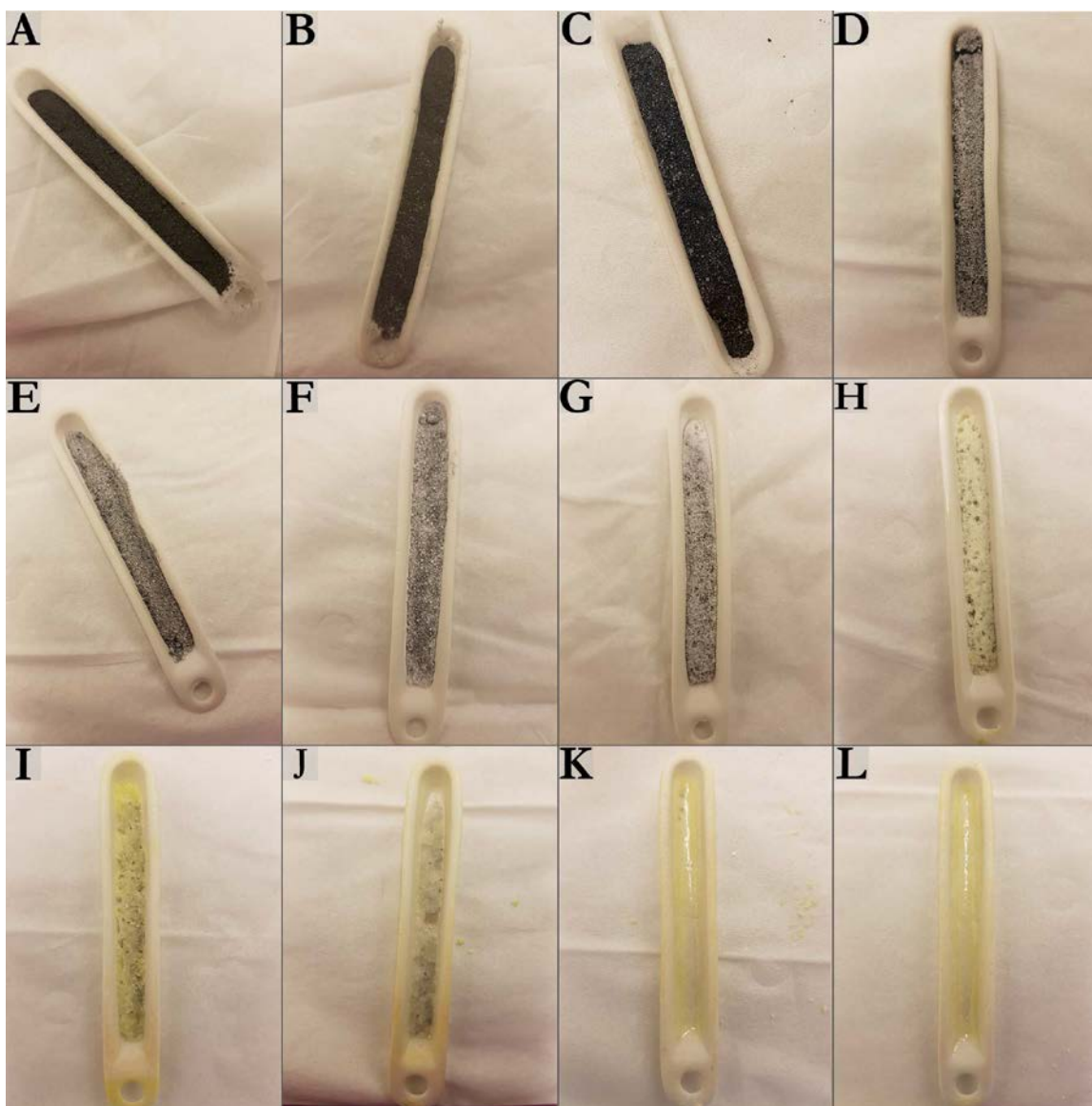
246 During the first mass loss of the tellurium (Ref1), and most likely the three samples (S1,
247 S2, S3) in Figure 3, a phase change from solid to liquid of the tellurium species is
248 occurring as indicated by the melting point of tellurium (725 K [4]) and that of TeO (643
249 K [3]). Furthermore, from observing the tellurium reference during this mass loss
250 something is being volatilized. What could be volatilized is either a tellurium vapor
251 species similar to the inert experiment, or a tellurium oxide. A minor difference is
252 occurring between the three samples and the reference of tellurium, as the reference has a
253 slightly slower mass decrease. This difference could be indicative of either a chemical
254 reaction in the samples or that the presence of sodium chloride alters the rate on its own.

255 After the first mass loss in the tellurium reference, a significant mass increase is
256 observed. This increase can be explained by the formation of α -TeO₂, as can be observed
257 in the Te-O phase diagram [13]. As a decreasing amount of tellurium would result in a
258 shift towards the vertical line of α -TeO₂. Moreover, TeO₂ melts at 1006 K [3] and thus a
259 phase change is taking place at this temperature. The phase diagram of Te-O [13] shows
260 that both a liquid and a gas phase exists above the melting point. Thus, the second mass
261 loss is explained by volatilization of TeO₂.

262 However, this increase of mass is only observed for the tellurium reference, as all three
263 samples and the sodium chloride reference do not have any mass increase stage. This is
264 indicative that something has altered the behavior of the tellurium. An explanation could
265 be that the mere presence of sodium chloride could prevent the oxidation of tellurium in
266 the crucible by physically preventing the oxygen from reaching the tellurium. However,
267 another possibility could be that a chemical reaction has occurred between the tellurium
268 and sodium chloride with the result being the formation of a new readily volatilized
269 compound. This new compound would then either surpass the effect of mass increase
270 from the formation of TeO₂ by volatilization or by reducing the formation of the oxide.

271 Furthermore, the difference between the three samples are minor, if any, and can be
272 explained by the content of sodium chloride. Increasing the content of sodium chloride
273 results in the sample behaving more similarly to the sodium chloride reference. Thus, this
274 would mean that even small amounts of sodium chloride (a fourth of the weight of
275 tellurium, e.g. a fifth of the weight of the total sample) would affect the tellurium
276 volatilization.

277 To further evaluate the oxidizing conditions, furnace experiments were carried out and
278 the results can be seen in Figure 4. The initial state of the mixture resembles the crucible
279 in image A; the two parts are tellurium (black powder) and sodium chloride (white
280 powder)



281

282 **Fig. 4** Crucibles containing the sample, as seen after the furnace experiment. The initial
283 composition of the samples was 1:1 of tellurium and sodium chloride (2 g). In total eight,
284 temperatures were investigated: (A) 473 K, (B) 573 K, (C) 623 K, (D) 673 K, (E) 723 K,
285 (F) 773 K, (G) 823 K, (H) 873 K, (I) 923 K, (J) 973 K, (K) 1023 K and (L) 1073 K.

286 In Figure 4 several crucibles can be seen, containing what was left after the furnace
287 experiments. Each crucible represents an investigated temperature (473-1073 K) and
288 shows how heating to the temperature affects the sample of 1:1-ratio of tellurium and
289 sodium chloride.

290 What can be observed is that for the temperatures 473 K (A), 573 K (B) and 623 K (C),
291 the sample remains seemingly unchanged after the experiment. Above 673 K (D) the first
292 observable change can be seen, as white particles (sodium chloride based on the original
293 content of the sample) increase in appearance.

294 At 723 K (E), the black powder (tellurium based on the original content of the sample)
295 seemingly starts to disappear, which lasts until 873 K (H). At this temperature, the next
296 change can be observed, as a slightly yellow phase starts to emerge that is observable,
297 both on the mixture and on the crucible. Moreover, the sample parts have now merged
298 together and formed a solid mass.

299 Increasing the temperature to 923 K (I) resulted in the yellow phase becoming even more
300 obvious. The sample has also become even more of solid and the sodium chloride has
301 started to lose its original shape.

302 At the next temperature, 973 K (J), the mixture has become a solid slug at the bottom of
303 the crucible and occupies a considerable less volume.

304 Increasing the temperature again to 1023 K (K) drastically changes the appearance as
305 nothing except the yellow phase remains. Some black spots can be observed, but these
306 are most likely tellurium encapsulated in the yellow phase.

307 The final sample heated to 1073 K (L), show no significant difference from the sample
308 heated to 1023 K.

309 From the images in Figure 4, it is possible to see that up to 623 K nothing observable
310 happens to the samples containing tellurium (black particles) and sodium chloride (white
311 particles). This would be consistent with what would be expected based on the melting
312 point of tellurium (725 K [4]). The sample at 673 K shows an increasing number of white
313 particles, the reason for which is not clear based on these images. Increasing the
314 temperature further to 823 K shows more of the white particles. The first significant
315 change that can be seen in these images is the appearance of a yellow phase at 873 K.
316 According to the literature [4], there are two possible compounds of the involved
317 elements constituting the sample that have this color; TeCl_4 that has a pale-yellow color

318 and yellow TeO₂ (orthorhombic). Of these, only TeCl₄ has a melting point and boiling
319 point below 1000 K [3].

320 Sodium chloride has no phase change up to 1000 K that would change the appearance of
321 it, according to the melting point (1074 K) and the boiling point (1686 K) [3]. Observing
322 the result in Figure 4 for the 1023 K temperature, nothing except the yellow phase
323 remains. This is indicating that something has formed that has removed the sodium
324 chloride or reacted with it, forming something more volatile than the sodium chloride.

325 Comparing the TGA result and the furnace experiments, during the first mass change of
326 the sample (S2) in Figure 3, something is slowly being volatilized between the
327 temperatures 673 and 873 K. Observing the crucible at these temperatures in Figure 4,
328 this correlates to the increasing appearance of the white particles of the sample. Thus, a
329 potential cause of the mass loss observed by the TGA can be correlated to the black part
330 (tellurium) of the sample.

331 At the temperature 873 K in Figure 3, the sample (S2) is still slowly losing mass.
332 Correlating this to the result from the furnace experiment in Figure 4, a yellow phase is
333 being formed on the sample and the crucible. Moreover, the black part has decreased
334 significantly. Thus, an explanation could be that the yellow phase is what is being
335 volatilized as it covers the sample and the crucible.

336 Observing the two samples heated to 923 K and 973 K, only a slight change can be seen
337 as the sample goes from a mixture (or close to it) to an almost melted stage. Comparing
338 this to the TGA result (S2) in Figure 3, no drastic change occurs between 923 K and 973
339 K. Indicating that it is the same species that is continuously volatilized at these
340 temperatures.

341 For the final two samples in Figure 4, heated to temperatures of 1023 K and 1073 K, the
342 samples are almost completely consumed; only the yellow phase remains, forming a
343 yellow glazed surface. The TGA result at the same temperature (S2) in Figure 4, is
344 showing a mass loss of the sample, the tellurium and the sodium chloride reference.
345 However, the sodium chloride reference is only starting to lose mass whereas the other

346 two are showing significant mass losses. Considering the boiling point of sodium
347 chloride (1686 K [3]), there should not be a rapid loss of sodium chloride at these
348 temperatures. Thus, this is indicative that something has interacted with the sodium
349 chloride and formed a more volatile compound.

350 Thus, by comparing both TGA and the furnace results it is possible that the tellurium is
351 affected by the sodium chloride, as the behavior of the latter is not consistent with what
352 would be expected if no interaction occurred.

353 **Conclusions**

354 In this paper, the effect of sodium chloride on the volatilization of tellurium in the
355 vicinity of the core was investigated both under inert and oxidizing conditions. Using a
356 TGA, samples containing different ratios of tellurium and sodium chloride were heated
357 from ambient temperature to 1173 K and the consequential mass loss was recorded.
358 Moreover, reference sample containing only the individual parts were heated to the same
359 temperature and the results were compared to experiments when tellurium and sodium
360 chloride were heated together. To attain a visual overview of the samples after heating,
361 experiments were carried out to produce samples at several temperatures (473 K and
362 several temperatures in the interval 573-1073 K). This was done only for a 1:1 ratio of
363 tellurium and sodium chloride.

364 The experimental results for the inert conditions showed little difference between the
365 reference and the samples. Observing the behavior of the two reference samples, there is
366 the potential that most of the tellurium is gone by the time a chemical reaction could take
367 place. Thus, the reaction cannot be completely excluded.

368 A mass increase was observed for the tellurium reference case between 800-1000 K
369 under oxidizing conditions. This was attributed to the tellurium-oxide formation. This
370 increase was not present when sodium chloride was added to tellurium. Instead, a slight
371 decrease was noticed. This could be explained by either sodium chloride physically
372 preventing the oxidation of the tellurium in the crucible or the formation of a reaction

373 product that is more volatile than tellurium oxide, or alternatively a reaction product that
374 prevents the oxidation of tellurium. Moreover, the sodium chloride mass loss behavior
375 was very similar in both atmospheres. Any change is therefore only due to either the
376 tellurium or to the tellurium and sodium chloride interaction. This was supported by the
377 observation in the furnace experiments, where the sodium chloride changes occurred at a
378 lower temperature compared to the melting point.

379 It is not possible to give a definitive answer if a possible reaction occurred in the gas
380 phase, liquid phase, solid phase or phase boundaries. However, based on the melting
381 points and boiling points, the possible reaction observed most likely occurred in the
382 liquid-liquid or liquid-solid phase. This would not exclude a gas-phase interaction, but
383 this would not be observable in the TGA or furnace experiments, as anything volatilized
384 is almost directly transported away from the sample. Thus, no gas reaction can be noticed
385 by the scale or in the crucible.

386 The results found in this study indicates that a dryout after using seawater for cooling
387 could increase releases of tellurium under oxidizing conditions. As tellurium is entrapped
388 by the cladding and requires oxidizing conditions to be released, such a scenario is
389 feasible. Therefore, should a dry-out occur after using seawater the result would be an
390 increase in the tellurium source term.

391 For future studies, the next step would be to use a system capable of online measurement
392 of the volatilized material, specifically speciation. Moreover, as tellurium has a low
393 boiling point a setup using several furnaces could also be used to allow for preheating
394 and consequently volatilization of the materials. The volatilized material would then be
395 transported to a reaction zone, maintained at a higher temperature.

396 **Acknowledgments**

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398 this project.

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