Influence of the La$_6$W$_2$O$_{15}$ Phase on the Properties and Integrity of La$_{6-x}$WO$_{12-\delta}$–Based Membranes

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Abstract

The aim of the present work is to evaluate the influence of La$_6$W$_2$O$_{15}$ secondary phase on the properties and integrity of La$_{6-x}$WO$_{12-\delta}$–based membranes. Structural, microstructural and thermo–chemical study was carried out evidencing significant crystallographic and thermal expansion anisotropy: the reason for poor thermo–mechanical stability of La$_6$W$_2$O$_{15}$. Conductivity of La$_6$W$_2$O$_{15}$ was one to two orders of magnitude lower compared to the phase pure La$_{6-x}$WO$_{12-\delta}$ in the range of 300 to 900 °C. The relaxation study showed that the hydration process was faster for the La$_6$W$_2$O$_{15}$ compared to the LWO phase, due to the higher electronic contribution to the total conductivity. Short–term stability tests in H$_2$ at 900 °C and in a mixture of CO$_2$ and CH$_4$ at 750 °C were conducted and material remained stable. Remarkable reactivity with NiO and YSZ at elevated temperatures was further evidenced compared to the relative inert behavior towards MgO and CGO.

Keywords: La$_6$W$_2$O$_{15}$, La$_{6-x}$WO$_{12-\delta}$, mixed protonic–electronic conductor, dense ceramic membrane, hydrogen separation.

1. Introduction

H$_2$/CO$_2$–gas separation by means of dense ceramic membranes is an advanced approach to realize the Carbon Capture and Storage (CCS) concept in the pre–combustion power plants (Jordal et al. 2004, Fontaine et al. 2007, Czyperek et al. 2010) along with the production of H$_2$ with high purity for a number of applications, e.g. electricity production, mobile applications, chemical industry, etc. ((a) Norby et al. 2006). High temperature proton conducting membranes could be integrated in, for example, catalytic membrane reactors, for non–oxidative coupling of methane and aromatization (Li et al. 2002) making possible the improvement of the process selectivity and efficiency by means of the in–situ removal of hydrogen.

In order to be efficiently implemented in H$_2$–separation tasks, materials have to exhibit mixed protonic–electronic conductivity and significant mechanical and thermal stability (Meulenberg, Ivanova et al. 2011, (a) Ivanova et al. 2012). Ceramic materials of several structural classes exhibit protonic and

The state–of–the art oxides with perovskite structure (cerates and zirconates), especially their substituted forms, reveal the highest proton conductivity \((10^{-2} – 10^{-3} \text{ S}\cdot\text{cm}^{-1})\), which upon an appropriate substitution can be further modified and reach appreciable levels of mixed conductivity and, respectively, H₂–flux at moderate to elevated temperatures (Meulenberg, Ivanova et al. 2011, (a) Ivanova et al. 2012). Cerates, however, suffer from insufficient stability in reducing and CO₂– and H₂O–containing atmospheres, whereas zirconates demonstrate better stability, but lower protonic conductivity due to the high grain boundary resistances (Meulenberg, Ivanova et al. 2010).

A novel class of ceramic materials: the rare–earth tungstates, having a general formulae Ln₃WO₆₊₁.₅ₓ, with \(x \approx 6\) (further referred as LnWO) and ordered defect fluorite (or disordered pyrochlore) structure (Chang et al. 1964, Mc Carthy et al. 1972), is recently at the research focus as a potential candidate for high temperature H₂-separation from gas mixtures.

Early study of Yoshimura et al. (Yoshimura et al. 1975) reported the electrical conductivities measured in the range of 500 to 1500 °C. It was shown that solid solutions in the system CeO₂–La₂WO₁₂ exhibit predominantly electronic conductivity at high temperatures and ionic conductivity at low temperatures. No effects attributed to protons were considered and clarified in this study.

In 2001 Shimura et al. (Shimura et al. 2001) demonstrated that La₆₆₅ₓWO₁₁.₇ₓ (\(x \approx 6\), further referred as LWO) exhibits considerable proton conductivity under hydrogen–containing atmospheres. Proton conductivity of LWO–compound with stoichiometry La₆₆₅ₓWO₁₁.₇ₓ was about \(5 \times 10^{-3} \text{ S}\cdot\text{cm}^{-1}\) at 900 °C in wet H₂. The conductivity was also measured as a function of \(p₀₂\) at 900 °C in wet atmospheres and a wide \(p₀₂\)-independent region was observed meaning a broad ionic domain. At high \(p₀₂\) a small increase of the conductivity was observed with a slope smaller than \((1/4)\) or \((1/6)\), suggesting limited p–type contribution. In the low \(p₀₂\) regime, conductivity increases due to the n–type contribution, resulting from \(\text{W}^{6+}\)-reduction.

Mixed protonic–electronic conductivity of both nominal and partially substituted LnWO with Ln = La, Nd, Gd, Er was furthermore evidenced by Haugsrud ((b) Haugsrud 2007). A comparison between the ambipolar conductivities of undoped LWO and 5%–Yb–substituted SrCeO₃, which is a state–of–the art mixed protonic–electronic material, came to the conclusion that the undoped LWO has a potential as a membrane material for separation applications (Haugsrud 2008).

The feasibility of the rare–earth tungstates as membrane materials for H₂ separation, in terms of the H₂ flow through them, was supported theoretically \(^{34}\) based on the Wagner equation for H₂ flux (Eq. 1), where a membrane thickness of 10 µm and H₂ feed–side pressure of 10 atm were considered.

\[
j_{H^2}^′ = -\frac{RT}{2F^2} \cdot \frac{1}{E} \ln \frac{\rho_{\text{H}_2}^\prime}{\rho_{\text{H}_2}} \int \sigma_{\text{H},\text{H}_2} t_e d\ln p_{\text{H}_2} \tag{1}\]

Assuming that the H₂–transport through the membrane is dominated by the bulk diffusion mechanism, hydrogen permeation of about \(2 \text{ ml}\cdot\text{min}^{-1}\cdot\text{cm}^{-2}\) was calculated for LWO at 800 °C. This value was higher than values similarly calculated for SrCeO₃ and Er₆₆₅ₓWO₁₁.₇ₓ: \(1 \text{ ml}\cdot\text{min}^{-1}\cdot\text{cm}^{-2}\) and less than \(0.1 \text{ ml}\cdot\text{min}^{-1}\cdot\text{cm}^{-2}\), respectively.

across a Nd₅₋ₓWO₁₂₋ₓ membrane varies between 5·10⁻⁵ and 5·10⁻² ml·min⁻¹·cm⁻² measured at 1000 °C (depending on the feed composition, i.e., H₂ vol.% and H₂O vol.%) ((b) Escolástico et al. 2011), while flux of up to 0.1 ml·min⁻¹·cm⁻² was demonstrated for Laₓ₋₅WO₁₂₋ₓ membrane. By doping of Laₓ₋₅WO₁₂₋ₓ and Ndₓ₋₅WO₁₂₋ₓ using transition metals, it was possible to achieve flux values of above 0.3 ml·min⁻¹·cm⁻² at 1000 °C, which was the highest value reported for this class of materials.

In the chemical stability context, Shimura et al. (Shimura et al. 2001) commented that despite the transition nature of the W⁺⁺⁺–cations, Laₓ₋₅WO₁₁₋₇ is stable and no decomposition effects were detected after carrying out the electrochemical measurements in the range of 600 – 1000 °C.

According to (b) Haugsrud et al. (2007), the chemical stability of rare–earth tungstates is their major disadvantage in terms of application. LnWO may react with carbon–containing gases and form stable carbides and oxycarbides. Nevertheless, Escolástico et al. (Escolástico et al. 2009) demonstrated good short term stability at 700 and 800 °C for Ndₓ₋₅WO₁₂, which remained stable after exposure in both dry and humid gas flow consisting of 10 vol.% CO₂ and 90 vol.% CH₄ for 72 h.

Other issues might be related to the volatility of WO₆–species ((b) Haugsrud et al. 2007), which was considered as negligible in (Yoshimura et al. 1975), and to the high activity of La, possibly affecting the material stability against water vapor and CO₂. The evaporation of WO₆ from LnWO becomes, however, an issue at higher temperatures and long–term operation regimes. As a consequence of the WO₆–volatility, LWO phase equilibrium shifts to the La₂O₃–rich region of the phase diagrams, according to phase studies on the binary system La₂O₃–WO₃ (Ivanova et al. 1970, Yoshimura et al. 1976). The unreacted and highly hygroscopic La₂O₃ readily forms La(OH)₃ with the atmospheric moisture, that practically leads to pulverization of a dense sintered sample in several hours. Figure 1 (a) documented this effect: a LWO-specimen sintered at 1450 °C for 24 h has pulverized after exposure to atmospheric air for several hours. Such negative deviations from the equilibrium can be effectively restricted and controlled during the material synthesis by W–overstoichiometry as reported in (Magrasó et al. 2009, Serra et al. 2012, Seeger, Ivanova et al.: article in preparation). Phase pure LWO was synthesized in the range of nominal La:W ratios 5.2 ≤ x ≤ 5.7 (Magrasó et al. 2009). In spite of the minor experimental fluctuations falling out of this “single–phase” region, the most of the LWO–based materials prepared in our Labs (Seeger, Ivanova et al.: article in preparation) showed very good consistency with (Magrasó et al. 2009).

Another instability effect is observed, when the equilibrium is shifted to the WO₂–rich region of the phase diagram, resulting in formation of the secondary phase Laₓ₋₅W₁₂O₃₁₅, along with the main LWO phase. In order to prevent the possible sub–stoichiometry of Laₓ₋₅Oₓ, a proper pre–synthesis heat treatment of the Laₓ₋₅Oₓ used as a raw material is particularly important. The formation of Laₓ₋₅W₁₂O₃₁₅ was reported in the early studies on the binary system Laₓ₋₅–WO₃ (Ivanova et al. 1970, Yoshimura et al. 1976). Although these studies contain certain contradictions regarding to the LWO compound and its thermodynamic stability, which will not be discussed here, they all report the phase transitions of the Laₓ₋₅W₁₂O₃₁₅ phase with the temperature.

Based on the DTA measurements, two phase transitions were evidenced at 630 °C and 930 °C (α → 650 °C → β → 930 °C → γ), according to Ivanova et al. (Ivanova et al. 1970).

Reversible thermal delays, detected at 619 °C and 929 °C on heating and at 598 °C and 922 °C on cooling, were reported by Yoshimura et al. (Yoshimura et al. 1976).

Similarly, Chambrier et al. (Chambrier et al. 2010) registered two endothermic peaks at 615 °C and 944 °C on heating and two exothermic peaks at 586 °C and 918 °C on cooling, respectively. The high temperature X–Ray Diffraction (HT–XRD) study showed furthermore shifts in the phase transition temperatures (γ → β → α) compared to the early studies (Note 1).

Furthermore, the high temperature α–Laₓ₋₅W₁₂O₃₁₅ was an object of ab–initio computational study based on the in–situ HT–XRD and Neutron Powder Diffraction (NPD) data (Chambrier et al. 2010). A structural model of the α –polymorph was elaborated, according to which, the α –Laₓ₋₅W₁₂O₃₁₅ structure comprises both ordered and disordered groups and structural similarities were suggested for the two other polymorphs, β and γ, as well.

As observed in our Labs, the presence of the secondary phase Laₓ₋₅W₁₂O₃₁₅ in the LWO–bulk matrix was inevitably associated with an intensive crack formation that practically hinders the manufacturing of
gas–tight LWO–based membranes or other functional components. Figure 1 (b) shows a micrograph of a LWO bulk membrane, containing impurities of the secondary phase La$_6$W$_2$O$_{15}$. It can be clearly seen that the cracks are located in the areas identified as La$_6$W$_2$O$_{15}$, while the main LWO phase exhibits dense microstructure.

In the context of the discussed instability issues described in the literature and based on our practical experience with the LWO–based material, the present study on the functional characteristics of La$_6$W$_2$O$_{15}$ was strongly motivated to enlighten the overall influence of this secondary phase on the properties and integrity of the targeted LWO–based ceramics.

2. Experimental

2.1 Sample preparation

Powder of La$_6$W$_2$O$_{15}$ was synthesized of La$_2$O$_3$ (99.999%, Sigma–Aldrich, CAS 1312–81–8) and WO$_3$ (99.9%, Fluka) via the solid state reaction. Prior to weight, La$_2$O$_3$ was dried and decarbonated at 1000 °C for several hours. Stoichiometric amounts of the corresponding oxides were weighted, mixed and milled in ethanol. The resulting suspension was dried until complete ethanol evaporation. The synthesis took place in closed Pt crucibles at 1000 °C for 12 hours with heating and cooling ramps of 3 K·min$^{-1}$. The product of the solid state reaction was then wet milled in ethanol, dried and grinded in agate mortar. Thus obtained powder was used for chemical composition verification and structural investigations, as well as for carrying out the stability tests and the chemical compatibility experiments.

Powder samples used for the chemical compatibility tests were prepared by mixing of previously synthesized single phase La$_6$W$_2$O$_{15}$ powder with the oxides CGO (CeO$_2$ doped with 20 mol.% Gd$_2$O$_3$, Treibacher, Austria), YSZ (ZrO$_2$ doped with 8 mol.% Y$_2$O$_3$, UCM Advanced Ceramics, Germany), NiO (99.0% min., J.T. Baker, USA) or MgO (99.995%, Sigma Aldrich) in weight ratio of 1:1. After mixing in a mortar the resulting powders were heat treated for 12 hours at temperatures ranging from 800 °C to 1400 °C. The products were finally ground and phase composition was studied by means of the X–ray powder diffraction (XRD).

Pellets used for the microstructural studies, as well as for measuring the electrical conductivity vs $T$ and $p_{O_2}$, were prepared by the uni–axial pressing and sintered in air at 1400 °C for 12 hours with heating and cooling ramps of 2 K·min$^{-1}$. Sintered specimens with 21 mm diameter and 1.3 mm thickness were coated with platinum paste (Ferro GmbH) for the electrical measurements and additionally heat treated at 1000 °C/2 h and 1200 °C/2 h. Bar–shaped samples with dimensions of 40x4x1 mm$^3$ were used for the conductivity relaxation study. As electrodes, 4 Ag–wires were contacted to the bar by means of Ag–ink and consequently heat treated.

2.2 Characterization techniques

Stoichiometry of the synthesized La$_6$W$_2$O$_{15}$ powder was controlled via the ICP–OES (Inductively Coupled Plasma – Optical Emission Spectrometry). No deviations from the nominal chemical composition could be detected.

Phase composition and thermal stability of the compound prepared by the solid state reaction were investigated by room temperature and in–situ high–temperature XRD.

Room temperature measurements were carried out using a Bruker–AXS D4 powder diffractometer in Bragg–Brentano scattering geometry with Cu–Kα radiation. Patterns were acquired between 10° and 80° 2Theta with a stepwidth of 0.02° and a diffracted beam monochromator. The software package X'Pert HighScorePlus 3.0 (Panalytical B.V., the Netherlands) was used for phase identification (ICDD PDF2 Release 2004). Lattice parameters were refined applying Pawley and LeBail method (Bruker–AXS TOPAS 4.2), assuming an orthorhombic unit cell.

A D5000 X–ray diffractometer (Siemens, Germany) equipped with a HDK S1 high–temperature chamber (Buehler, Germany) and a diffracted beam monochromator was used to study the phase stability in air as a function of the temperature. Scans were taken in the Bragg angle range from 18° to 49° (Cu–Kα radiation), in which the relevant reflections of the studied phase were located. In order to achieve a homogenous thin dense
layer for this study, the powder was deposited onto a dc–heated Pt strip via sedimentation from ethanol slurry. HT–XRD scans were recorded in the temperature range from 100 to 1100 °C in steps of 50 °C and heating speed of 3 K·min⁻¹ between the temperature steps. 10 min delay time was applied before starting a scan at each temperature for achieving thermal and thermodynamic equilibrium. The same temperature program was realized in the cooling mode.

The microstructure of sintered samples was characterized by means of SEM and TEM. SEM was carried out using a FEI Helios Nanolab 400s and a Zeiss Ultra55 electron microscope. The TEM specimen preparation was performed by Focused–Ion Beam process (FIB, FEI Helios Nanolab 400s) with subsequent argon–ion milling. The TEM investigation was carried out by means of a FEI Tecnai G2 F20 instrument, operated with an acceleration voltage of 200 kV and equipped with an EDAX energy dispersive X–ray spectrometer. The total ac–electrical conductivity of La₆W₂O₁₅ was measured at fixed frequency (11.9 kHz) as a function of temperature and oxygen partial pressure (pO₂). Temperature dependence was studied in the range of 300 to 900 °C for 6 different atmospheres: both wet and dry Ar, (4%H₂–Ar) and synthetic air. Saturation of 2.5 vol. % H₂O was achieved by bubbling the gas through water at room temperature. For drying the gas, commercial molecular sieve was used as a desiccant. The pO₂ dependence of the conductivity was investigated at selected temperatures by mixing synthetic air and Ar under dry conditions by means of the ProGasMix™ (NorECs, Norway) (Norby 1988). The disc–shaped sample, initially contacted with Pt, was mounted in the ProboStat™ holder (NorECs, Norway) and 4 Pt–wires were connected pairwise to it. The conductivity was measured with the Alpha–A High Performance Frequency analyzer (Novocontrol Technologies GmbH, Germany) equipped with ZG4 test interface and controlled by the WinDeta software. Oscillation voltage of 0.4 Vrms was applied to the sample. The sample was heated to 900 °C with a ramp of 7.5 K·min⁻¹ in the corresponding atmosphere and it was held at this temperature for 8 h. Then the frequency sweeps were recorded in the range of 100 Hz to 10 MHz downwards to 300 °C with T–steps of 25 °C and holding time of 0.5 h at each temperature. A stray capacitance of 5 pF, originating from the measurement rig, was subtracted from the raw data. For seek of reproducibility, the measurements were repeated three times under the described experimental set of conditions, each time using a fresh sample, and the obtained results matched very well.

Conductivity relaxation experiments were performed using a 4–probe bar configuration by means of PSM 1735 with an IAI interface from Newtons4th Ltd. A 100 Hz constant frequency was selected in order to avoid electrode contributions to the resistance. Measurements were performed from 450 to 750 °C in air by switching from dry to wet (2.5 vol. % H₂O) conditions in a very fast step of ~5 s: time negligible with respect to the conductivity relaxation time (Solís et al. 2011). Monitoring was carried out by means of a Balzers mass spectrometer.

The chemical compatibility of La₆W₂O₁₅ with CGO, YSZ, NiO and MgO was studied by XRD using D4 ENDEAVOR diffractometer by Bruker AXS with Cu–Kα radiation. Patterns were recorded between 10° and 80° 2Theta with a stepwidth of 0.02°. The software package XPert HighScorePlus 3.0 (Panalytical B.V./Netherlands) has been used for phase identification (ICDD PDF2 Release 2004).

The chemical stability of La₆W₂O₁₅ against carbonation and reduction was tested in two short–term experiments. During the first test, 1 g of La₆W₂O₁₅ powder was exposed to the action of wet (2.5 vol.% H₂O) gas mixture consisting of 10 vol.% CO₂ and 90 vol.% CH₄ for 72h at 750 °C. The second test was carried out with 1 g of La₆W₂O₁₅ powder exposed to wet H₂ (2.5 vol.% H₂O) for 55 h at 900 °C. The post–treatment XRD analysis of the powder material was carried out by a PANalytical X’Pert PRO diffractometer, using Cu–Kα radiation and a X’Celerator detector in Bragg–Brentano geometry in order to detect changes in the crystal structure of the material or formation of new phases as a result of the exposure to the experimental conditions.

3. Results and discussion

3.1. Structural characterization

3.1.1. Phase analysis

Figure 2 shows a typical Bragg–Brentano scan of the La₆W₂O₁₅ powder manufactured by the solid state reaction at 1000 °C/12 h. A single phase material was formed. The absence of an amorphous background and
the clear sharp reflections with a narrow full width at half maximum (FWHM) indicate a high degree of crystallinity and lattice perfection. All reflections could be indexed as belonging to the orthorhombic $\gamma$–La$_6$W$_2$O$_{15}$ (PDF 99–000–0026). This result is in a good agreement with data reported at 40 °C by Chambrier et al. (Chambrier et al. 2010).

3.1.2. Structural transformations and microscopic thermal expansion coefficients

Figure 3 (a) is a pseudo–3D plot of the in–situ scans illustrating the structural changes that La$_6$W$_2$O$_{15}$ undergoes by heating from 100 °C to 1100 °C recorded in steps of 50 °C and in the 2Theta range of 18 – 37.5°. Figure 3 (b) displays the top view onto the stack of scans recorded in the temperature range from 400 to 1100 °C and back to 400 °C in the 2Theta range from 26.4° to 35.4°.

The thermo–diffraction study showed that the low temperature phase $\gamma$–La$_6$W$_2$O$_{15}$ undergoes structural changes with increasing temperature. Applying cluster analysis (i.e. analysis of similarity) to the recorded scans at 25 °C and in the studied range of 100 – 1100 °C, four temperature ranges with relatively stable scans could be determined: 25 – 150 °C ($S1$), 400 – 600 °C ($S2$), 650 – 800 °C ($S3$), and 900 – 1100 °C ($S4$), indicating the existence of four stable structures referred as $S1$ to $S4$.

Previously discussed structural transitions at about 600 °C ($S2$–to–$S3$) and 900 °C ($S3$–to–$S4$) correspond well to the earlier works (Ivanova et al. 1970, Chambrier et al. 2010). The transition from $S1$ to $S2$ over a metastable structure, existing in the temperature range of 150 – 400 °C, has no equivalent in the literature.

As seen from Figure 3, the reflections intensity does not change dramatically within the temperature ranges, indicated above. However, individual reflection groups do not behave equally with increasing temperature. Some of them shift towards the smaller Bragg angles, whereas others nearly do not change their positions or even move towards the larger Bragg angles. This different behaviour can be understood by an anisotropic thermal expansion of the unit cell. Each reflection represents a set of certain lattice planes. In dependence of their orientation in the unit cell, they reflect certain thermal expansion anisotropy. If a lattice plane distance increases with increasing temperature the corresponding reflection moves to lower Bragg angles, and vice versa.

Between the defined structural stability ranges, recorded reflections with strong intensity do not change considerably, while those with lower intensity disappear and later appear at different angle, indicating a partial atomic rearrangement. For example, the main peak of the reflection group at 34.5° shifts smoothly to the smaller Bragg angles, while the peak of higher intensity recorded at 28.7° remained unchanged with the temperature. We assume that the sublattices of heavy La$^{3+}$– and W$^{6+}$–ions (with corresponding strong intensity reflections) remain considerably stable, while oxygen and its rearrangements is responsible for the evidenced structural changes. The loss of oxygen with increasing temperature induces sublattice distortions and initiates structural transformations.

In Figure 3 (b), this anisotropic thermal expansion of the individual unit cells, together with the unit cell structure transformations, becomes very clear. While strong reflections exhibit rather smooth shifts (relatively stable sublattice(s) of heavy ions), low intensity reflections are shifted within the ranges of structural stability and change its position discontinuously in between.

In order to determine the microscopic thermal expansion coefficients, the most representative scan of each stability range were indexed using TOPAS 4.2 resulting in a space group and lattice parameters. These data were used in the next step to refine the lattice parameters of the unit cell by parametric Pawley refinement with TOPAS. Microscopic thermal expansion coefficients as a function of the crystallographic structure are presented in Figure 4. Results of the calculations are summarized in Table 1.

The orthorhombic symmetry remains in the entire temperature range. Between 700 and 850 °C the symmetry increases through face centring, which correlates with the maximum of microscopic thermal expansion coefficient due to the oxygen expelled from the lattice. The increased mobility of light species in the crystal lattice enables the geometric rearrangement of the heavier ones, as well.

Due to the identified structural changes and the pronounced thermal expansion anisotropy of the unit cell, the thermal treatment of La$_6$W$_2$O$_{15}$ usually results in an intensive crack formation, which cannot be controlled or

61
suppressed even by very slow heating and cooling rates. The structural transformations of this phase take place in the temperature range of membrane application. Therefore its presence in the LWO–membrane ought to be prevented.

3.2. Microstructural study

Figure 5 (a) presents a SEM micrograph of the unpolished surface of untreated La₆W₂O₁₅ sample, sintered at 1400 °C for 12h, while the micrographs in Figure 5 (b) and Figure 5 (c) show, respectively, the unpolished and polished surface of the sample after exposure to different gas environments, thermal cycles and voltage during the conductivity tests.

The as–sintered sample showed well shaped polygonal grains with an average size in the range from 3 to at least 10 µm. The low amount of isolated pores, which are randomly distributed, indicates optimal sintering. After exposing the sample to the conductivity test conditions for about 145 hours, followed by continuous thermal cycles in the range of 25 – 900 °C, particles a few µm in size can be observed, forming uneven surface (Figure 5 (b)).

Additionally, there is a number of cracks visible in Figure 5. The high crack density suggests strong thermo–mechanical stresses due to the polymorphism, which are especially intensive after the conductivity measurements (Figure 5 (c)).

The TEM study was carried out on cross sections of La₆W₂O₁₅ samples before (Figure 6 (a)) and after (Figure 6 (b) and (c)) the conductivity measurements, aiming to collect further evidence on the microstructural and functional degradation of the material. The sample surface was covered by protection layers added during the TEM–specimen preparation procedure. The cover layers are indicated on the micrographs.

As it can be seen from Figure 6 (a–c), clear difference in the surface (beneath the cover layers) quality before and after the tests can be observed, attributed to the microstructure degradation due to material operation under the respective test conditions.

In Figure 6 (a) crystal grains and cracks are clearly visible in the as–sintered specimen and no secondary phase was evidenced by the EDX. On the contrary, islands of precipitates can be observed on the treated sample surface, shown in Figure 6 (b), whereas the bulk remained unchanged. The area, indicated with a white rectangle in Figure 6 (b), is shown at higher magnification in Figure 6 (c), revealing a precipitate with inhomogeneous contrast.

The chemical composition at these degraded surface locations (the area in Figure 6 (c) marked with white circle) was analyzed by the EDX and the corresponding spectrum is shown in Figure 7 (a). For comparison, the EDX spectrum of the as–sintered bulk material is shown in Figure 7 (b).

Cu–lines in both spectra originate from the supporting net. The surface particles showed chemical composition corresponding to the following stoichiometry: La (20 at.%), Fe (10 at.%), O (65–70 at.%). Traces of sulphur of less than 2 % were found, as well. The elemental distribution in these particles is inhomogeneous, that makes difficult to ascertain a specific occurred phase.

The reason for the presence of iron in such an amount remains, however, unclear. In any case, it cannot be attributed to the raw materials quality. The impurities contained in the raw materials were analyzed by means of the LA–ICP–MS (Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry) carried out by Agilent 7500ce at the Central Department of Chemical Analysis of the Research Centre Jülich. Iron in a concentration less than 77 ppm was detected for example in the WO₃, which oxide has lower purity than the La₂O₃. This amount is, however, much below the detected quantity in the post–treated sample, which is about 125 300 ppm.

3.3. Electrical conductivity study

3.3.1. Total conductivity as a function of temperature and gas environments
The total conductivity of La$_6$W$_2$O$_{15}$, measured as a function of temperature in (a) dry air and air saturated with H$_2$O, (b) dry Ar and Ar saturated with H$_2$O and (c) dry mixture of 4% H$_2$ in Ar and when saturated with H$_2$O, is presented in Figure 8.

Two major trends were highlighted by these results and are discussed respectively here.

- **Conductivity–defects concentration correlation**

The total conductivity is higher in wet compared to dry atmospheres at low to intermediate temperatures (300 – 650 °C) as seen from Figure 8. This effect can be assigned to the material hydration, meaning that the protons contribute significantly to the total conductivity in the mentioned range. Figure S1 from the supporting section illustrates furthermore the predominant protonic contribution in the discussed temperature range. By comparing the conductivity data obtained for O$_2$ saturated with H$_2$O and D$_2$O, a clear isotope effect, which lays within the theoretical value for the ratio $\sigma$(H$_2$O)/$\sigma$(D$_2$O), can be observed to about 630 °C (the temperature of the $\gamma$–to–$\beta$ phase transition).

The most pronounced protonation effect at low temperatures was observed in Ar–atmosphere and it corresponds to a conductivity increase of at least one order of magnitude upon saturation with water. The conductivity becomes independent on water vapor pressure with further increase in the temperature and this trend holds true for all three atmospheres. In Ar, the difference in conductivity between dry and wet atmospheres vanishes at about 750–800 °C, whereas in air and 4% H$_2$ in Ar this effect can be observed at about 650 °C and 600 °C, respectively. The proton concentration decreases with increasing the temperature due to the exothermic nature of oxide hydration. However, the observed difference in the dehydration temperature as a function of the environment can be assigned to the proton defects concentration, which affects the dehydration temperature. This implies that the proton defects concentration decreases as the environment changes from wet Ar to wet air and, finally, to wet mixture of 4% H$_2$ in Ar, which is satisfied by the defect chemistry prediction. The electroneutrality condition in wet air or H$_2$–containing inert gas can be expressed as $[h^*]+[\text{OH}^-]=[e']$, meaning that in such conditions electron holes and the proton defects are charge compensating for defect electrons. In the case of Ar–atmosphere, saturated with H$_2$O, the electroneutrality requires that the condition $[2v^-]+[\text{OH}^-]=[e']$ is fulfilled. However, the oxygen vacancies are additionally hydrated that would increase the concentration of proton defects incorporated in the lattice.

Figure 9 shows the total conductivity of La$_6$W$_2$O$_{15}$ measured as a function of the oxygen partial pressure in a log–log plot under dry conditions at various temperatures.

The following equations in Kröger–Vink notations describe the two boundary conditions:

**Dry oxidizing conditions:**

$$\frac{1}{2}O_{2\text{(gas)}} + v^-_O \rightarrow O^+_O + 2h^* \quad (2a)$$

$$K_p = \frac{[O^+_O][h^*]^2}{[v^-_O]P_{O_2}^{1/2}} \quad (2b)$$

$$[h^*] \propto (p_{O_2})^{1/4} \quad (2c)$$

**Dry reducing conditions:**

$$O^+_O \rightarrow v^-_O + 2e^+ + \frac{1}{2}O_2 \quad (3a)$$

$$K_n = \frac{[v^-_O][e^+]^2 p_{O_2}^{1/2}}{[O^+_O]} \quad (3b)$$

$$[e^+] \propto (p_{O_2})^{-1/4} \quad (3c)$$
The obtained experimental results, plotted in Figure 9, are in a good agreement with the defect chemical model, according to which La₆W₂O₁₅ exhibits conductivity of n-type, when exposed to low $p_{O2}$ – environments (Eq. 3). The observed dependence holds true within the whole temperature range and the slope of ($\sigma$) is a clear indication for that. Although the slope deviates from the predicted value at lower temperatures (300 °C), the conductivity of La₆W₂O₁₅ is not entirely independent on the $p_{O2}$, meaning that La₆W₂O₁₅ is essentially a mixed electronic–ionic conductor in dry atmospheres and in the tested range of $p_{O2}$. In oxidizing conditions, the electron holes also start to contribute to the conductivity (Eq. 2). However, this effect is less pronounced for the corresponding set of experimental conditions.

The relatively low activation energies for conductivity obtained in the temperature range 300 – 600 °C (see Figure 8 and Figure S2), might be assigned to the electronic conductivity under dry conditions (0.10 – 0.15 eV), as shown in Figure 9, and to the protonic or mixed protonic–electronic conductivity under wet conditions (0.15 – 0.20 eV), as defined by the defect–chemical model regarded above and supported by the experimental data in Figure 8, respectively. Furthermore, considering the significant contribution of the oxygen ions at elevated temperatures, the higher activation energies above 600 °C (to about 0.85 eV for dry atmospheres) might be referred to the oxygen ion mobility, which is normally assigned to the high activation enthalpies. Nevertheless, it is difficult to ascertain the relative contributions of different charge carriers with reaction conditions, but possibly expected pressure dependencies might be deduced for given electroneutrality conditions. In any case, no pronounced differences in the activation energies with the tested gas conditions were found for the two temperature ranges (300 – 600 °C and 600 – 900 °C) of consideration. Therefore, apart from the defect thermodynamics, another aspect related to the structural features of the material and the local arrangements in vicinity to the incorporated protons may come into play, when data are interpreted.

- Conductivity–structure correlation

As seen in Figure 8, and additionally Figure S1, the conductivity does not follow the typical Arrhenius behavior $\log (\sigma) \propto 1/T$ over the entire range of temperatures. Two linear ranges may be recognized with transition temperature of about 600 °C and regardless to the experimental gas atmosphere. This behavior can be ascribed both to i) the change in the dominant charge carrier concentrations and respectively, the conduction mechanism, as a function of the temperature and ii) the phase transition that takes place at nearly the same temperature, as shown in the structural part of the present paper and previously described in (Ivanova et al. 1970, Yoshimura et al. 1976, Chambrier et al. 2010). The second phase transition, which takes place at temperatures higher than 900 °C and leads to the high–temperature $\alpha$ –polymorph, cannot be visualized in the present conductivity plots due to the limitation in the temperature range.

As previously discussed, the gradual de–protonation of the oxide with the temperature, which was evidenced by decreasing proton conductivity, and the dominant role of the oxygen ions and electrons at higher temperatures, as evidenced by the higher thermal activation, are reflected by point i). The fact that the activation energies for conductivity in all dry atmospheres have very close values, and the same holds true for the set of measurements carried out in wet atmospheres, supports this observation.

The second point ii) reflects the fact that the conductivities measured in the lower temperature range and associated with relatively low activation energies (0.10 – 0.20 eV) correspond to the low temperature polymorph, referred as the $\gamma$ –form. Consecutively, the upper temperature range corresponds to the $\beta$–La₆W₂O₁₅ and related conductivities are associated with higher activation energies (0.55 – 0.85 eV).

As discussed by Kreuer (Kreuer 2003), in the light of the hydrogen bond thermodynamics, an activation enthalpy of long–range diffusion of not more than 0.15 eV might be expected (that suggests linear configuration O–H…O, as well as O–O separation less than ~2.5 Å). The data obtained in the present study for wet or H₂–containing atmospheres in the lower temperature range (300 – 600 °C) are therefore in a good agreement with the considered literature data. Activation enthalpies for proton mobility ranging from 0.4 to 0.6 eV were determined for the cubic perovskites due to the contribution of other complex interactions not discussed here.

Furthermore, according to (Chambrier et al. 2010), the proposed structural model for the high temperature $\alpha$ –form, usually existing above 900 °C, can be adopted by the two other polymorphs based on similarity.
Therefore, the present conductivity data are regarded in terms of the structural features of the only studied and modeled $\alpha$–form.

As the structural model describes, the $\alpha$–structure comprises ordered [La–O]–motifs, forming double ribbons (La$_2$O)$_3$, as well as disordered [WO$_3$]–tetrahedra, leading to [La$_2$O$_3$][WO$_3$]$_2$ as a general formula of the compound. Furthermore, the La–O interatomic bond distances range from ~2.3 to ~3 Å and are larger than the W–O distances (ca. 1.7 – 1.9 Å). The [W$_2$O$_{15}$]–unit must fit in one crystallographic site, thus implying disorder and possible origin of the phase transition, while at lower temperatures non–equivalent W–atomic positions may be adopted leading to ordering of the structure. Furthermore, the [W$_2$O$_{15}$]–entity is formed by two corner–sharing [WO$_6$]–octahedra with a distance between the two W–atoms equal to 4.13 Å. However, when the distance $d$(W–W) increases, disorder is induced, as in the case of the [WO$_3$]$_2$–units having $d$(W–W) of 5.55 Å (Chambrier et al. 2010).

In the light of the findings for the cubic perovskites (Kreuer 1999, Kreuer 2003), and for the $\alpha$–polymorph (Chambrier et al. 2010), we propose that 1) the protons, incorporated in the crystal lattice, are preferentially allocated in proximity to the [W–O] structural units, thus affecting the W–W distance and possibly inducing ordering; and 2) the proton mobility paths are allocated in the vicinity of the W–atoms due to the shorter W–O distance. In this context, it is remarkable that the activation energy change is less abrupt when water is present in the surrounding atmosphere (Figure S3 (b)). This effect can be eventually assigned to the local structural re–arrangement or relaxations, introduced by the protonation of the oxide. The incorporation of protons could possibly “stabilize” the [W–O] structural motifs and the sharp $\gamma$– to $\beta$–polymorph transition might be affected indeed. With increasing temperature the structure dehydrates, but this process has a gradual character, therefore the break around the temperature of polymorph transition is not as sharp as in dry atmospheres. However, these suggestions will need further experimental support by e.g. HT–XRD studies in wet atmosphere to elucidate the role of water on the structure and polymorphism of La$_6$W$_2$O$_{15}$, as well as atomistic modeling to clarify the proton positions and the proton mobility paths.

3.3.2. Conductivity relation between La$_6$W$_2$O$_{15}$ and La$_{6.4}$WO$_{12.8}$

The total ac–conductivity of La$_6$W$_2$O$_{15}$ was compared to that of LWO, both measured as a function of the inverse temperature in different atmospheres (Figure 10). This comparison aims to illustrate the influence of the orthorhombic La$_6$W$_2$O$_{15}$ phase on the electrical properties of the LWO main phase. The frequency value was fixed at about 12 kHz for giving an insight into the bulk conductivity of the two materials.

As it can be inferred from the figure, the two tested materials exhibit close conductivity values at 900 °C. Nevertheless, in the low to intermediate temperature range (300 – 650 °C), the observed difference in the conductivities became larger and extends over two orders of magnitude, with higher values measured for the LWO compound.

Therefore, it can be concluded that the presence of the La$_6$W$_2$O$_{15}$ compound as a secondary phase in the LWO–based membranes or components will affect negatively the overall electrical conductivity, apart from the microstructural and thermal drawbacks, as discussed in the previous sections.

3.3.3. Conductivity relaxation study

The oxidation and hydration kinetics have been studied by conductivity relaxation upon stepwise changes in the oxygen or water vapour activities, aiming to analyze diffusion ($D$) and surface exchange coefficients ($K$) of La$_6$W$_2$O$_{15}$ in a hydration process. A number of proton conductors such as SrCo$_{0.95}$Yb$_{0.05}$O$_{2.975}$ (Yoo et al. 2008), doped SrZrO$_3$ (Kudo et al. 2008), doped BaTiO$_3$ (Song et al. 2000) and LWO (Solís et al. 2011) were similarly studied.

Figure 11 (a) shows the dc–conductivity at 450 °C as a function of time upon a change from dry to wet air. It can be observed that the conductivity increases, when the atmosphere is humidified, due to the protonic transport and it follows a single–fold monotonic behavior with one diffusion coefficient.

A similar behavior, ascribed to the ambipolar water diffusion, was reported for La$_{5.5}$WO$_{12.5}$ compound (Solís et al. 2011). The obtained curve can be fitted to the analytic solution of Fick’s second law. For a rectangular
bar \((2l_x \times 2l_y \times 2l_z)\) it can be described with Eq. 4, according to (Song \textit{et al.} 1999, Søgaard \textit{et al.} 2007), where \(\sigma\) is the total conductivity as a function of time, \(\sigma_0\) and \(\sigma_\infty\) are the conductivities at time zero and infinitum, respectively.

\[
\frac{\sigma - \sigma_0}{\sigma_\infty - \sigma_0} = 1 - \sum_{n=1}^{\infty} \beta_{n,x}^2 \left( \frac{2L_x^2}{l_x^2} \right)^{\beta_{n,x}} \exp \left( \frac{-\beta_{n,x}^2 DT}{l_x^2} \right) \sum_{n=1}^{\infty} \beta_{n,y}^2 \left( \frac{2L_y^2}{l_y^2} \right)^{\beta_{n,y}} \exp \left( \frac{-\beta_{n,y}^2 DT}{l_y^2} \right) \]

\[
\exp \left( \frac{-\beta_{n,z}^2 DT}{l_z^2} \right) \sum_{n=1}^{\infty} \beta_{n,z}^2 \left( \frac{2L_z^2}{l_z^2} \right)^{\beta_{n,z}} \exp \left( \frac{-\beta_{n,z}^2 DT}{l_z^2} \right)
\]

(4)

Coefficients \(D\) and \(k\) obtained from the fitting of the hydration transients from 450 to 750 °C are shown in Figure 11 (b) as a function of the inverse temperature. It can be observed that the diffusion coefficients in air are in the range \(4 \times 10^{-4} \text{–} 7 \times 10^{-4} \text{ cm}^2 \text{ s}^{-1}\) from 450 to 750 °C, which has similar magnitude as the coefficients previously reported for other proton conductors (Yoo \textit{et al.} 2009). Surface exchange coefficients range between \(1 \times 10^{-2} \text{–} 2 \times 10^{-2} \text{ cm} \text{ s}^{-1}\) and these values are similar to other oxygen ion conductors (Preis \textit{et al.} 2004).

Furthermore, a possible change in the activation energy of \(D\) at around 650 °C (not observed for \(k\)) can be associated with the structural change around that temperature. This fact evidences unambiguously the direct impact of the phase transition on the ionic transport (Solís \textit{et al.} 2011). Moreover, activation energies for diffusion in the range of 0.55 – 1.59 eV are very similar to those, reported previously for oxygen and oxygen vacancies (Kreuer \textit{et al.} 1994).

Consequently, together with the single–fold monotonic behavior of relaxation, the two coefficients, \(k\) and \(D\), reflect migration of charge carriers not related with protons/deuterons, e.g. oxygen vacancies/oxygen ions through the polycrystalline oxide. Furthermore, the hydration process in La\(_6\)W\(_2\)O\(_{15}\) phase was found to be faster compared to the LWO phase (Solís \textit{et al.} 2011), possibly due to the higher electronic contribution to the total conductivity of La\(_6\)W\(_2\)O\(_{15}\).

3.4. Chemical compatibility of La\(_6\)W\(_2\)O\(_{15}\) with conventional substrate materials

In terms of several industrial applications, a better membrane performance can be achieved when the membrane thickness is decreased, usually by fabrication of functional layer on a suitable porous substrate. Therefore, the chemical compatibility of the La\(_6\)W\(_2\)O\(_{15}\) with substrate materials was tested.

Materials selected for the compatibility experiment were NiO, YSZ and CGO used in the conventional SOFC technology, in addition to the MgO as a possible substrate solution in the manufacturing of supported membranes for gas separation. Table 2 summarizes the conditions and products of the corresponding reactions. Diffraction patterns of the reaction products of La\(_6\)W\(_2\)O\(_{15}\) with a) CGO; b) YSZ; c) NiO and d) MgO at 800 °C/12h and 1400 °C/12h are presented in Figure S4.

Results clearly showed that the La\(_6\)W\(_2\)O\(_{15}\) did not form any reaction products with CGO and MgO within the whole tested temperature range, as well as with YSZ at 800 °C and 1000 °C. At 1400 °C, La\(_6\)W\(_2\)O\(_{15}\) and YSZ form a pyrochlore-structured compound La\(_2\)Zr\(_2\)O\(_7\) (PDF 01–071–2363), as well as La\(_8\)W\(_2\)O\(_{19}\) (PDF 00–034–0704) (Ivanova \textit{et al.} 1970, Yoshimura \textit{et al.} 1976, Marrero–Lopez \textit{et al.} 2008). With NiO there was no reaction detected at 800 °C, whereas at \(T \geq 1000 \text{ °C}\), the orthorhombic phase LaNi\(_0.8\)W\(_0.2\)O\(_3\) (PDF 01–086–1178) was formed. Similar reaction products and temperatures were reported for Nd\(_6\)WO\(_{12}\) (NdWO) (Escolástico \textit{et al.} 2009). A recent study on the compatibility of LWO with the same substrate materials carried out in our Labs (Seeger, Ivanova \textit{et al.:} article in preparation) evidenced identical reactivity issues. Therefore, when present as a secondary phase in the LWO–based membrane, La\(_6\)W\(_2\)O\(_{15}\) will not affect considerably the chemical compatibility of LWO with the tested variety of substrate materials.
3.5. Chemical stability of the $\text{La}_6\text{WO}_{15}$ compound in reducing atmospheres

$\text{H}_2$–separating dense ceramic membranes need to exhibit significant chemical stability at elevated temperatures, especially in humid reducing atmospheres and $\text{CO}_2$–rich environment. Certain membrane materials, e.g. cerate–based, suffer from insufficient stability induced by carbonation, hydroxide formation, and reduction when exposed to the above mentioned conditions, leading to mechanical and functional degradation.

In order to estimate the short–term chemical stability of $\text{La}_6\text{WO}_{15}$ and its influence on the LWO–based membrane, tests were carried out in: (1) wet (2.5 vol.% $\text{H}_2\text{O}$) gas flow of 10% $\text{CO}_2$ in $\text{CH}_4$ at 750 °C for 72 h, and (2) wet (2.5 vol.% $\text{H}_2\text{O}$) flow of 100 vol.% $\text{H}_2$ at 900 °C for 55 h. These environments were selected to simulate the conditions of $\text{H}_2$/CO$_2$ separation using a dense ceramic membrane. With respect to the carbonation test, temperature of 750 °C is high enough for carbonation evolution, but below carbonate decomposition (Jeavanadam et al. 2001, Escolástico et al. 2009).

Figure 12 displays the XRD patterns of $\text{La}_6\text{WO}_{15}$ recorded for a fresh sample after sintering and for samples exposed to the two corresponding sets of experimental conditions.

It can be clearly observed from the figure that no new phases appear. This result demonstrates that $\text{La}_6\text{WO}_{15}$ remains stable to carbonation and reduction in the selected experimental window by analogy to NdWO (Escolástico et al. 2009) and LWO (Seeger, Ivanova et al.: article in preparation). Therefore, it may be concluded that the stability of LWO–based membrane will not be affected by instabilities of the $\text{La}_6\text{WO}_{15}$ secondary phase under the considered conditions.

4. Conclusion

Single phase $\text{La}_6\text{WO}_{15}$ material was synthesized via the conventional solid state route from stoichiometric amounts of constituent oxides. Investigation on the crystal lattice structure over the temperature was carried out in the range from room temperature up to 1100 °C both in a heating and cooling mode. Four stable structures were detected in the studied temperature range, one having no analogue in the literature. These structural transformations were found to be associated with strong variations in the microscopic thermal expansion coefficients. As a result, internal tensions are accumulated in the material, leading to cracked microstructure, as evidenced by the electron microscopy. Apart from the negative microstructural influence, the presence of $\text{La}_6\text{WO}_{15}$ was identified as disadvantageous also for the electrical properties of LWO membrane. The conductivity measurements performed for $\text{La}_6\text{WO}_{15}$ and LWO at similar experimental conditions showed that the electrical conductivity of $\text{La}_6\text{WO}_{15}$ was several orders of magnitude lower than that of the LWO, especially in the low to intermediate temperature range. The secondary phase exhibits proton conductivity in humid atmospheres as evidenced by the electrical characterization and conductivity relaxation study, while at low $p_{\text{O}_2}$ electronic and mixed conductivity dominates. Surface exchange and diffusion coefficients have been determined by means of conductivity relaxation study, showing that the hydration of the $\text{La}_6\text{WO}_{15}$ phase is faster than in the LWO phase. The presence of the $\text{La}_6\text{WO}_{15}$ is not expected to affect the chemical compatibility of LWO with various standard substrate materials due to the similarities in the reaction behaviour of the two compounds. $\text{La}_6\text{WO}_{15}$ demonstrated short term stability against carbonation and reduction when exposed to simulated $\text{H}_2$/CO$_2$ separation conditions, hence the stability of LWO–membrane under similar conditions will not be affected by the secondary phase $\text{La}_6\text{WO}_{15}$.

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Eurenius, K.E.J.; Ahlberg, E.; Ahmed, I.; Eriksson, S.G.; Knee, C.S. (2010). Investigation of proton conductivity in Sm$_{1.92}$Ca$_{0.08}$Ti$_2$O$_{7-δ}$ and Sm$_2$Ti$_1.92$Y$_{0.08}$O$_{7-δ}$ pyrochlores. Solid State Ionics 181, 148–153.


**Notes**

Note 1. Note that according to Ivanova *et al.* (Ivanova *et al.* 1970) the high temperature phase was referred as “γ”, whereas Chambrier *et al.* (Chambrier *et al.* 2010) refers to it as “α”. In the present work the notation according to Chambrier *et al.* was used.

Note 2. Crystal lattice parameters, given in Table 1, correspond to the underlined value of temperature.
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Table 1. Space groups, lattice parameters and thermal expansion coefficients (TECs) determined for \( \text{La}_6\text{W}_2\text{O}_{15} \) from the HT–XRD study.

<table>
<thead>
<tr>
<th></th>
<th>Structure 1 (S1)</th>
<th>Structure 2 (S2)</th>
<th>Structure 3 (S3)</th>
<th>Structure 4 (S4)</th>
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<tr>
<td>Temp. range:</td>
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<td>400–600 °C</td>
<td>650 (700)–800 °C</td>
<td>900 (950)–1100 °C</td>
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<td>Space group:</td>
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<td>C2221</td>
<td>F222</td>
<td>C2221</td>
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<tr>
<td>Lattice parameters</td>
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<td></td>
</tr>
<tr>
<td>( a_0 ) (Å)</td>
<td>17.881(2)</td>
<td>17.927(2)</td>
<td>25.441(1)</td>
<td>12.642(1)</td>
</tr>
<tr>
<td>( b_0 ) (Å)</td>
<td>25.483(3)</td>
<td>25.375(1)</td>
<td>18.251 (1)</td>
<td>9.219(1)</td>
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<tr>
<td>( c_0 ) (Å)</td>
<td>35.665(4)</td>
<td>35.817(2)</td>
<td>11.766(1)</td>
<td>5.992(1)</td>
</tr>
<tr>
<td>TEC</td>
<td></td>
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<td></td>
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<tr>
<td>( \alpha_a ) ( \times 10^5 \cdot \text{K}^{-1} )</td>
<td>5.0</td>
<td>17.2(7)</td>
<td>-3.9(3)</td>
<td>-9.3(3)</td>
</tr>
<tr>
<td>( \alpha_b ) ( \times 10^5 \cdot \text{K}^{-1} )</td>
<td>14.0</td>
<td>11.8</td>
<td>18.6(3)</td>
<td>18.7(3)</td>
</tr>
<tr>
<td>( \alpha_c ) ( \times 10^5 \cdot \text{K}^{-1} )</td>
<td>12.5</td>
<td>12.2(5)</td>
<td>46.0(3)</td>
<td>34.4(3)</td>
</tr>
<tr>
<td>( \alpha_{\text{average}} ) ( \times 10^5 \cdot \text{K}^{-1} )</td>
<td>10.5</td>
<td>13.7</td>
<td>20.4</td>
<td>14.6</td>
</tr>
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</table>

Table 2. Conditions and products of the chemical reactivity of \( \text{La}_6\text{W}_2\text{O}_{15} \) with CGO, YSZ, NiO and MgO used as substrate materials in the supported membrane manufacturing.

<table>
<thead>
<tr>
<th>Powder mixture</th>
<th>Heat treatment</th>
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</thead>
<tbody>
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<td>800 °C, 12 h</td>
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<tr>
<td>( \text{La}_6\text{W}<em>2\text{O}</em>{15} ) + CGO</td>
<td>No reaction</td>
</tr>
<tr>
<td>( \text{La}_6\text{W}<em>2\text{O}</em>{15} ) + YSZ</td>
<td>No reaction</td>
</tr>
<tr>
<td>( \text{La}_6\text{W}<em>2\text{O}</em>{15} ) + NiO</td>
<td>No reaction</td>
</tr>
<tr>
<td>( \text{La}_6\text{W}<em>2\text{O}</em>{15} ) + MgO</td>
<td>No reaction</td>
</tr>
</tbody>
</table>
Figure 1. (a) Photograph of LWO bars sintered at 1450 °C for 24 h in air. The pulverization of the specimen was observed after several hours in atmospheric air due to the free La₂O₃ contained as a secondary phase; (b) Micrograph of a LWO membrane sintered at 1450 °C for 24 h in air. The cracks are located in the bright phase, identified via the EDX as the secondary phase La₆W₂O₁₅.

Figure 2. Diffraction pattern of La₆W₂O₁₅ powder after the solid state synthesis at 1000 °C/12h in air.
Figure 3. Thermo–diffraction patterns for La₆W₂O₁₅ recorded in: (a) a heating mode in the temperature range of 100 – 1100 °C and 2 Theta range from 18° to 37.5° as stacked patterns; and (b) in a heating and cooling mode in the temperature range of 400 – 1100 °C and 2 Theta range from 26.4° to 35.4°.

Figure 4. Microscopic thermal expansion coefficients in the three spatial directions (αₐ, αₐ, αₐ) and the average value αₐavrg for La₆W₂O₁₅ determined from the HT–XRD study.
Figure 5. Microstructure of La$_6$W$_2$O$_{15}$. SEM images of (a) as sintered specimen; (b) unpolished surface after conductivity measurements and (c) polished surface after conductivity measurements.

Figure 6. TEM bright–field micrographs of La$_6$W$_2$O$_{15}$ show specimen cross–sections. The sample was investigated before (a) and after conductivity measurements (b). Area indicated with a white rectangle in (b) is shown at higher magnification in (c). The white circle marks the region at which the EDX measurements were performed.
Figure 7. EDX spectra taken at the surface precipitate (a) (cf. Fig. 6 (c)) and the bulk (b) of the La\textsubscript{6}W\textsubscript{2}O\textsubscript{15} sample after conductivity measurements.

Figure 8. Total electrical conductivity of La\textsubscript{6}W\textsubscript{2}O\textsubscript{15} measured as a function of the inverse temperature at fixed frequency (11.9 kHz) under wet and dry a) synthetic air; b) Ar; c) mixture of 4% H\textsubscript{2} in Ar.
Figure 9. Total electrical conductivity of the La$_6$W$_2$O$_{15}$ at 11.9 kHz as a function of $p_{O_2}$ in dry atmosphere.

Figure 10. Total electrical conductivities of La$_6$W$_2$O$_{15}$ (a) and LWO (b) as a function of the inverse temperature at 11.9 kHz under wet and dry conditions in different atmospheres (synthetic air, Ar and mixtures of 4% H$_2$ in Ar).
Figure 11. (a) $dc$–conductivity of La$_6$W$_2$O$_{15}$ at 450 °C as a function of time when the atmosphere is switched from dry air ($p_{O_2} = 0.21$ atm) to wet air ($p_{H_2O} = 0.025$ atm, $p_{O_2} = 0.21$ atm); (b) surface exchange coefficient ($k$) and diffusion coefficient ($D$) for hydration process plotted as a function of the temperature.

Figure 12. Diffraction patterns of La$_6$W$_2$O$_{15}$ before and after exposure to the carbonation test at 750 °C for 72 h and the reduction test at 900 °C for 55 h.
Figure S1. Total electrical conductivity of La$_6$W$_2$O$_{15}$ measured as a function of the inverse temperature at fixed frequency of 100 Hz in dry O$_2$ and in O$_2$ moisturized with 2.5 vol. % H$_2$O and 2.5 vol. % D$_2$O.
Figure S2. Activation energies for the total conductivity of La$_6$W$_2$O$_{15}$ in different wet and dry atmospheres.
Figure S3. Total electrical conductivity of La$_6$W$_2$O$_{15}$ measured as a function of the inverse temperature at fixed frequency of 11.9 kHz in dry (a) and wet (b) conditions.
Figure S4. Diffraction patterns of the reaction product(s) of La$_6$W$_2$O$_{15}$ with a) CGO; b) YSZ; c) NiO; d) MgO at 800 °C/12h and 1400 °C/12h.