

## Demonstrated fossil-fuel-free energy cycle using magnesium and laser

T. Yabe, S. Uchida, K. Ikuta, K. Yoshida, C. Baasandash et al.

Citation: *Appl. Phys. Lett.* **89**, 261107 (2006); doi: 10.1063/1.2423320

View online: <http://dx.doi.org/10.1063/1.2423320>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v89/i26>

Published by the [American Institute of Physics](#).

---

### Additional information on *Appl. Phys. Lett.*

Journal Homepage: <http://apl.aip.org/>

Journal Information: [http://apl.aip.org/about/about\\_the\\_journal](http://apl.aip.org/about/about_the_journal)

Top downloads: [http://apl.aip.org/features/most\\_downloaded](http://apl.aip.org/features/most_downloaded)

Information for Authors: <http://apl.aip.org/authors>

## ADVERTISEMENT



**Goodfellow**  
metals • ceramics • polymers • composites  
70,000 products  
450 different materials  
**small quantities fast**

[www.goodfellowusa.com](http://www.goodfellowusa.com)

## Demonstrated fossil-fuel-free energy cycle using magnesium and laser

T. Yabe,<sup>a)</sup> S. Uchida, K. Ikuta, K. Yoshida, C. Baasandash, M. S. Mohamed, Y. Sakurai, Y. Ogata, M. Tuji, Y. Mori, Y. Satoh, T. Ohkubo, M. Murahara, and A. Ikesue  
*Entropia Laser Initiative, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552, Japan*

M. Nakatsuka

*Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan*

T. Saiki, S. Motokoshi, and C. Yamanaka

*Institute for Laser Technology, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan*

(Received 7 July 2006; accepted 25 November 2006; published online 27 December 2006)

The authors propose an energy cycle based on a renewable fuel. Magnesium is chosen as an energy carrier and is combusted with water to retrieve energy using many power devices. MgO, the combustion residue, is reduced back to Mg by laser radiation generated from solar and other renewable energy sources. They have achieved an energy recovery efficiency of 42.5% for converting MgO to magnesium, using a laser. Combined with a demonstrated 38% efficiency for converting an artificial sunlight source (metal halide lamp) into laser output energy indicates that the proposed energy cycle is already in a feasible range for practical use. © 2006 American Institute of Physics. [DOI: 10.1063/1.2423320]

There is no doubt that we need an energy cycle free of fossil fuels that otherwise emit greenhouse gases causing global warming. Although solar energy is the ultimate renewable energy source, it is far from fully realized. Furthermore, since sunlight is available only in the clear daytime, it cannot be an alternative to thermal power stations unless effective and large power storage systems are available. Here we propose the chemical potential of magnesium as such an energy reservoir. Heat and hydrogen from the reaction of magnesium with water are used for turbines, reciprocal engines, fuel cells, and so on. The remaining “ash,” MgO, has to be deoxidized in order to make the energy cycle renewable. The deoxidization process is driven by the energy from a solar-energy-pumped laser,<sup>1-5</sup> a laser diode<sup>6</sup> powered by a wind-power generator, or other sources. Since laser radiation can be focused into a small spot, a very high temperature (exceeding 4000 K, needed for MgO deoxidization) can easily be obtained. Once such MgO deoxidization technology is developed, unsteady solar power can be stored in Mg form to provide a stable supply of energy.

This letter reports experimental demonstrations of key technologies: a solar-energy-pumped laser (sunlight laser), a magnesium combustion system, and magnesium recovering (deoxidization) system. We have achieved 38% conversion efficiency from an artificial sunlight source (metal halide lamp) to laser output by Cr-doped Nd-YAG (YAG denotes yttrium aluminum garnet) laser,<sup>5</sup> 42.5% energy recovery efficiency for deoxidization of MgO, and a method for controlled combustion of magnesium. These three experiments prove that the energy cycle is already in a feasible range for practical use.

As an energy reservoir, magnesium is superior to hydrogen because it provides more compact energy storage at 43 GJ/m<sup>3</sup>, compared to 4.3 GJ/m<sup>3</sup> for 70 MPa hydrogen. When magnesium is heated up to 850 K, it strongly reacts with water as follows:



A part of the excess heat of 86 kcal/mol sustains the reaction temperature. Therefore, once the reaction starts, it will run by itself without additional heat.

Hydrogen obtained from this reaction under low power conditions can be used in fuel cells (low power reaction). Conversely, hydrogen can be obtained under high power where it also undergoes combustion (high power reaction) with the reaction



An experimental setup for a low power reaction is shown in Fig. 1(a), where Mg plates of 20×40×0.3 (or 0.6) mm<sup>3</sup> were placed inside a chamber at the beginning of each experiment run. The Mg plates were ignited by Ohmic heating fed from an external power supply. Water was added at various controlled rates as the reaction proceeded. As the figure shows, the speed of reaction (1) can be readily controlled by changing the thickness of Mg and the rate of water supply. Hydrogen was produced for 20–30 min in a steady manner with only 80–150 g Mg supplied. The temperature of the hydrogen generated was almost constant at about 80 °C due to the relatively slow Mg combustion. The hydrogen was generated at 0.28–0.63 g/min, corresponding to 0.57–1.3 kW if the hydrogen was burned as reaction (2).

By reducing the size of Mg to 2×2×0.6 mm<sup>3</sup>, reaction (1) proceeds much faster. As shown in Fig. 1(b), the hydrogen gas produced was ejected through a hole of 4 mm diameter and was directed onto a turbine of 80 mm in diameter having eight fins of 30×40×1 mm<sup>3</sup>. In this experiment, 80±2 g of water was initially added to the chamber, with varying amounts of Mg. It was found that the moles of consumed water were almost twice the initial Mg. Presumably, some of the water evaporated and was exhausted with H<sub>2</sub> driving the turbine together, while most of the MgO re-

<sup>a)</sup>Electronic mail: yabe@mech.titech.ac.jp

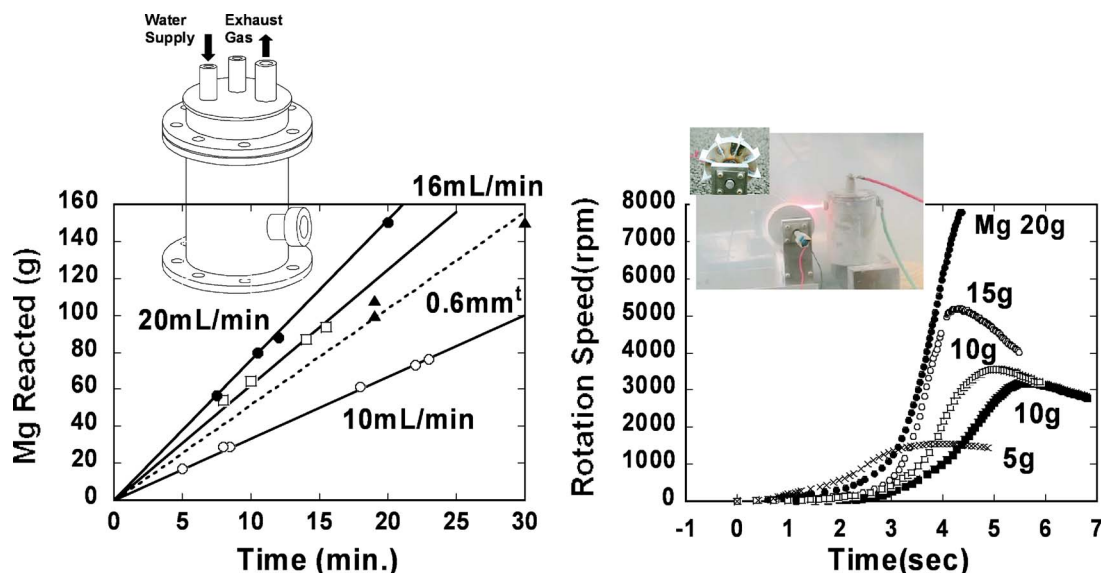


FIG. 1. (Color online) (a) Steady and controlled hydrogen generation was demonstrated for 20–30 min using about 100 g of Mg composed of  $20 \times 40 \times 0.3 \text{ mm}^3$  or  $20 \times 40 \times 0.6 \text{ mm}^3$  plates. After initial ignition by Ohmic heating, reaction was maintained by water input from the top. Solid lines show results for various water supply rates with 0.3 mm thick Mg, while dashed line shows results with 0.6 mm thick Mg and 20 ml/min water supply rate. The linearity shows that the reaction proceeds with constant speed regardless of Mg consumed. (b) High power reaction with Mg of  $2 \times 2 \times 0.6 \text{ mm}^3$  generated 8000 rpm of the turbine shown in the top-left corner. The turbine was driven by exhaust gas from the reaction chamber as shown. Note that the specific area (area/volume) of Mg fuel is now twice that of the slow reaction fuel. The peak rotation speed and acceleration depend not only on the shape of Mg but also on the total amount of Mg.

mained in the chamber. Since  $\text{H}_2$  is 20 times lighter than  $\text{MgO}$ , it obtains a much larger velocity and preferentially escaped the chamber.

Figure 1(b) shows the time evolution of rotational speed of the turbine, with the initial amount of Mg as a parameter. The acceleration of the turbine rotation looks similar among all cases, despite the different initial Mg loading. This suggests that the burning speed was nearly constant, depending only on the shape of Mg present, so the final rotation speed was approximately proportional to the total amount of Mg loaded. A maximum rotation of 8000 rpm was achieved after 4 s using 20 g of Mg. A high speed camera observation revealed that the speed of the exhaust gas was 150 m/s.

Although Mg is abundant (the second richest metal element in seawater at 1.3 g/l and the eighth richest in earth's crust), Mg needs to be retrieved through a refinement process, which requires a large amount of energy to be drawn from the energy cycle. With present technology of Mg refinement,  $\text{MgO}$  and  $\text{CaO}$  are obtained by baking dolomite that contains  $\text{MgCO}_3$  and  $\text{CaCO}_3$ . Under reaction with  $\text{FeSi}$ , Mg is separated from  $\text{CaO}$  and  $\text{MgO}$  at a relatively low temperature, 1500 K. Since  $\text{FeSi}$  is consumed in the reaction and is difficult to recover after the process, an alternative technology that does not require  $\text{FeSi}$  needs to be developed.

A laser is a very suitable energy source for raising the temperature well above 4000 K, the temperature required for complete separation of Mg and O in equilibrium. After evaporation, Mg vapor moves upward because it is slightly lighter than air and condenses to form Mg metal as in a conventional thermal reduction system. However, at atmospheric pressure, Mg atoms collide with  $\text{O}_2$  within a distance of only 100 nm and recombine back to  $\text{MgO}$ . Instead of using impractically high vacuum to suppress the collision, we here propose to use an inert gas flow to prevent Mg atoms from “reoxidation” during the cooling phase, as shown in Fig. 2(a). As Mg atoms cool down, the rate of Mg oxidation diminishes.

A series of experiments demonstrating deoxidization of  $\text{MgO}$  has been performed with three different laser conditions. Table I summarizes the results. After evaporation, Mg was transported to adhesive carbon tape or a copper plate by

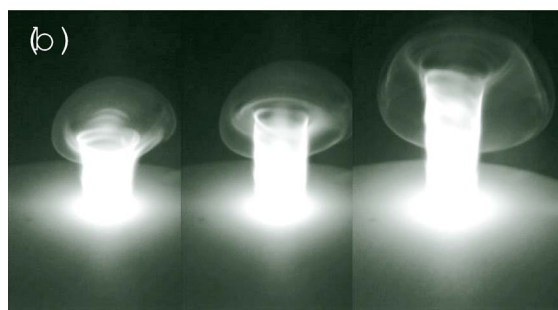
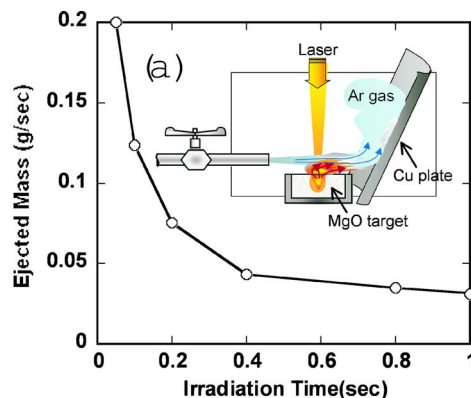


FIG. 2. (Color online) (a) Dissociated Mg from laser illumination is blown off by Ar flow and is accumulated onto a Cu plate to avoid reoxidation. Ejected mass rate (given by ejected mass divided by irradiation time) decreases with increasing irradiation time and reaches an asymptotic value. High speed imaging revealed that intense generation of  $\text{MgO}$  debris took place during first 0.2 s followed by steady vaporization. (b) High speed camera shows the mass ejection of the ringlike structure at the peripheral zone surrounding laser spot for 1 kW  $\text{CO}_2$  with 0.1 s irradiation on the ceramic  $\text{MgO}$ . Such mass ejection under evaporation temperature might increase the efficiency of Mg reduction.

TABLE I. Deoxidization experiments with three different laser conditions. The reduction efficiency significantly increases with the aid of gas flow even under atmospheric conditions. Ar+Ice means the copper plate was cooled by ice. The resulting improvement from cooling implies the importance of cooling speed. The  $4 \text{ s} \times 3$  for the irradiation time means three shots of 4 s duration are accumulated onto the plate. The MgO was in the form of ceramic for YAG laser; otherwise most of the powder was blown off due to extremely high pressure induced by the pulsed laser. MgO powder was used for the CO<sub>2</sub> lasers because the ceramic was broken after a single shot by thermal stress.

	Laser	Irradiation time	Gas flow	Collect	Chamber pressure	Mole fraction of Mg (%)
CO <sub>2</sub>	100 W	10 min	Ar	Cu plate	0.1 MPa	27
		10 min	Ar (2 m/s)	Cu plate	0.1 MPa	29.5
		10 min	Ar (2 m/s)	Cu plate	0.1 MPa	22.8
	1000 W	2 s	He (2 m/s)	Carbon	0.1 MPa	33
		$4 \text{ s} \times 3$	Ar (10 m/s)	Carbon	0.1 MPa	32
		$4 \text{ s} \times 3$	Ar (5 m/s)	Carbon	0.1 MPa	31
		$0.2 \text{ s} \times 10$	Ar (15 m/s)	Cu plate	700 Pa	20
		$0.2 \text{ s} \times 10$	Ar (15 m/s)+Ice	Cu plate	700 Pa	32.6
	YAG 1.4 J/10 ns	15 min (10 Hz)	Ar (15 m/s)	Cu plate	500 Pa	43.4
		15 min (10 Hz)	Ar (22 m/s)	Cu plate	500 Pa	38.5
		60 min (10 Hz)	No gas flow	Cu plate	100 Pa	0

the inert gas flow and was deposited there. We analyzed the content of Mg among the deposited material by an electron probe microanalyzer. The analysis indicated that 20%–43% of the Mg atoms introduced as MgO were collected as unoxidized Mg, as shown in Table I.

Considering latent heats of melting  $L_m=1.94 \text{ kJ/g}$  and evaporation  $L_b=8.27 \text{ kJ/g}$  and the dissociation energy for MgO  $L_d=9.22 \text{ kJ/g}$ , we can estimate the maximum evaporation rate  $X \text{ (g/s)}$  of MgO from  $(C+L_m+L_b+L_d\alpha)X=P$ , where  $P \text{ (kW)}$  being the incident laser power and  $C$  being the sensible heat of about  $5.4 \text{ kJ/g}$ . If the mole fraction  $\alpha$  of dissociated Mg at 0.2 s is used, this gives  $X=0.054 \text{ g/s}$ , which is smaller than the experimental result. This implies that some MgO was ejected in the liquid phase from the peripheral heat-affected zone surrounding the laser spot (where high pressure was generated by evaporation),<sup>7</sup> as shown in Fig. 2(b).

The ejection rate in Fig. 2(a) and the efficiency at 0.2 s irradiation in Table I indicate that a reduction energy efficiency of 42.5% has been achieved (equal to Mg reaction energy/energy for Mg production). This translates to 61 ton/GW h.

It is well known that 40% of world's population will need new water resources by 2025. If desalination plants are the only solution, 1500 new plants with 200 000 ton/day capability will need to be constructed. It is interesting to note that condensed seawater produced from a desalination process of 200 000 ton/day capacity contains 650 ton of magnesium, and thus we can accumulate  $3.6 \times 10^8$  ton every year from 1500 desalination plants.

The authors are greatly thankful to K. Grabowski for his comments to this letter.

<sup>1</sup>C. G. Young, *Appl. Opt.* **5**, 993 (1966).

<sup>2</sup>V. Krupkin, Y. Kagan, and A. Yogev, *Proc. SPIE* **2016**, 50 (1993).

<sup>3</sup>M. Landoa, J. Kagana, B. Linyekina, and V. Dobrusin, *Opt. Commun.* **222**, 371 (2003).

<sup>4</sup>A. Ikesue, K. Kamata, and K. Yoshida, *J. Am. Ceram. Soc.* **78**, 2545 (1995).

<sup>5</sup>T. Saiki, S. Uchida, S. Motokoshi, K. Imasaki, M. Nakatsuka, H. Nagayama, Y. Saito, M. Niino and MT. Mori, *Proceedings of the International Astronautical Congress 2005*, paper No. IAC-05-C3.4-D2.8.09.

<sup>6</sup>P. A. Crump, M. Grimshaw, J. Wang, W. Dong, S. Zhang, S. Dus, J. Farner, M. Devito, L. S. Meng, and J. K. Brasseur, *Conference on Lasers and Electro-Optics, Quantum Electronics and Laser Science Conference (CLEO/QELS 06)*, 21–26 May 2006, Long Beach, CA, Paper No. JWB24.

<sup>7</sup>T. Yabe, F. Xiao, and T. Utsumi, *J. Comput. Phys.* **169**, 556 (2001).