Long-term heat-storage ceramics absorbing thermal energy from hot water

Yoshitaka Nakamura1,* , Yuki Sakai2,3 , Masaki Azuma2,3 , Shin-ichi Ohkoshi4,*

In thermal and nuclear power plants, 70% of the generated thermal energy is lost as waste heat. The temperature of the waste heat is below the boiling temperature of water. Here, we show a long-term heat-storage material that absorbs heat energy at warm temperatures from 38°C (311 K) to 67°C (340 K). This unique series of material is composed of scandium-substituted lambda-trititanium-pentoxide (\(\lambda\)-Sc\(_x\)Ti\(_3\)O\(_5\)). \(\lambda\)-Sc\(_{0.09}\)Ti\(_{2.91}\)O\(_5\) not only accumulates heat energy from hot water but also could release the accumulated heat energy by the application of pressure. \(\lambda\)-Sc\(_{0.09}\)Ti\(_{2.91}\)O\(_5\) has the potential to accumulate heat energy of hot water generated in thermal and nuclear power plants and to recycle the accumulated heat energy on demand by applying external pressure. Furthermore, it may be used to recycle waste heat in industrial factories and automobiles.

INTRODUCTION
Generated thermal energy cannot be efficiently converted to electric power at thermal and nuclear power plants. Seventy percent of the generated thermal energy is discarded as waste heat (1–4). The temperature of this waste heat is below the boiling temperature of water, i.e., 100°C (373 K) (5). The waste heat is currently released into the atmosphere through water or air, negatively affecting the environment (6–12). Storing and using this waste heat would provide numerous benefits due to the improved energy efficiency and environmental compliance. In the present paper, we report a long-term heat-storage ceramic, scandium-substituted lambda-trititanium-pentoxide, absorbing thermal energy by a solid-solid phase transition below boiling temperature of water. The ceramic can repeatedly use thermal energy by pressure and heating. This heat-storage performance could provide a sophisticated energy reuse technology for thermal and nuclear power plants and mitigate negative environmental impact of the waste heat.

RESULTS
First-principles calculations of formation energy
In an effort to realize heat-storage materials (13, 14) capable of absorbing low-temperature waste heat, our research has focused on metal-substituted lambda-trititanium-pentoxide (\(\lambda\)-M\(_x\)Ti\(_3\)O\(_5\)). \(\lambda\)-Ti\(_3\)O\(_5\) exhibits photo- and pressure-induced phase transitions (15–19). To date, several types of metal-substituted \(\lambda\)-Ti\(_3\)O\(_5\) have been reported (20–22). We surveyed metal cations suitable for metal substitution of the Ti ion in \(\lambda\)-Ti\(_3\)O\(_5\). Specifically, we conducted first-principles calculations and determined the formation energies of the various \(\lambda\)-M\(_x\)Ti\(_3\)O\(_5\) using 54 different elements. Figure 1A and fig. S1 show the results, where blue denotes that metallic ion substitution stabilizes the formation energy, while orange destabilizes the formation energy. Of these elements, only six have a stabilizing effect: Sc, Nb, Ta, Zr, Hf, and W (Fig. 1, B and C). Thus, we synthesized these \(\lambda\)-M\(_x\)Ti\(_3\)O\(_5\). Substituting with Nb, Ta, Zr, Hf, and W yields the \(\beta\) phase. However, Sc-substituted Ti\(_3\)O\(_5\) assumes the \(\lambda\) phase (fig. S2). Here, we report the synthesis, crystal structure, and heat-storage properties of Sc-substituted \(\lambda\)-Ti\(_3\)O\(_5\).

Crystal structure
We used an arc-melting technique to synthesize the Sc-substituted \(\lambda\)-Ti\(_3\)O\(_5\) (23–27). Figure 2A overviews the synthetic procedure. Precursors of Sc\(_2\)O\(_3\), TiO\(_2\), and Ti powders are mixed, and an 8-mm pellet of the mixture is prepared. Arc melting was used to melt the pellet in an Ar atmosphere. Then, the sample is shaped into a spherical ball (Fig. 2A). The obtained sample is milled by hand. The formula of the sample is determined to be Sc\(_{0.09}\)Ti\(_{2.91}\)O\(_5\) by x-ray fluorescent (XRF) measurements (see Materials and Methods). We performed synchrotron x-ray diffraction (SXRD) measurements using beamline BL02B2 at SPring-8 to determine the crystal structure (28). Figure 2B shows the SXRD pattern of the as-prepared sample at room temperature. From the Rietveld analysis, the crystal structure is monoclinic (space group C2/m) with lattice parameters of \(a = 8.94195\) (4) Å, \(b = 3.79151\) (1) Å, \(c = 9.98618\) (4) Å, \(\beta = 91.1207\) (3)°, and a unit cell volume of \(V = 372.572\) (3) Å\(^3\) (fig. S3).

These characteristics correspond to the crystal structure of \(\lambda\)-Ti\(_3\)O\(_5\). \(\lambda\)-Sc\(_{0.09}\)Ti\(_{2.91}\)O\(_5\) has a slightly larger unit cell volume than that of \(\lambda\)-Ti\(_3\)O\(_5\) with a 0.4% expansion. In addition, the \(\beta\) phase is present as the minor phase. The \(\beta\) phase adopts a monoclinic crystal structure (space group C2/m) with lattice parameters of \(a = 9.7930\) (4) Å, \(b = 3.8064\) (14) Å, \(c = 9.4375\) (4) Å, \(\beta = 91.5611\) (3)°, and \(V = 351.66\) (2) Å\(^3\). The scanning transmission electron microscopy (STEM) image shows stripe-like domains measuring approximately 100 nm \(\times\) 200 nm (Fig. 2C).

Pressure-induced phase transition
Next, we measured the pressure-induced phase transition using SXRD (fig. S4). The as-prepared sample was compressed by pressures of 0.2 to 1.7 GPa with a hydraulic press. As the pressure increases, the \(\lambda\)-phase fraction decreases, while the \(\beta\)-phase fraction increases (Fig. 3A). The crossover pressure is 670 MPa (Fig. 3B). The sample after the pressure-induced phase transition (Fig. 3A) was heated,
and the temperature evolution of the SXRD patterns was collected (fig. S5). Figure 3C shows the peaks of $\lambda$-(203), $\lambda$- and $\beta$-(20-3), and $\alpha$-(023). The $\lambda$ and $\beta$ peaks are constant until 50°C (323 K), and then the $\beta$ phase decreases and the $\lambda$ phase increases at 75°C (348 K), indicating reversibility due to pressure and heating. The $\lambda$ phase transforms into the $\alpha$ phase above 175°C (448 K) but, upon cooling, returns to the $\lambda$ phase in the absence of a transition back to the $\beta$ phase (fig. S6).
Heat-storage property
We measured the heat absorption mass of the sample after the pressure-induced phase transition by differential scanning calorimetry (DSC). We swept the sample compressed at 1.7 GPa with 22.7% of the $\lambda$ phase and 77.3% of the $\beta$ phase from 0°C (273 K) to 300°C (573 K). Heat absorption is observed with an absorption peak at 67°C (340 K) (Fig. 3D). Considering the conversion of the $\lambda$ and $\beta$ phases, the heat absorption mass is 75 kJ liter$^{-1}$. The pressure- and heat-induced phase transitions were repeatedly observed (fig. S7).

Compared to the previous work (16), the heat-storage temperature from the pressure-produced $\beta$ phase to $\lambda$ phase in the present study is 67°C, which is a remarkable reduction from 197°C. This reduction is attributed to the decrease in the formation energy difference between the two phases, which reduces the crossing temperature of the two Gibbs energy curves (29). First-principles calculations support these results. The Gibbs energy versus temperature is described in Fig. 4 and in Materials and Methods.

Thermodynamic mechanism of long-term heat storage and pressure-induced phase transition
According to previous reports on $\lambda$-Ti$_3$O$_5$ (15, 16), the reversible phase transition between the $\lambda$ phase and $\beta$ phase by pressure and heat is considered to be attributed to the energy barrier between the two phases, which originates from the elastic interaction within the material. To understand the mechanisms of long-term heat storage and the low pressure-induced heat energy release, we show the Gibbs free energy of the system ($G_{sys}$) using a thermodynamic model based on the Slichter and Drickamer mean-field model (SD model) (30) (see Materials and Methods). The Gibbs free energy in the SD model ($G_{sys}$) is described as $G_{sys} = x\Delta H + \gamma x(1 - x) + T[R\ln x + (1 - x)\ln(1 - x)] - x\Delta S$, with a
The cooperative interaction parameter ($\gamma$) between the $\lambda$ phase and $\beta$ phase due to the elastic interactions within the crystal. $x$ is the ratio of $\lambda$ phase, and $R$ is the gas constant. From the result of the DSC measurement, the transition enthalpy ($\Delta H$) is 75 kJ liter$^{-1}$ (4.0 kJ mol$^{-1}$), and the transition entropy ($\Delta S$) is 0.22 kJ K$^{-1}$ liter$^{-1}$ (12 J K$^{-1}$ mol$^{-1}$). When the interaction parameters are set as a particular combination of values, the SD model calculation well reproduces the measurement data (i.e., the phase transition of $\beta$ phase $\rightarrow$ $\lambda$ phase occurs around 350 K). Then, the thermally produced $\lambda$ phase is maintained even at low temperatures in the cooling process (Fig. 5, A and B). Thus, the reason why the $\lambda$ phase is maintained for a long period is that the presence of the energy barrier between the $\lambda$ and $\beta$ phases prevents the transformation of the $\lambda$ phase into the $\beta$ phase. The prepared $\lambda$-Sc$_{0.09}$Ti$_{2.91}$O$_5$ shows good stability; i.e., $\lambda$-Sc$_{0.09}$Ti$_{2.91}$O$_5$ is perfectly maintained after 248 days (about 8 months) and 367 days (1 year) from the XRD measurement.

Furthermore, we reproduced the pressure-induced phase transition from the $\lambda$ phase to $\beta$ phase. Applying pressure to the system causes the energy barrier to disappear and induces a phase transition from the $\lambda$ phase to $\beta$ phase (Fig. 5C). This pressure-induced phase transition is caused by the change in the $\gamma$ value upon applying external pressure (see Materials and Methods). Therefore, the system...
is trapped as the $\lambda$ phase at room temperature, but applying pressure overcomes the energy barrier, resulting in a phase transition to the $\beta$ phase.

**DISCUSSION**

Figure 6 schematically illustrates the heat-storage system using Sc-substituted $\lambda$-Ti$_3$O$_5$. Cooling water for a turbine in a power plant is pumped from a river or sea. As the water passes through the turbine, the water temperature increases due to heat exchange. The energy of hot water is transferred to Sc-substituted $\lambda$-Ti$_3$O$_5$ in tanks. Subsequently, water with a reduced thermal energy returns to the river or the sea. This system can mitigate the rise of river or sea water temperatures. Moreover, the heat absorption temperature can be easily controlled by changing the Sc content in $\lambda$-Ti$_3$O$_5$, which absorb heat from hot water. After conducting first-principles calculations, we synthesize Sc-substituted $\lambda$-Ti$_3$O$_5$ ceramics with a heat absorption temperature less than 100°C. This heat absorption material below 100°C can recover the thermal energy from cooling water in power plant turbines, mitigating the rise in sea water temperatures. Moreover, the heat absorption temperature can be easily controlled by changing the Sc content in $\lambda$-Ti$_3$O$_5$ according to the target application.

These heat absorption temperature changes are attributed to the crossover temperature change of Gibbs energies. We successfully synthesize $\lambda$-$\text{Sc}_{0.108}\text{Ti}_{2.892}\text{O}_5$ with a heat absorption temperature at 45°C (318 K) and $\lambda$-$\text{Sc}_{0.108}\text{Ti}_{2.892}\text{O}_5$ with a heat absorption temperature at 38°C (311 K; see Materials and Methods and fig. S9). Sc-substituted $\lambda$-Ti$_3$O$_5$ will expand opportunities to use thermal energy as it can use thermal energy that is currently in the unused temperature range. In addition to electric power plants, other applications of the present material such as heat-storage usage to collect waste heat from factories, transportation vehicles, mobile phones, and electronic devices should be possible.

**MATERIALS AND METHODS**

**First-principles calculations**

In consideration of the valences between six-coordinated Ti$^{3+}$ and Ti$^{4+}$ in $\lambda$-Ti$_3$O$_5$ (15, 16, 31), the total electronic energies of $\lambda$-Ti$_3$O$_5$ substituted by trivalent or tetravalent elements from one of three Ti sites were calculated by first-principles calculations using the Vienna ab initio simulation package (VASP) code. The crystal structure of $\lambda$-Ti$_3$O$_5$ shown in (16) was used as calculation models for the initial structure. The lattice parameters and atomic positions
The samples were sealed in glass capillaries for the SXRD measurement at SPring-8 (28). The samples were melted and turned over three or four times on a copper cooling stage after solidification. These solidified samples were milled by hand before the measurements. The composition was confirmed by XRF, and the formula was determined to be \( \text{Sc}_{0.09} \text{Ti}_{2.91} \text{O}_5 \): calcd: Ti, 62.4; O, 35.8; Sc, 1.8%; found: Ti, 62.0; O, 36.0; Sc, 2.0%, which is identical to the mixed ratio of the starting materials. \( \text{Sc}_{0.105} \text{Ti}_{2.895} \text{O}_5 \) and \( \text{Sc}_{0.108} \text{Ti}_{2.892} \text{O}_5 \) samples were also synthesized, and we measured their x-ray diffraction patterns (fig. S2). Moreover, \( \text{Ti}_3 \text{O}_5 \) samples, substituted by 3 atomic % (at %) of Zr, Nb, Hf, Ta, and W, were synthesized and their x-ray diffraction patterns were measured (fig. S9). The normalized temperature in Fig. 4 was set at 575°C (848 K), which is the crossover temperature of the free energies of \( \text{Ti}_3 \text{O}_5 \). The calculated crossover temperature was underestimated compared with the phase transition temperature, which was likely because the magnetic interaction was not taken into account during the phonon calculations. The formation energies corresponding to the Gibbs free energies (\( G \)) at 0 K were \(-2362.47 \text{ eV (} \beta \text{-Ti}_3 \text{O}_5)\), \(-2376.44 \text{ eV (} \lambda \text{-Ti}_3 \text{O}_5)\), \(-2372.45 \text{ eV (} \beta \text{-Ti}_3 \text{O}_5)\), and \(-2381.65 \text{ eV (} \lambda \text{-Ti}_3 \text{O}_5)\).

**Thermal property measurement**

The heat absorption properties of Sc-substituted \( \lambda \text{-Ti}_3 \text{O}_5 \) samples were measured by DSC (Seiko Instruments, DSC 220C) at a heating-cooling rate of 10 K/min and an air gas flow of 100 ml/min. Before DSC measurements, the samples containing both the \( \lambda \) phase and the \( \beta \) phase were compressed at 1.7 GPa to transform them from the \( \lambda \) phase to the \( \beta \) phase. In addition, the thermal properties of \( \lambda \text{-Sc}_{0.105} \text{Ti}_{2.895} \text{O}_5 \) and \( \lambda \text{-Sc}_{0.108} \text{Ti}_{2.892} \text{O}_5 \) samples were measured (fig. S9).

**First-principles calculation of Gibbs free energy**

To interpret the phase transition temperature, the Gibbs free energies of Sc-substituted \( \lambda \text{-Ti}_3 \text{O}_5 \) and \( \beta \text{-Ti}_3 \text{O}_5 \) with supercells (1 \( \times \) 3 \( \times \) 1) and a \( k \)-mesh of 2 \( \times \) 2 \( \times \) 2 of the optimized structures were calculated using the Phonopy code in cooperation with the VASP code for the interatomic force constants calculations (33, 34). The Sc substitution ratio was set to about 3 at % (Sc\(_{0.05} Ti_2.91 O_5\)). That is, 1 of 36 Ti atoms was substituted by an Sc atom in the supercells. The differential energy of \( \lambda \) and \( \beta \) phase was calculated \((\Delta G = G_\lambda - G_\beta)\). The calculated \( \Delta G \) of \( Ti_3 O_5 \) and Sc-substituted \( Ti_3 O_5 \) are shown in Fig. 4. Ti\(_3\)O\(_5\) shows \( \Delta G = 0 \) at 575°C (848 K), which is the crossover temperature of the calculated free energies corresponding to the phase transition temperature (29). Sc-substituted \( Ti_3 O_5 \) showed \( \Delta G = 0 \) at 341°C (614 K). The normalized temperature in Fig. 4 was set at 575°C (848 K), which is the crossover temperature of the free energies of Ti\(_3\)O\(_5\). The crossover temperature of Sc-substituted Ti\(_3\)O\(_5\) decreased about 27.6% from the temperature of Ti\(_3\)O\(_5\). This temperature decrease ratio agreed well with the experimentally obtained decrease ratio of 27.7% calculated from the phase transition temperature of 470 K (197°C) reported in \( \beta \text{-Ti}_3 \text{O}_5 \) (16) and 340 K (67°C) measured in \( \lambda \text{-Sc}_{0.05} \text{Ti}_{2.9} \text{O}_5\). The calculated crossover temperature was underestimated compared with the phase transition temperature, which was likely because the magnetic interaction was not taken into account during the phonon calculations. The formation energies corresponding to the Gibbs free energies (\( G \)) at 0 K were \(-2362.47 \text{ eV (} \lambda \text{-Ti}_3 \text{O}_5)\), \(-2376.44 \text{ eV (} \lambda \text{-Ti}_3 \text{O}_5)\), \(-2372.45 \text{ eV (} \beta \text{-Ti}_3 \text{O}_5)\), and \(-2381.65 \text{ eV (} \lambda \text{-Ti}_3 \text{O}_5)\).

**Thermodynamic analysis**

In the SD model calculations, the \( \gamma \) value depends on the temperature and pressure (i.e., \( \gamma = \gamma_a + \gamma_b T + \gamma_c P \)). From the DSC measurement result, the \( \Delta H \) value was 4.0 kJ mol\(^{-1}\), and the \( \Delta S \) value was 11.7 J K\(^{-1}\) mol\(^{-1}\). When the parameters of \( \gamma \) were set as \( \gamma_a = 7 \text{ kJ mol}^{-1}, \gamma_b = -1.2 \text{ J K}^{-1} \text{ mol}^{-1}, \) and \( \gamma_c = -0.37 \text{ J MPa}^{-1} \text{ mol}^{-1} \), the SD model calculations reproduced the long-term heat storage and pressure-induced phase transition, as shown in Fig. 5.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/27/eaaz5264/DC1

**REFERENCES AND NOTES**

1. D. Butler, Super savers: Meters to manage the future. Nature 445, 586–588 (2007).
2. D. Lindley, The energy should always work twice. Nature 458, 138–141 (2009).
3. U.S. Energy Information Agency, Form EIA-923 detailed data [accessed 15 January 2019]; http://www.eia.gov/electricity/data/eia923/.
4. S. A. Rattner, S. Garimella, Energy harvesting, reuse and upgrade to reduce primary energy usage in the USA. Energy 36, 6172–6183 (2011).
5. D. B. Gingerich, M. S. Mauter, Quantity, quality, and availability of waste heat from united states thermal power generation. Environ. Sci. Technol. 49, 8297–8306 (2015).
6. M. T. H. van Vliet, J. R. Yearsley, F. Ludwig, S. Vögele, D. P. Lettenmaier, P. Kabat, Vulnerability of US and European electricity supply to climate change. Nat. Clim. Chang. 2, 676–681 (2012).
20. S. Ohkoshi, Y. Maeno, T. Nasu, Metal-substituted titanium oxide, and method for manufacturing titanium oxide sintered body, International Patent Application Number PCT/JP2017/010769 (2017).

21. Z. Shen, Q. Shi, W. Huang, B. Huang, M. Wang, J. Gao, Y. Shi, T. Lu, Stabilization of a metal oxide with a room-temperature photoversible phase transition. Nat. Chem. 2, 539–545 (2010).

22. H. Tokoro, M. Yoshikiyo, K. Imoto, A. Namai, T. Nasu, K. Nakagawa, N. Ozaki, F. Hakoe, K. Tanaka, K. Chiba, R. Makikura, K. Prassides, S. Ohkoshi, External stimulation-controllable heat-storage ceramics. Nat. Commun. 6, 7037 (2015).

23. S. Ohkoshi, H. Tokoro, K. Nakagawa, M. Yoshikiyo, F. Jia, A. Namai, Low-pressure-responsive heat-storage ceramics for automobiles. Sci. Rep. 9, 13203 (2019).

24. B. Li, Y. Kawakita, S. Ohira-Kawamura, T. Sugahara, H. Wang, J. Wang, Y. Chen, S. I. Kawaguchi, S. Kawaguchi, G. Chan, H. Wang, D. Yu, M. M. Makhatadze, K. Kikuchi, S.-I. Yano, A. Takahashi, K. Nakajima, Z. Zhang, Colossal barocaloric effects in plastic crystals. Nature 567, 506–510 (2019).

25. D. Matsunami, A. Fujita, K. Takenaka, M. Kano, Giant barocaloric effect enhanced by the frustration of the antiferromagnetic phase in Mn2GaN. Nat. Mater. 14, 73–78 (2015).

26. S. Ohkoshi, Y. Maeno, T. Nasu, Metal-substituted titanium oxide, and method for producing metal-substituted titanium oxide sintered body, International Patent Application Number PCT/JP2017/010769 (2017).

27. Z. Shen, Q. Shi, W. Huang, B. Huang, M. Wang, J. Gao, Y. Shi, T. Lu, Stabilization of microcrystal 1-Ti3O5 at room temperature by aluminium-ion doping. Appl. Phys. Lett. 111, 191902 (2017).

28. M. Wang, W. Huang, Z. Shen, J. Gao, Y. Shi, T. Lu, Q. Shi, Phase evolution and formation of δ phase in Ti3O5 induced by magnesium doping. J. Alloys Compd. 774, 1189–1194 (2019).

29. S. Andersson, B. Collin, U. Kuylenstierna, A. Magnéli, Phase analysis studies on the titanium-oxygen system. Acta Chem. Scand. 11, 1641–1652 (1957).

30. C. N. R. Rao, S. Ramdas, R. E. Loehman, J. M. Honig, Semiconductor-metal transition in Ti2O3. J. Solid State Chem. 3, 83–88 (1971).

31. S.-H. Hong, Crystal growth of some intermediate titanium oxide phases γ-Ti2O3, δ-Ti2O3, Ti3O5, and Ti2O3 by chemical transport reactions. Acta Chem. Scand. 36A, 207–217 (1982).

32. M. Onoda, Phase transitions of Ti3O5. J. Solid State Chem. 136, 67–73 (1998).

33. H. Y. Chung, M. B. Weinberger, J. B. Levine, A. Kavner, J.-M. Yang, S. H. Tolbert, R. B. Kaner, Synthesis of ultra-incompressible superhard rhenium diboride at ambient pressure. Science 316, 436–439 (2007).

Acknowledgments

Funding: This work was supported, in part, by JSPS Grant-in-Aid for Specially Promoted Research (grant 15H05697), Grant-in-Aid for Scientific Research(A) (grant 20H00369), and Collaborative Research Projects, Laboratory for Materials and Structures, Tokyo Institute of Technology. The synchrotron-radiation experiments were performed at SPring-8 with the approval of Japan Synchrotron Radiation Research Institute (JASRI) Proposal nos. 2018A1642 and 2018B1797. We are grateful to T. Takizawa (Panasonic Corporation) for setting up the first-principles calculation using VASP and Phonopy codes, H. Tamaki (Panasonic Corporation) for use of the arc-melting equipment, H. Katoaka (Panasonic Corporation) for use of a hydraulic press, and F. Shinsyu (Panasonic Corporation) for collecting the SEM and STEM images. We are grateful to F. Jia (The University of Tokyo) and H. Tokoro (University of Tsukuba) for the thermodynamic calculation, K. Imoto (The University of Tokyo) for the enthalpy calculation, K. Nakagawa (The University of Tokyo) for XRF measurement, and M. Yoshikiyo (The University of Tokyo) for the discussion of the manuscript. Author contributions: Y.N. designed and coordinated this study, contributed to all the measurements and calculations, and wrote the paper. Y.S. and M.A. conducted the SXRD measurements. S.O. designed this study and wrote the paper. All the authors discussed the results and commented on the manuscript.

Competing interests: Y.N. is an author on a patent filed by Panasonic Intellectual Property Management Co. Ltd. (no. PCT/JP2019/010402, published on 19 September 2019). Y.N. is author on a patent application filed by Panasonic Intellectual Property Management Co. Ltd. (no. JP 2019-124064, filed on 2 July 2019). The others declare no other competing interests.

Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 16 September 2019
Accepted 19 May 2020
Published 1 July 2020
10.1126/sciadv.aaz5264

Citation: Y. Nakamura, Y. Sakai, M. Azuma, S. Ohkoshi, Long-term heat-storage ceramics absorbing thermal energy from hot water. Sci. Adv. 6, eaaz5264 (2020).