The volatilization of chromium species from chromium containing materials is a well-documented phenomenon which holds consequences for SOFCs, human health, and the environment. Using chromia as an example for a source, in the presence of oxygen and absence of water vapor, the dominant volatilization pathway proceeds according to Reaction 1.1-4

\[
\frac{1}{2} \text{Cr}_{2}O_{3}(s) + \frac{3}{4} O_{2}(g) = \text{CrO}_{3}(g) \quad [1]
\]

If, however, water vapor is present in addition to oxygen, then the dominant volatilization pathway proceeds according to Reaction 2.1-7

\[
\frac{1}{2} \text{Cr}_{2}O_{3}(s) + \frac{3}{4} O_{2}(g) + H_{2}O(g) = \text{CrO}_{3}(OH)_{2}(g) \quad [2]
\]

The generation of these gas/vapor species is well understood, but the same cannot be said of how they interact with (e.g. condense onto) other materials. This is of great importance for human health and the environment considering that chromium species may take toxic forms (hexavalent) or non-toxic forms (trivalent). This relative dearth of understanding also holds negative implications for SOFCs, and so many investigative efforts have been undertaken to understand how \(\text{CrO}_{3}(OH)_{2}\) interacts with ceramic components in SOFCs. Electrochemical reduction of \(\text{CrO}_{3}(OH)_{2}\) has often been observed to occur at the triple phase boundary (TPB), where cathode, electrolyte, and gas phase meet.8-10 This electrochemical reaction is not limited to the TPB, however, and can occur away from the TPB given: the formation of a continuous chromia layer for hole transport, a mixed conducting TPB, however, and can occur away from the TPB given: the formation of a continuous chromia layer for hole transport, a mixed conducting cathode.8

While there is evidence for preferential electrochemical reduction of \(\text{CrO}_{3}(OH)_{2}\).11,12 open circuit chemical reactions have also been observed with cathodes containing Mn or Sr.13 It should be noted that Cr transport to lanthanum strontium manganite (LSM) was observed via solid state diffusion, whereas vapor deposition of Cr was not observed. This has also been reported by Tucker et al.,14 who observed similar Cr transport behavior onto MnOx, except trace levels of chromium were noted to occur via vapor transport. Single element oxides such as \(\text{Co}_{3}O_{4}\) and \(\text{SrO}\), in addition to the mixed oxide lanthanum cobalt ferrite (LSCF), however, were observed to possess significant Cr contamination from both transport methods.

Strontium oxide has also been observed to form Sr-Cr compounds when volatile chromium interacts with SrO containing glass-ceramic sealants.15 Additionally, glass-ceramic sealants containing barium are observed to form Ba-Cr compounds when interacting with volatile chromium.16 Other glass, such as fused quartz, is also known to interact with \(\text{CrO}_{3}(OH)_{2}\). This interaction appears in the form of green or brown deposits, having been observed by Opila et al., Asteman et al., and Segerdahl et al.1,17,18 The solid green deposits were identified as \(\text{Cr}_{2}O_{3}\) using X-ray diffraction.1 Solid brown deposits were examined using secondary ion mass spectrometry and XPS, and were determined to consist of chromium oxide in the trivalent and hexavalent state.18 Liquid brown deposits were determined to be in the hexavalent state by spectrophotometric analysis and were therefore correlated with chromic acid,1 but the identity of this deposit was not confirmed.

Additional interaction behavior is available from the development of volatile chromium collection techniques for the examination of volatile chromium release from potential SOFC interconnect materials. Volatile chromium species \(\text{CrO}_{2}(OH)_{2}\) is known to react with sodium carbonate coated denuder tubes to form sodium chromate.19 Alumina plates, silica wafers, and quartz wool have also been used to collect volatile chromium species,20-22 but to the knowledge of the authors these techniques were only used for chromium quantification using energy dispersive X-ray spectroscopy, Rutherford backscattering spectroscopy, and inductively coupled plasma mass spectroscopy. Neither the identity of chromium compounds nor the oxidation state of chromium on these collector surfaces appears to have been pursued.

A large library of work is also available from research into supported chromium catalysts. Several support materials have been used, but alumina and silica supports are of interest for this study. There appears to be general agreement that on hydrated surfaces, the isoelectric point of the ceramic surface will influence which chromium species are stable.23-25 On calcined surfaces, factors such as hydroxyl populations and acid/base properties of the hydroxyl groups are believed to influence which chromium species are stable.25-26 The temperature and amount of chromium loaded onto a surface will also influence speciation.26-31

Regarding speciation, chromium compounds with oxidation states 2-6 have been claimed in literature on alumina and silica surfaces.24,25,29,31-33 Some of these claims appear to be contradictory. For example, some contend that compounds such as \(\text{CrO}_{2}\) and \(\text{CrO}_{3}\) are of mixed valences, consisting of 3+ and 6+,33,36 while others claim +4 and +6,37 whereas others claim the Cr within \(\text{CrO}_{2}\) to be pentavalent.31 This study aims to expand the current
knowledge in this area, and attempt to test the validity of previous claims.

In this study, aluminosilicate fibres were used to collect volatile chromium oxyhydroxide species at 100–230°C evolved from FSS T409 at 700°C in humidified air. Upon collection, these fibres became discolored, with discoloration appearing as regions of light yellow, green, and/or dark brown. X-ray photoelectron spectroscopy (XPS) was used to search for possible links between stain color and the oxidation state of chromium.

**Experimental Methods**

Sheets of FSS T409 (see Table I for composition) were cut lengthwise using foot shears into strips of approximate dimensions 125 mm × 14 mm × 1.48 mm. Four strips of T409 were used in each experiment which were each measured, massed, and stamped for identification pre-exposure. These strips were used to generate volatile chromium species to contaminate aluminosilicate fibres of approximate mass 2 g which were placed downstream of the chromium source. The strips were placed in a quartz crucible which was housed in the center of a 30 mm OD quartz tube. The quartz tube was placed in a GSL-1100x tube furnace and flanges sealed with O-rings were used to connect the quartz tube to inlet and outlet tubing. The inlet to the furnace was supplied using house air and controlled by an Omega FL-3613 G rotameter to establish a flow rate of 900 sccm. A three-way valve was used to direct flow to a 1 L glass bubbler which was fitted with a frit of porosity rating P1. The bubbler was filled with water and heated to approximately 55°C, yielding an estimated $P_{H_2O}$ of ~0.16 bar. The inlet gas/vapor interacts with stainless steel strips at 700°C and passes through aluminosilicate fibers outside of the furnace. Condensation zones of 100–230°C were observed on the fibers using an Amprobe IR608A infrared thermometer. After passing through the fibers, effluent was initially routed into a 500 mL Erlenmeyer flask to condense water vapor. Condensate was assumed to contain negligible chromium, in line with previous unpublished results. The effluent is then directed to a fume hood for venting. See Figure 2 for clarification.

The furnace ramp rate was 30°C/min and exposure time at 700°C was 150 hours. After the exposure period elapsed, power to the furnace was discontinued and dry air was used during cool down. Upon cooling to room temperature, steel strips and fiber were re-massed. A Physical Electronics 5600 X-ray Photoelectron Spectrometer (XPS) system was used to characterize discolored regions on aluminosilicate fibers. To compensate for the insulating nature of these samples, a stainless-steel mesh screen was placed over fiber samples, and an electron flood gun was used. The stainless steel mesh screen is attached to a conductive metal frame, which is grounded to the sample mount. Emission of photoelectrons from insulating samples may lead to differential charging due to a buildup of positive charges on the surface. Using a stainless steel mesh screen, in addition to a flood gun supplying low energy electrons, allows for a more uniform electric potential at the sample surface, and swift supply of electrons to areas beginning to accumulate positive charges. It will be noted that chromium signal from the mesh was precluded, as the mesh consists of 2 mm × 2 mm square sizes, with an analysis area of 1 mm × 1 mm which is marked on the sample image screen for easy targeting. The reliability of this targeting is checked by Image and Chemical Analysis Laboratory staff at Montana State.

Spectra were adjusted as necessary by setting Al 2p to 74.4 eV. A pass energy of 46.95 eV was used with 0.2 eV/step and 40 ms/step, and the collection area was set to a +/− 7° solid angle.

It will be noted here that some compounds to be examined, such as Cr$_2$O$_3$, may have a finely structured multiplet splitting pattern. These structures are uncovered through XPS examination of a high purity compound. In the analysis of surfaces with mixtures of compounds which follows, these structures would quickly become numerous and unwieldy, and so broad Gaussian-Lorenzian (GL) peak fits are used instead. It may be imagined that convolution of the undisplayed multiplet splitting structures would result in the displayed broad GL peaks. This is demonstrated visually in Figure 2, where work from Biesinger et al. (left), and Pradier et al. (right) is compared. The left spectrum is high purity Cr$_2$O$_3$, whereas the spectrum on the right consists of a mixture of chromium containing oxides. The boxed broad GL peak in the right spectrum can be imagined to be a convolution of the multiplet splitting structure of the high purity Cr$_2$O$_3$ spectrum on the left.

**Results/Discussion**

Figures 3 and 4 display representative colors observed on aluminosilicate fibers. Figure 3 is an image of aluminosilicate fibers post exposure, where Figure 4 shows disassembled fiber regions with brown (4a), green (4b), and yellow (4c) staining. In Figure 3, the flow progressed through the fibers from right to left, and a progression from brown, to brown yellow, to yellow, to light staining, to no visible staining is noted. The transition region between heavy and light staining, seen in Figure 3 as the point at which the brown begins to fade, was noted to occur at approximately 150°C.

Figures 5–7 display the XPS spectra for brown, green, and yellow discoloration on the fibers, respectively. Tables II–IV give

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**Table I. Composition of FSS T409.**

|   | Fe    | C     | Mn  | Si   | P    | S    | Cr  | Ni  | Ti  |
|---|-------|-------|-----|------|------|------|-----|-----|-----|
| 409 | Bal   | max:0.08 | max:1.0 | max:1.0 | max:0.045 | max:0.045 | min:10.5 | max:0.5 | min:0.48 | max:0.75 |

---

**Figure 1.** Experimental setup.
Figure 2. Comparison of high purity Cr$_2$O$_3$ multiplet splitting structure (left)\textsuperscript{38} with broad GL peak fit representation for mixed Cr oxides (right).\textsuperscript{40}

Figure 3. Representative staining observed on aluminosilicate fibers post exposure.

GL peak information for the brown, green, and yellow spectra, respectively. Discoloration arose on aluminosilicate fibers after 150 hours of exposure to CrO$_2$(OH)$_2$ over a temperature range of 100–230°C. Examination of Cr 2p$_{3/2}$ peaks in Figures 5–7 revealed varied Cr(VI) content and Cr(III) multiplet-split components for different discolored regions. While differences in color may be generally associated with oxidation state,\textsuperscript{24} it may be more precise to attribute colors to specific chromium compounds. Hexavalent chromium, for example, may appear as yellow, orange, red, or brown.\textsuperscript{1,23,24} Given that the human eye is inadequate for discerning subtle mixtures of color, for example “pure” brown from “mixed” brown, it is reasonable to expect mixed compounds in each stain.

For all three spectra, the hexavalent peak is the highest binding energy peak. The lowest binding energy peak has been assigned as trivalent chromium, or more specifically as chromia. A peak position of 576–576.3 eV (as is observed in the spectra) is well supported in literature for chromia.\textsuperscript{25,41,42} This assignment will be discussed in further detail below.

The brown stain (Figure 5) not only possessed a greater proportion of hexavalent chromium, but the hexavalent chromium was also of higher binding energy than the other colors examined. As hexavalent chromium has no unpaired electrons in its valence shell, it manifests as a single peak. This peak may broaden, however, if it contains multiple different hexavalent chromium compounds of differing binding energies. Values ranging from 1.3 eV to upwards of 4 eV have been used for a full width at half maximum (FWHM) of mixed hexavalent chromium species.\textsuperscript{32,39,43,44} The FWHM is attributable to the energy resolution of the instrument and the natural line width of the photoelectron peak. A FWHM of 2 eV was used here for hexavalent GL peaks based on fit with the spectra. This value was also used for chromia GL peaks based on fit. This value resides within the range of FWHM values for chromia multiplet splitting components observed in literature, from 0.9 eV for multiple component peak fits, up to 3 eV for single peak fits.\textsuperscript{38,39} The authors could not find explicit reporting for Cr$_2$O$_3$ and Cr$_3$O$_8$ FWHM values. From XPS spectra in literature, these values are estimated to fall between 2–5 eV for a single peak fit.\textsuperscript{36,45}

Concerning the hexavalent chromium content in Figure 5, a likely prominent hexavalent compound is the anhydrous form of the incident chromium species CrO$_2$(OH)$_2$ - CrO$_3$. Evidence supporting this conclusion includes similar binding energies reported in literature for CrO$_3$,\textsuperscript{36,38,39,42} in addition to the color of pure CrO$_3$ being a dark brown. The presence of CrO$_3$ has also been observed in literature for temperatures less than and greater than the estimated temperature range in this study (100–230°C).\textsuperscript{57,31} The stability of CrO$_3$ is temperature dependent, however, and can give rise to other compounds beginning at temperatures as low as 200°C.\textsuperscript{31} Compounds claimed in literature include M-CrO$_4$, M-Cr$_2$O$_7$ (where M = Al, Si), Cr$_2$O$_5$, Cr$_3$O$_8$, CrO$_2$, Cr$_2$O$_3$, and CrO$_3$.\textsuperscript{24,25,29,31–35}

Figure 4. Stained regions on aluminosilicate fibers examined using XPS. From left to right: brown (a), green (b), and yellow (c).
Figure 5. Cr 2p$_{3/2}$ energy window for brown staining on aluminosilicate fibers. Peaks 1, 2, 4, and 5 are trivalent multiplet-split components. Peak 3 is the hexavalent component.

Figure 6. Cr 2p$_{3/2}$ energy window for green staining on aluminosilicate fibers. Peaks 1 and 2 are trivalent multiplet-split components. Peak 3 is the hexavalent component.
Theories regarding the formation of these compounds are also available from literature. Formation of chromate (M-CrO₄) is believed to be caused by an esterification reaction between CrO₃ and surface hydroxyl groups which may occur near 200°C, and subsequently stabilize the hexavalent form for temperatures exceeding 1000°C.²⁴,³¹,⁴⁶,⁴⁷ Dichromate (M-Cr₂O₇) is believed to form from anchored chromate as chromium loading increases on the sample surface.²⁷,²⁸,⁴⁸ Thermal decomposition of CrO₃ may begin at temperatures as low as 200°C, which may cause melting and effervescing, resulting in a loss of oxygen.²⁶,³¹,³⁴,⁴⁵ This loss of oxygen may give rise to Cr₂O₅, Cr₃O₈, CrO₂, and Cr₂O₃.

Based on this literature background, different discolored regions may be understood by proposing a succession of events regarding volatile chromium deposition and its subsequent breakdown. This sequence of events is illustrated below in Figures 8–10. Chromium oxyhydroxide, the dominant volatile chromium product formed in air and water vapor, comes into contact with aluminosilicate fiber surfaces over 100–230°C. At this temperature range, the volatile chromium species is likely physisorbed to the surface. Physisorption is likely as the temperature is near/below the condensation point of the gas, and since this deposition has been precluded in literature if the temperature rises too far above the upper limit on the range.¹ Physisorbed Cr₂O₇(OH)₂ may dehydrate to form CrO₃. Chromate species may form from CrO₃ through an esterification reaction with the surface.²⁴,⁴⁶,⁴⁷ Hydroxyl groups act as anchoring points which allow for stabilization and dispersion of hexavalent chromate.²⁸,⁴⁹,⁵⁰

Table II. Peak information for brown staining on aluminosilicate fibers (Figure 5). Secondary inferred compounds are compounds which are believed to contribute to some extent to the peak signal, but to a lesser degree than the primary inferred compound.

| Peak | Area % | Peak Position | Oxidation State | Primary Inferred Compound(s) | Secondary Inferred Compound(s) | Intensity | FWHM | % Gauss |
|------|--------|---------------|-----------------|------------------------------|--------------------------------|-----------|-------|--------|
| 1    | 19.1   | 577.79        | +3              | Cr₂O₅ and/or Cr₃O₈           | -                              | 390       | 1.2   | 70     |
| 2    | 22.8   | 576.10        | +3              | Cr₃O₈                        | -                              | 280       | 2     | 70     |
| 3    | 30.6   | 579.92        | +6              | CrO₂                         | Chromate species, Cr₂O₅ and/or Cr₃O₈ | 375       | 2     | 70     |
| 4    | 16.1   | 578.80        | +3              | Cr₂O₅ and/or Cr₃O₈           | -                              | 330       | 1.2   | 70     |
| 5    | 11.4   | 577.06        | +3              | Cr₂O₅ and/or Cr₃O₈           | -                              | 234       | 1.2   | 70     |

Table III. Peak information for green staining on aluminosilicate fibers (Figure 6). Secondary inferred compounds are compounds which are believed to contribute to some extent to the peak signal, but to a lesser degree than the primary inferred compound.

| Peak | Area % | Peak Position | Oxidation State | Primary Inferred Compound(s) | Secondary Inferred Compound(s) | Intensity | FWHM | % Gauss |
|------|--------|---------------|-----------------|------------------------------|--------------------------------|-----------|-------|--------|
| 1    | 40.4   | 577.64        | +3              | Cr₂O₅ and/or Cr₃O₈           | -                              | 280       | 2     | 90     |
| 2    | 40.9   | 576.30        | +3              | Cr₂O₅                        | -                              | 260       | 2     | 70     |
| 3    | 18.7   | 579.00        | +6              | Chromate species CrO₃, Cr₂O₅ and/or Cr₃O₈ | 130     | 2     | 90     |
over time which may result in the formation of Cr$_3$O$_5$, then Cr$_2$O$_5$, followed by CrO$_2$, and lastly Cr$_2$O$_3$. At this stage the color would appear to be green (Figures 4b, 6, and 10). Decomposition of CrO$_3$ to Cr$_2$O$_3$ would likely leave remaining surface chromate species as the primary contributor to the hexavalent peak in Figure 6.

Chromium(II) oxide has also been observed, but only under reducing conditions which are not present in this study, so its presence is not considered plausible. The presence of CrO$_2$ is plausible under these conditions, as it has been repeatedly observed under oxidizing conditions. The Cr 2p$_{3/2}$ peak for CrO$_2$ is anticipated to appear around 575.2 eV. While this value may seem to be in contradiction with the chemical shift theory, CrO$_2$ has been observed to have a lower binding energy than Cr$^{3+}$ species repeatedly. This peak, however, does not appear to be present with appreciable intensity for any of the stains.

It is possible that the binding energy of CrO$_2$ may be inflated due to dehydroxylation of silica/alumina surfaces as temperature increases. As more hydroxyl sites are lost, the electron density of the surface diminishes. This decreased electron density likely results in a decrease in electron density of anchored chromium species, thereby increasing the binding energy. The impact of this effect and the influence of temperature has been reported by Liu et al. for hexavalent species from 100–800°C, over which the binding energy rises approximately 3 eV. This confounding factor may make differentiation of Cr$^{4+}$ and Cr$^{3+}$ difficult, though perhaps the presence of Cr$^{4+}$ is easier determined indirectly, or in other words by examining Cr$^{6+}$.

The binding energy of hexavalent chromium presented in this study ranges from 579–579.92 eV. These values are well within known norms for the binding energy of hexavalent chromium species. It seems that for these conditions, the extent of dehydroxylation
was minimal. This in turn means the peaks observed to range from 576–576.3 eV (lowest binding energy peak in each spectrum) are not due to an inflated Cr$^{4+}$ signal, but rather from Cr$^{3+}$. The observed range is well supported in literature for chromia.25,41,42

Determining if Cr$_2$O$_3$ and/or Cr$_3$O$_8$ are present may be challenging, as there are conflicting theories concerning these compounds in literature. Both Cr$_2$O$_3$ and Cr$_3$O$_8$ have been claimed as mixed valence compounds comprised of tetrahedral Cr$^{6+}$ and octahedral Cr$^{4+}$ linkages,37 and as tetrahedral Cr$^{3+}$ and octahedral Cr$^{3+}$ linkages.35,36 Claims have also been made that Cr$_2$O$_3$ is a single valence Cr$^{5+}$ species.25 These discrepancies may be insoluble using XPS alone, but the presence of these compounds may be inferred from the presented spectra.

Since the presence of tetravalent chromium was ruled out, and the lowest binding energy peak in each spectrum was assigned as chromia, this has implications for the middle peak(s) in each spectrum. Peaks in the chromia multiplet splitting structure have been observed to span approximately 3 eV, but the two major peaks in the structure are located near 576–577 eV.38,39 Given these facts, the presence of a compound other than chromia or hexavalent chromium appears necessary. All of the spectra have significant peak contributions at binding energies exceeding the dominant multiplet components of chromia. This has implications for the middle peak(s) in each spectrum. The middle peak to a mixed valence species.

The possibility of Cr$_2$O$_3$ existing as a pentavalent species has not yet been addressed. This species existing as a single valence compound can be consistent with the arguments made up to this point. The middle peak(s) could still consist of a Cr$^{5+}$ multiplet split structure derived from the multiple valence Cr$^{3+}$/Cr$^{6+}$ compound in Cr$_2$O$_3$, but Cr$_3$O$_8$ would now consist of a multiplet split structure for Cr$^{2+}$. The authors of the XPS analysis of Cr$_2$O$_3$ referenced in the previous paragraph, however, compare the structures of Cr$_3$O$_8$ and KCr$_3$O$_8$ and they are nearly identical. Other authors claiming the presence of Cr$^{2+}$ using XPS reported a range from 577.5–577.8 eV.51,52 Liu et al. claimed to observe Cr$^{5+}$ surface species at 200°C in air, though the evidence presented does not preclude a mixed valence species in place of the claimed Cr$^{5+}$.

Okamoto et al. claimed to observe Cr$^{5+}$ in reducing conditions and based the assignment of Cr$^{5+}$ largely on spin orbit splitting values ($\Delta E$). The rational being that $\Delta E$ tends to increase with decreasing oxidation number due to the exchange interaction of 2p and unpaired 3d electrons.35,36 Contributions assigned as Cr$^{5+}$ were observed to have $\Delta E$ values near hexavalent, but binding energies nearer to trivalent. As previously discussed, Cr$^{2+}$ bound with Cr$^{6+}$ would increase the binding energy relative to a high purity Cr$^{2+}$ sample, and thus decrease $\Delta E$. The requisite effect would need to be on the order of tenths of an electron volt, which seems plausible. While the studies from Liu et al. and Okamoto et al. are the only XPS studies the authors could find claiming Cr$^{5+}$, other studies using different characterization techniques also report the presence of Cr$^{5+}$.50,52

Additional work is necessary not only to resolve the possible presence of Cr$^{5+}$, but also to support the inferred conclusions based on XPS evidence and scrutiny of relevant literature. Phase identification techniques such as X-ray diffraction, if surface sensitive enough, or electron backscatter diffraction if not, would serve to support or contest phase inferences made here of chromate, CrO$_3$, Cr$_2$O$_3$, Cr$_3$O$_8$, and Cr$_2$O$_3$.
and Cr₂O₃. Characterization techniques sensitive to oxidation state, such as X-ray absorption spectroscopy, may be used to test the claims of mixed valence 3+4+/6+, 4+4+/6+, or pentavalent. Ellison et al. used extended X-ray absorption fine structure and X-ray absorption near-edge structure spectra to examine chromium compounds on silica and did report a mixed valence Cr 3+4+/6+ oxide in the form of Cr₂O₃₆. But called for additional careful studies using these techniques. While some of the inferences made here are contested (concerning Cr₂O₅ and Cr₃O₈), others are strongly supported in literature. The presence of chromate species, CrO₃, Cr₂O₃, and Cr₃O₈, in addition to the linking of certain colors to these compounds are reliably supported.

There are implications for aluminosilicate materials given the proposed chromium speciation mechanism. As a material exposed to volatile chromium, as aluminosilicate insulation in a catalytic converter might be, high chromium loading and temperatures exceeding 200°C appear optimal for maximizing trivalent species over hexavalent. As a getter for chromium vapor, a minimum temperature of 150°C appears necessary for volatile chromium collection. How long aluminosilicate fiber would collect, and with what efficiency, if similar to quartz wool at 800°C20 or greater, is not known to the best knowledge of the authors. The dependence of volatile chromium deposition on temperature, exposure time, and material will be explored in future work.

Conclusions

Aluminosilicate fibers were exposed to chromium oxyhydroxide at 100–230°C for 150 hours. After exposure distinct regions of yellow, brown, and green staining were observed on the fibers. These regions were isolated and characterized using XPS. Examination of Cr 2p_{3/2} peaks revealed distinct Cr(VI) and Cr(III) multiplet-split behaviors for each stain color. The brown stain was observed to contain the most and highest shifted hexavalent peak which was attributed to CrO₃. The green stain was inferred to arise from formation of chromia, the lowest binding energy peak on all spectra. The yellow stain was attributed to anchored chromate, a hexavalent species observed to have a lower binding energy than the other hexavalent component (CrO₃). The middle peak(s) on all spectra were inferred to consist of Cr₃+ multiplet splitting components of a Cr⁴+/Cr⁵+ mixed valence species, though the presence of Cr⁴+ was not discounted. These inferences were made on the basis of color, binding energy, and comparison to literature. This work adds to the current understanding of how volatile chromium species interact with ceramics. This understanding may allow for optimized material selection of components which preferentially interact with volatile chromium species in systems susceptible to degradation by these species, such as SOFCs, or encourage less hazardous chromium species to form in systems which may impact human health and the environment.

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