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Science AMA: I'm Jamie Holladay, a researcher at Pacific Northwest National Laboratory (PNNL) where we are using high-field magnets to produce low-cost liquid hydrogen. AMA!

JAMIE5091 [R/SCIENCE](#)

Hi Reddit! Sunday, October 8th, is National Hydrogen and Fuel Cell Day, so let's look at how far hydrogen fuel cell technology has come, and more importantly, where emerging technologies can take us. For decades, hydrogen fuel cells were an aspirational technology. Today, this ultra-low emission technology is on the brink of mainstream adoption, but it will require widespread support of a hydrogen supply and refueling infrastructure. The Achilles heel of this clean energy future: generating enough liquid hydrogen at a low enough cost. Hydrogen—the most abundant element in the universe—must be cooled to ~20 K (-253 °C/-423 °F) – and that's currently a rather energy-intensive process.

At PNNL (with partners at Emerald Energy NW, LLC, and AMES Laboratory), we're developing a novel approach based on magnetocaloric refrigeration. The system works by taking advantage of a physical phenomenon called the magnetocaloric effect. We believe this new method can reduce the cost of liquefying hydrogen by 25 percent or more. I'll be back here at 12 am PST (3 pm EST) to answer your questions.

Update: Dr. John Barclay, the inventor of active magnetic regenerators, a partner on our work, is also joining us this day. He is the President and CTO of Emerald Energy NW LLC.

Update: Thank you for your questions, Reddit! We will check back later to follow up on these threads. In the meantime, read more on this research area at <http://energyenvironment.pnnl.gov/highlights/highlight.asp?id=2487>. And to learn more about our work in energy, visit <https://energyenvironment.pnnl.gov/>. We also encourage you to follow PNNL on Facebook at www.facebook.com/PNNLgov and Twitter at @PNNLab and for more energy-focused topics on Twitter, @energyPNNL. You'll also find PNNL on Google+ and LinkedIn. Thanks again!

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Science AMA: I'm Jamie
Holladay, a researcher at
Pacific Northwest National
Laboratory (PNNL) where we
are using high-field magnets to

Could this technique be adjusted to produce high volumes of Deuterium?

[DelosBoard2052](#)

If the Deuterium is separated from normal Hydrogen prior to liquefaction, the magnetocaloric refrigeration could be used to efficiently liquefy Deuterium because it's liquid properties are similar to those of Hydrogen. If Deuterium gas is mixed with Hydrogen gas at near room temperature before liquefaction, a mixture of cryogenic liquid deuterium and hydrogen would be produced. A sophisticated separation system such as a distillation column would be required to separate them.

Hi there! I've got a second question regarding energy needs.

Can you give us some figures? How much unrecoverable energy is the current best option plagued with? (i.e.: If I need to store 1 kWh of energy in LH, how much energy can I recover in a usable form

produce low-cost liquid hydrogen. AMA!, *The Winnower* 4:e150729.94246 , 2017 , DOI: [10.15200/winn.150729.94246](https://doi.org/10.15200/winn.150729.94246)

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afterwards). And how much of this loss is due to cooling?

How does your method compare to it? How much can you improve it? Is it feasible for "simple" applications?

[lucaxx85](#)

To ideally liquefy hydrogen it takes 12 MJ/kg H₂ which is 10% of the lower heating value of hydrogen. Current technology, however, requires about 42 MJ/kg H₂ or 35% of the lower heating value of hydrogen. So current technology loses 35% of the energy during the liquefaction. Our method is twice as efficient. This means we project to use 18 to 21.5 MJ/kg (15-18% of the lower heating value of hydrogen). Thus we would double the efficiency compared to current technology. In addition, our technology eliminates the need for very expensive and hard to maintain hydrogen compressors. Our operating cost is projected to also be 50% of that of current technology.

Quick question(s). Could this same field be used in a bussard ram jet? Could this same field be used to protect the contents of a vessel between solar destinations?

[inquisitive_mind](#)

Hi Great question. I am not sure what you are asking. If 'field' is 'magnetic field', the answer to your questions is probably no because the magnetic fields used in magnetic refrigeration are about 6-8 tesla and localized in the liquefaction and the magnetic fields are too localized to shield a space ship from charged particles. On the other hand, if 'field' is an autocorrect for 'fuel', the answer to your first question is yes. There was a lot of work done at several types of jet engines up to about Mach 18. The answer to your second question is no because the fuel would be in thermally insulated storage tanks outside of normal crew areas.

Hi and thanks for joining us today!

Trillion dollar question ... for large-scale use who will be the ultimate winner:

- the decades-long, anemic hydrogen fuel cell market
- Tesla's push for lithium-ion
- Google's Malta (molten salt) technology

[PHealthy](#)

Thanks for the great question.

Can you help me understand what you mean by "large scale use"?

If you are referring to the vehicles, then, I feel there will be room for everyone. Electric vehicles are very interesting and getting better with longer ranges and shorter charge times. However, in the past few years there has been a dynamic shift in the fuel cell vehicle market. The number of vehicles sold or leased is increasing dramatically. Fuel cells have come a long way in sales, cost reduction and performance. The DOE projects fuel cell stack cost for a fuel cell vehicle to be around \$45/kW today which is over a 50% reduction in cost from 10 years ago and they have a reasonable plan to get the cost even lower.

Fuel cell vehicles offer longer ranges and fast filling. Current fuel cell vehicles can go 350+ miles on a single tank. The refill time is <10minutes. I think a hybrid fuel cell electric will be even better. In addition, there are new applications for fuel cells in areas where batteries would have challenges. For

example, several OEMs have announced fuel cell class 8 trucks. See for example <https://www.trucks.com/2017/05/02/kenworth-class-8-hydrogen-fuel-cell-truck/>, <http://www.truckinginfo.com/channel/fuel-smarts/news/story/2017/04/toyota-reveals-project-portal-hydrogen-fuel-cell-truck.aspx>, and <https://nikolamotor.com/one>. In addition, there are other applications where fuel cells are gaining ground such as for fork lifts where they are replacing battery powered fork lifts. For more information on these and other uses, you can take a look at this presentation by the DOE Fuel Cell Technologies Office which can be found at https://www.hydrogen.energy.gov/pdfs/review17/01_satyapal_plenary_2017_amr.pdf.

One of the limitations for fuel cell vehicle adoption has been the lack of hydrogen infrastructure. For example, California has made strategic investments into a hydrogen infrastructure which has resulted in increased sales. One of the challenges of the hydrogen infrastructure is how to transport the hydrogen from point of generation to the filling station. Liquid hydrogen can be economically and efficiently transported; however, the liquefaction process is inefficient and expensive. Our technology directly addresses these issues. The magnetocaloric hydrogen liquefaction technology offers the promise to double the efficiency of hydrogen liquefaction compared to current technologies. It is also modular and can be scaled down where current technology must be large scale for it to be economical.

As for the Google Malta technology, it converts electric power to thermal energy, stores the thermal energy and when needed, converts it back to electric power. This technology seems to be focused on Grid scale energy storage applications, not vehicle applications and is not likely to be applicable for vehicles. For grid scale energy storage, I do not know enough about its round trip efficiency to be able to make any comparisons with the various fuel cell and hydrogen based grid scale energy technologies that I am familiar with.

Hi there! I'll start with the most obvious question.

Can you dumb down for us the magnetocaloric effect? (if it's something that can be simplified enough?)

[lucaxx85](#)

Here is the answer we used in another question. I hope this helps. We are using the magnetocaloric effect. Magnetocaloric materials are ferromagnetic materials that when exposed to a large magnetic field heat up. When they are removed from the magnetic field they cool down. This effect can be used to make a refrigeration cycle similar to that of the vapor compression cycle. It is a 4 step cycle. The first step is the adiabatic insertion of the magnetocaloric material into a magnetic field. The magnetocaloric material heats up during the insertion. The second step is to remove heat and dump the heat to the environment. Step 3, is adiabatically removing the magnetocaloric material from the magnetic field. The magnetic material cools down. Step 4. The cooled material is used to cool the process stream. Here is a picture that can help with the cycle- <https://imgur.com/a/ya1zc>.

Obviously cooling hydrogen is one way to liquify and thereby reduce its density sufficiently to make it viable as a portable energy source, e.g. for automobiles. One other method I read about extensively in the early aughts was metal organic frameworks (MOFs) which are complex, elegant molecular 'sponges' that interact with hydrogen in a way that dramatically condense its volume without the need for external temperature manipulation. What say you the benefits, opportunities, pitfalls, shortcomings, challenges, etc. with this approach, as, say, compared to cooling with your magneto-thingsies?

[hyperproliferative](#)

Great question. I love MOFs. Our technology does not compete with MOFs but is an enabler for

MOFs. MOFs are intended to be a materials based hydrogen storage media suitable for on-board vehicle applications. Current MOF technologies require cryogenic temperatures and moderate pressures in order to have higher volumetric and gravimetric hydrogen storage capacities in excess of compressed hydrogen. In other words, MOFs require a high pressure cryogenic hydrogen source. Vaporization of liquid hydrogen can generate the high-pressure cryogenic hydrogen needed for MOF-based hydrogen storage. It has the potential to be less expensive than taking compressed hydrogen and cooling it for use in MOFs. It also can minimize the need for expensive compressors. By the way, compressors account for 50% of the cost of a hydrogen fueling station, so their elimination can greatly reduce hydrogen station costs.

What are your team's thoughts on the capital and operating inputs and economics of scaled - up application? Where are the risks?

Thanks for your AMA!

[49orth](#)

As we develop and demonstrate magnetic liquefaction technology, the projected capital and operating costs are regularly updated as a function of scale from ~1 metric ton/day to 30-60 metric ton/day capacities. The capital cost of magnetic liquefier systems is slightly less per kg/day than comparable conventional gas-cycle liquefiers because the much higher efficiency reduces footprint of the equipment. The higher efficiency reduces the liquefier power component of operating costs by 1/3 to 1/2 compared to liquefier power costs in existing plants. The net result is a significant reduction in cost of liquefaction at this scales. We haven't analyzed really large scale applications yet. If the risks are associated with developing the advanced liquefier technology, they are mostly associated with costs of certain ferromagnetic materials, high magnetic fields from superconducting magnets, and management of heat transfer fluids. All of these are manageable, i.e. there are enough design options that allow continued development as resources allow. If the risks you are inquiring about are associated with some of the cryogenic fuels such as LNG or LH2, these are flammable fuels that have to be comply with numerous codes and standards to identify and mitigate such risks. Go to www.H2tool.org for a good source of information on LH2.

The risks have been analyzed in detail.

This is way beyond me so I hope this isn't a stupid question or totally irrelevant, but would this technique be able to be applied to the production of gaseous hydrogen to make that cheaper?

Our company recently procured a hydrogen fuel cell car and we have to drive it 30-odd miles away to a filling station where it blasts hydrogen gas into the canisters at 700bar, but I believe there's a load of equipment next to the station doing all the conversion work using regular old water.

To fill it up (300 mile estimated range) costs about the same as it would to fill up with petrol, so I'm worried this will affect adoption since electric cars are much cheaper to run. Of course, EVs are hamstrung by slow recharging times, whereas refuelling a hydrogen FC car takes around the same time as filling with petrol/diesel, maybe a few minutes longer.

[r2001uk](#)

Hi, thank you for this question. Our technology does not produce hydrogen, so it would not make hydrogen production less expensive. It would reduce the cost of transporting and storing the hydrogen. In addition, if you vaporize the liquid hydrogen to generate high-pressure hydrogen for your car, you can minimize or perhaps even eliminate the compressors at the station. Compressor costs account for 50% of the hydrogen filling station capital so minimizing their expense can greatly reduce the cost of a

hydrogen infrastructure.

Hi! Thank you for doing this AMA!

Could you explain the effect you're using more precisely?

Do you need special infrastructure to make it work?

Do you believe it could be adopted easily by companies in the near future?

[Hafornin](#)

Could you explain the effect you're using more precisely? We are using the magnetocaloric effect. Magnetocaloric materials are ferromagnetic materials that when exposed to a large magnetic field heat up. When they are removed from the magnetic field they cool down. This effect can be used to make a refrigeration cycle similar to that of the vapor compression cycle. It is a 4 step cycle. The first step is the adiabatic insertion of the magnetocaloric material into a magnetic field. The magnetocaloric material heats up during the insertion. The second step is to remove heat and dump the heat to the environment. Step 3, is adiabatically removing the magnetocaloric material from the magnetic field. The magnetic material cools down. Step 4. The cooled material is used to cool the process stream. Here is a picture that can help with the cycle- <https://imgur.com/a/ya1zc> .

Do you need special infrastructure to make it work? Other than a source of hydrogen, no special infrastructure is needed. Remember that hydrogen is an energy carrier not a source of energy.

Do you believe it could be adopted easily by companies in the near future? Yes. Our intention is to develop the technology to the point where a turnkey facility is feasible. There is other research on using this technology for home A/C and/or refrigeration appliances. We are looking at the cryogenic uses.

Why is generating liquid hydrogen the Achilles heel? Is there no role for gaseous hydrogen?

[boo_baup](#)

Why is generating liquid hydrogen the Achilles heel? Is there no role for gaseous hydrogen?

There is definitely a role for gaseous hydrogen. One of the challenges for a hydrogen infrastructure is transporting the hydrogen from point of generation to point of use, unless the generation point is the point of use. The hydrogen can be generated at a filling station or industrial site, but often there are limitations (economic and regulatory) on where this can be done. The lowest cost hydrogen is generated in large volumes outside of the "city gate" and then transported to the point of use. The advantage of liquid hydrogen is that you can transport about twice the mass of hydrogen in a liquid state compared to a compressed gas state in the same size container. The liquid hydrogen can then be warmed up for use as a gas. If done correctly, the liquid hydrogen can be vaporized to generate high pressure compressed hydrogen minimizing the need for expensive compressors. For fuel cell vehicles, currently they are using high pressure compressed hydrogen. To achieve fast fueling, they pre-cool the hydrogen to -40C. In the future, they are looking to use lower pressure hydrogen. Several ways to do this include cryo-compressed, hydrogen sorbents, or even liquid hydrogen. For all of these applications, gaseous hydrogen must be cooled, which is expensive. If the hydrogen is transported to and stored at the fueling station in a liquid state, the hydrogen is already cold eliminating the expensive on-site precooling.

Hi Jamie, thank you so much for doing this and happy fuel cell day! I did a lot of research a few years ago on the feasibility of PEM, Phos Acid FC's and SOFC's and my findings were that they are not feasible at the moment unless you live in an area where utility prices are greater than 30 cents per kwh unless you're willing to wait over 20 years for your ROI (the study was published in 2015) so what makes you say they are on the brink of mainstream adoption? Also, at the rate of research of your field, when do you think magnetocaloric refrigeration will be adopted in the mainstream in order to reduce the economy of scale when considering this technology? Also would this method of supercooling affect the compatibility of the fuel cell it can be used with? (ex. only PEM but not phosphoric acid?)

[shawnnwasim](#)

Hi Jamie, thank you so much for doing this and happy fuel cell day! I did a lot of research a few years ago on the feasibility of PEM, Phos Acid FC's and SOFC's and my findings were that they are not feasible at the moment unless you live in an area where utility prices are greater than 30 cents per kwh unless you're willing to wait over 20 years for your ROI (the study was published in 2015) so what makes you say they are on the brink of mainstream adoption? Also, at the rate of research of your field, when do you think magnetocaloric refrigeration will be adopted in the mainstream in order to reduce the economy of scale when considering this technology? Also would this method of supercooling affect the compatibility of the fuel cell it can be used with? (ex. only PEM but not phosphoric acid?) Thanks for the question. In the past few years there has been an increase in hydrogen fuel cell vehicle sales, an increase in the hydrogen infrastructure particularly in California, and an increase in other uses of hydrogen. For example, there are over 15,000 fuel cell forklifts either deployed or ordered. Please see this excellent presentation by the DOE Fuel Cell Technology Office for other information on the growth of fuel cell technologies.

https://www.hydrogen.energy.gov/pdfs/review17/01_satyapal_plenary_2017_amr.pdf.

Hydrogen isn't so much a fuel as it's an energy delivery system. We will never get back from it the amount of energy needed to produce, store and deliver it. So won't it always have to be secondary to another renewable source of energy?

[free_as_in_speech](#)

You are correct. Hydrogen is an energy carrier and not a energy producer. It can be generated from a renewable source of energy such as wind, solar, or hydroelectric. When produced from renewable resources, a fuel cell vehicle operating on hydrogen generates no criteria pollutants or green house gases. Current fuel cell vehicles have a driving range in excess of 300 miles per tank and the filling stations are designed to fill the tank in less than 10 minutes and faster fills are possible. Thank you for your question.