WHAT A WASTE

How recycled nuclear fuels can power the US for the next thousand years

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WHAT A WASTE

EXECUTIVE SUMMARY

Nuclear waste is not a problem - it's a myth. Virtually all the heavy material currently classified as 'waste' in America can be re-used in a new generation of reactors that could give virtually unlimited 24/7 carbon-free power to our country for almost unimaginable spans of time - many centuries in fact, without the need to mine another scrap of uranium.

In this report we assess the US nuclear inventory with a focus on the potential for recycling two specific components - spent fuel and depleted uranium - into fuel for a new generation of fast reactors.

These reactors have been built and successfully operated before in the US, and the technology is now the focus of many startup companies developing 'waste-burner' SMRs. They include Terrapower's 'Natrium' reactor, currently beginning construction in Wyoming, and Moltex's 'Stable Salt Reactor - Wasteburner', as well as Thorizon (tagline: 'No energy to waste') and many others.

According to our calculations, the US nuclear inventory currently totals about 590,000 tonnes of recyclable heavy metals: 500,000 tonnes of depleted uranium and 90,000 tonnes of spent fuel from first and second-generation light-water reactors.

This is not waste, it is fuel for the future. But for how long could it power the United States? According to our calculations (set out in detail below, with sources) this amount of fuel could realistically power America at current rates of electricity use for over 1,000 years.

That's right - there's a millennium's worth of fuel in the material currently categorised as 'waste' and that is the focus of so much legacy opposition to nuclear power. This report shows that we should not waste the waste. Doing so would be literally throwing away a thousand years'-worth of clean power.

popular depictions of nuclear power and waste bear no resemblance to reality

THE NUMBERS

The United States has two major sources of potential future fuel for a new generation of fast reactors. **The first is spent fuel** from first and second-generation light-water reactors. Even though this fuel has already been through a reactor core, **98% of the energy in the original uranium is still available** once the spent fuel is reprocessed into new fuel.

The **second source is depleted uranium**, which is uranium-238 left over from 'enrichment' activities - meaning the process by which the proportion of U-235 has been increased in the past to make fissionable fuel for the first-generation reactors (for more on this see below). It is this U-238 that can now be repurposed into fuel for fast reactors.

The total US spent nuclear fuel inventory was approximately 91,400 metric tonnes of heavy metal (MTHM) at the end of 2012[1].

There are slightly differing estimates of how much depleted uranium/U-238 are in the US inventory.

According to World Nuclear, the US owns some 700,000 tonnes of DU tails from past fuel enrichment[2].

Two additional[3] sources[4] give a figure of 800,000 tonnes of DU held by the US government's DOE at the Paducah and Portsmouth sites. Note this is held in the form of UF6 (uranium hexaflouride) - see below for how this converts to metric tonnes of U.

The US General Accounting Office in a recent report[5] gives a total DU inventory figure of 67,000 cylinders - each cylinder reportedly contains 10-13 tonnes of UF6, which would make the total somewhere between 670,000 to 871,000 tonnes.

To calculate the uranium proportion of the mass of UF6 we need to multiply by 0.676[6]. So this equates to 448,900 to 583,000 MTHM in the form of U-238. If we add 90,000 MTHM in spent fuel we have a rounded total of **590,000 MTHM total US inventory as a starting point for our calculation.**

Next, we need to find out how much energy this amount of fuel can produce. Nuclear physics sources put this energy release from the fission of atomic nuclei at about 80 TJ (terajoules) per kg[7]. This applies roughly equally to all nuclear fuels, including thorium, uranium, plutonium and other actinides in spent fuel.

We need to convert the units next.

80TJ = 22 GWh[8]. That's for each kg.
So each tonne gives 22,000 GWh.

590,000 *22,000 = 12,980,000,000 GWh heat. However, heat does not convert directly to electricity - the efficiency is roughly a third.

/3 = 4,326,666,666 GWh electricity

/1000 = 4,326,666 TWh electricity.

US electricity annual useage = 4,000 TWh[9]

4,326,666/4,000 = **1081 years**

Thus in this idealised calculation we can run the United States at current rates of electricity consumption in a closed fuel cycle using existing inventories for 1081 years.

HOW FAST REACTORS WORK

It has been understood since the 1950s that fast reactors would be able to 'breed' more fuel than they consume, and that this could provide an energy source that is essentially limitless over human timescales. Most obviously, this reduces the urgency for the development of incredibly physically challenging nuclear fusion, which is usually justified on the basis of concerns about waste and long-term fuel supply with fission. Both these issues are definitively solved using fast reactor technology, while fusion – despite recent much-hyped breakthroughs – remains decades from any prospect of commercialisation.

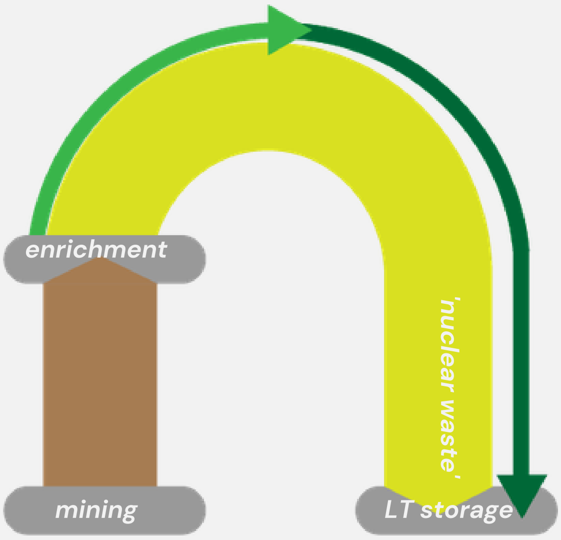
Many countries in the past have run fast reactor prototypes, such as EBRII in the United States, Phénix in France, Monju in Japan and the Russian BN fast reactor programme. The Western programmes were closed down prematurely for a combination of political and technical reasons, with only the Russian effort currently continuing. Economically, conventional pressurised water reactors using fission in the thermal neutron spectrum[10] have been cheap enough to run, because using once-through enriched fuel and then disposing of it is only a small part of the overall cost of building and running a reactor. With fresh uranium fuel extremely cheap in a historically oversupplied market, there has been little incentive to use fissionable materials more efficiently in fast reactors.

STANDARD REACTOR "ONCE THROUGH" FUEL CYCLE

- **less than 1%** of mined uranium is fissioned
- fissile material is consumed and not replenished
- spent fuel is not reprocessed and needs long duration storage
- **16 tons of natural uranium** needed for every **1 TWh of electricity** generated

Light-water reactors use fissile isotopes, primarily uranium-235, which must be 'enriched' from natural uranium through complicated fabrication processes such as cascades of centrifuges. This is because U-235 comprises only 0.7% of natural uranium, with the remainder being uranium-238, which is not fissile. Enrichment was originally designed to isolate sufficient U-235 to produce atomic bombs, which need very high proportions of fissile isotopes (over 90%) in order to enable chain reactions swift enough to yield explosive power.

Uranium enriched to lower levels, around 5%, is sufficient to run light-water reactors to generate electricity. However, this means that most of the remaining uranium in their fuel, primarily U-238 plus un-fissioned U-235, is left over at the end in highly radioactive fuel assemblies and in the 'depleted uranium' from which most of the U-235 has been separated*. The used fuel assemblies contain a mix of mostly short-lived 'fission products' such as caesium-137 and strontium-90, along with long-lived 'actinides' such as plutonium, curium, americium and neptunium, as well as the leftover uranium, and remain significantly radioactive for millennia (though at increasingly weak levels) unless the long-lived materials can be removed and refashioned into fuel.



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*Depleted uranium is considered useless except in dubious military application as raw material for the manufacture of high density armour-penetrating projectiles.

HOW FAST REACTORS WORK

Unlike thermal reactors, which exploit the fact that U-235 is far more likely to fission when hit with slowed down 'thermal' neutrons, fast reactors do not use a 'moderator' to slow down neutrons in the fission chain reaction. Fast reactors are designed to run using fresh, fast neutrons directly, as soon as they are released by a fission event. Fast neutrons are far less likely to cause fission – making it harder to achieve a chain reaction – but they are more likely to cause fission events that yield greater numbers of neutrons, which are then available to transmute 'fertile' materials like U-238 into fissionable fuels like plutonium. This is known as 'breeding' fissile fuels from fertile materials.

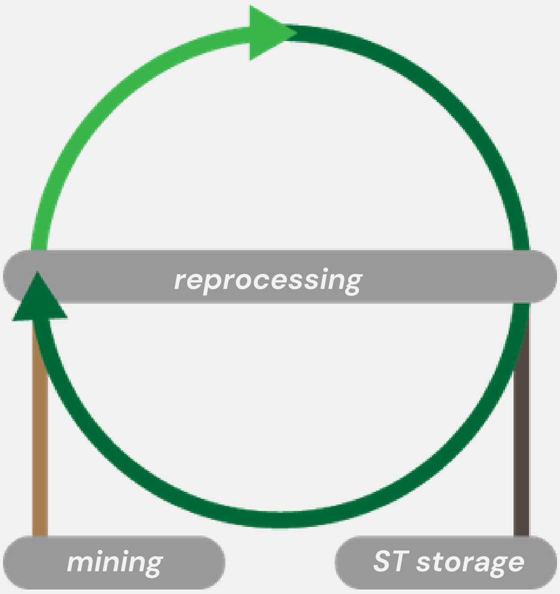
Plutonium is a key fuel for fast reactors because it tends to yield more neutrons when fissioning than uranium. Plutonium-239 is a fissile isotope that does not occur naturally on Earth, and which was originally generated by transmutation of U-238 in military nuclear reactors optimised for plutonium production, and isolated in order to be used in nuclear bombs. Light-water reactors also get about a third of their heat from the generating and fissioning of Pu-239, but fast reactors – albeit through multiple recycling and refabrication cycles of fuel – are much more efficient fuel 'breeders' and are thus able to utilize essentially all their uranium this way.

Fast reactors will also be able to use all the actinides left over in spent nuclear fuel. These actinides are what make spent fuel radioactive for very long periods of time because they have long half-lives, even though they are primarily alpha emitters and are thus not a significant concern in terms of any likely effects on future people. However, if they are removed from fuel and burned in fast reactors, the radioactivity of the remaining waste – which will then be composed mostly of fission products with short half-lives – will decline to the original uranium ore levels within as little as 200–300 years, making surface storage feasible and reducing and simplifying, if not removing altogether, the need for deep geological disposal with unnecessarily complex design considerations taking into account million-year timescales. Shortening the time frames of radioactive waste storage and disposal processes could make it easier to demonstrate their safety and communicate this to the general public.

These inherent advantages raise the question of why fast reactors have not so far been deployed at scale in our nuclear power fleets. The main reason – apart from the political choices made to discontinue Western research programmes on the dubious grounds of concerns about weapons proliferation – is that uranium has been cheap enough that there has not been a need to utilise it more efficiently.

FAST BREEDER REACTOR CIRCULAR FUEL CYCLE

- more than 99% of mined uranium is fissioned
- fissile material is created as much as is consumed
- only useless fission products are sent to disposal
- 0.1 tons of natural uranium needed for every 1 TWh of electricity generated



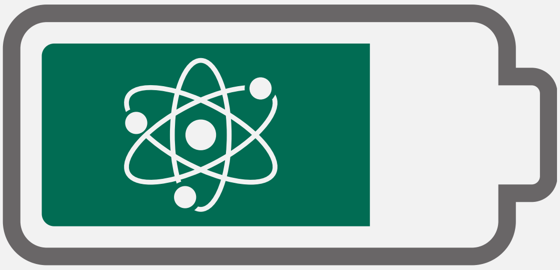
HOW FAST REACTORS WORK

Additionally, designing and licensing a new type of reactor and new type of fuel is an enormous R&D investment, something which commercial operators have not been very interested in so far, especially as just licensing and maintaining conventional nuclear has been difficult enough.

In other words, more uranium could simply be enriched and fabricated from mining sources, and spent fuel stored indefinitely, while the issue of deep geological disposal could be endlessly pushed down the line. This is known as the 'once-through' uranium fuel cycle. And there has been no economic need to close the fuel cycle, because nuclear fuel is a very small component of the overall cost of running a reactor, even if only 1% of mined uranium is used productively. This is different to fossil fuels, where the cost of the fuel is the main consideration with running power-generating plants, and is more akin to renewables, where the fuel – solar or wind – is essentially free once the capital cost of the generating plant has been covered.

However, this is now changing. With the ongoing reconsideration of nuclear power, driven by the acknowledgement by most experts that net zero targets on stable electricity grids will not be achievable without it, uranium reserves are a consideration for the long term. Modular fast reactor designs have now been produced by reputable companies in numerous countries – varying from startups to older engineering companies – several of which are already close to prototype or first-of-a-kind deployment - see our list of some of the most promising designs in this report. (Due to the war in Ukraine, we do not discuss the Russian fast reactor programme further in this report.) Fast reactor designs often promise full passive safety, meaning there is no risk of meltdown and the associated release of radiation such as happened at Fukushima in Japan following the tsunami disaster in March 2011.

Many of the new fast reactor designs also include a load-following component, such as via thermal storage in molten salts, which will allow the generating plant to rapidly respond to changing grid needs in order to balance intermittent power delivered by wind and solar, and provide peaking power in place of traditional natural gas plants. Thus, while the majority of electrical power for most of the year could be met with renewables, these new reactors can solve the intermittency problem that will otherwise make 100% clean grids difficult to achieve, due to the lack of cost-effective large-scale electricity storage options. Batteries are far too resource-intensive and costly for use as seasonal storage of electricity, and hydrogen is not much better due to its inherent difficulties of production, transport and storage.

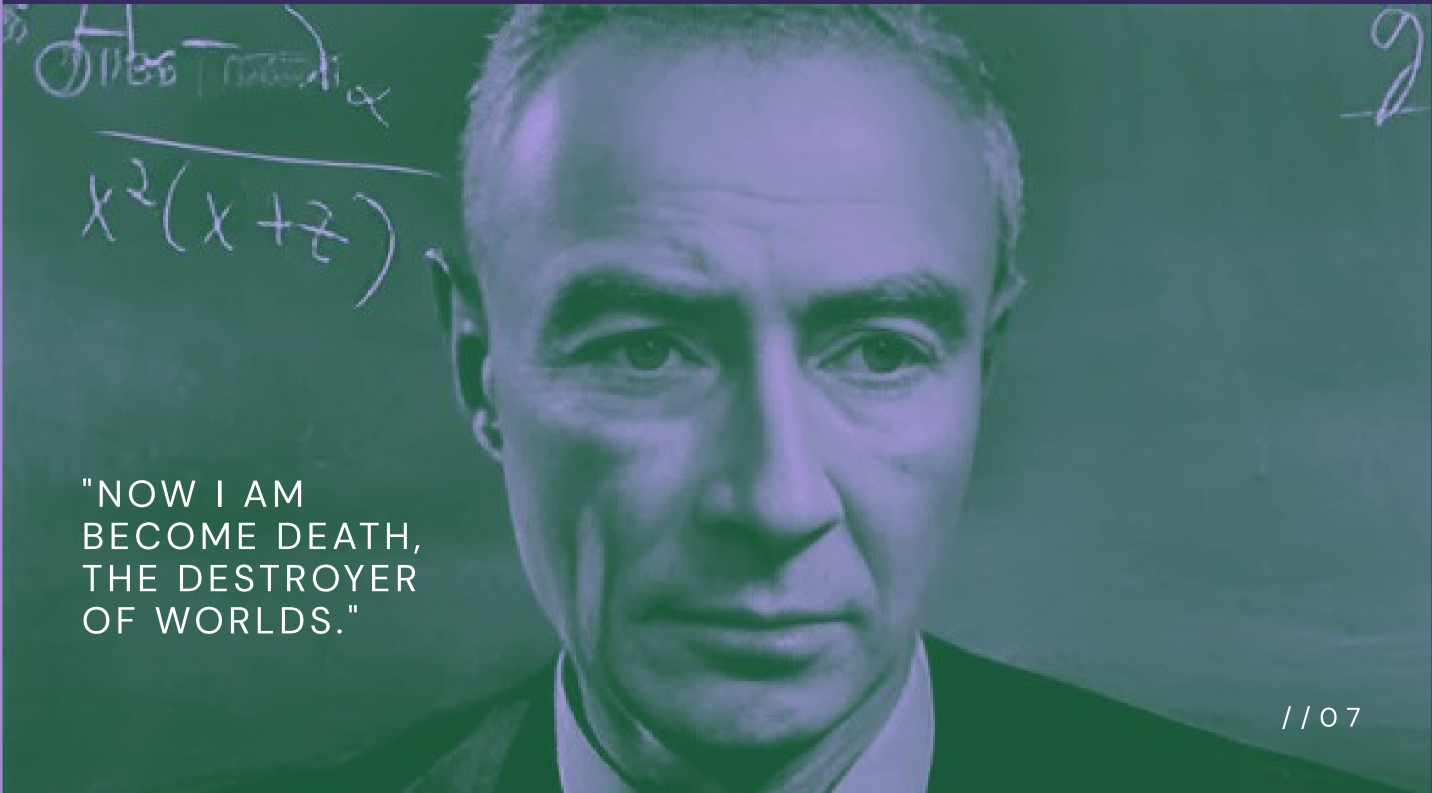


WEAPONS PROLIFERATION

Fast reactors operate largely by converting 'fertile' U-238 into 'fissile' Pu-239. This raises proliferation concerns because plutonium, like U-235, can be made into fuel for atomic bombs. Plutonium from fuel assemblies from fast reactors can be separated chemically and thus more easily than uranium can be enriched to weapons-grade. Indeed there are concerns that a fast reactor currently being built in China, which is surrounded by much secrecy, is intended largely for plutonium production rather than civilian power[11].

To avoid this risk on a larger scale, there needs to be full international visibility of the entire nuclear fuel cycle by the IAEA under the Non-Proliferation Treaty, as is currently the situation globally in non-nuclear weapons states. At the current time, almost 900 nuclear facilities and several hundred other locations in 57 non-nuclear-weapons countries are subject to regular inspection[12].

WePlanet believes control and ultimately elimination of nuclear weapons is essential for humanity's long-term survival and fully supports international controls of the fuel cycle as fast reactors become more widely deployed.



"NOW I AM BECOME DEATH, THE DESTROYER OF WORLDS."

CURRENT FAST REACTOR SMR DESIGNS

The ongoing nuclear renaissance has seen the development of many proposed designs for a new generation of fast reactors, most of which are 'small modular reactors' or SMRs. Below is a list of a few that have caught our attention.

NewCleo: Small modular lead-cooled fast reactor, with 200MWe output, using MOX fuel. Currently in pre-licensing[13].

Natrium reactor from Terrapower[14]: A 345-MW sodium fast rector coupled with molten-salt energy storage system to integrate with renewables and deliver flexible to the grid. Having broken ground in Wyoming, it is the first advanced reactor to move from design into construction[15].

Moltex's Stable Salt Reactor - Wasteburner is optimised to run almost entirely on spent fuel from previous reactors. It also has thermal storage capacity and is in pre-licensing in Canada[16].

Oklo - A much smaller version of the EBR-II that operated in the United States up until the fast reactor program was cancelled by President Clinton in 1994. Oklo will burn nuclear waste at a scale of 75MW[17].

Naarea is developing an even smaller modular fast reactor at 40MW electric. It aims to utilise nuclear waste, and the website confirms our analysis in this report, stating: "The spent radioactive material stored in France will provide a reserve lasting for at least several hundred years."[18]

Westinghouse is proposing a 600MW **lead-cooled fast reactor (LFR)** design that can also perform grid load following, and operate at high temperatures allowing for the cheap production of green hydrogen[19].

The ARC-100 is a sodium-cooled fast reactor offering full 'walk-away' passive safety, operating at atmospheric pressure and also based on the US EBR-II[20].

In France, **Hexana** is proposing to integrate sodium-cooled fast reactors with thermal energy storage based on the French Phénix and Superphénix programs[21].

HOW LONG CAN NUCLEAR LAST?

Of course, the calculation above is merely an idealised scenario to illustrate scale. We are not proposing 100% of generation from fast reactors in any realistic scenario, especially given that renewables are also limitless - the fusion energy of the sun is not going to run out any time soon.

However the numbers are impressive. If we allow future uranium mining, they get even larger: including uranium still in the ground in economically proven reserves, this gives another 6.2 million tonnes, enough for about 2,000 years of clean power globally at current electricity use rates. There are even larger amounts of uranium in unconventional resources, such as dissolved in seawater or as trace amounts in common rock.

And uranium is not the only potential nuclear fuel. We can also use the thorium fuel cycle, as pioneered in India and proposed for a new generation of thorium reactors. Thorium-232 breeds into fissile uranium-233 by neutron capture, making this another fuel source. Thorium is three to four times more abundant than uranium on Earth, making it a source of power which could support human civilisation for tens of thousands of years, merely using conventional reserves.

Nuclear and renewables are thus both realistically limitless on any meaningful timescale, and should both therefore be considered fully sustainable in this sense.

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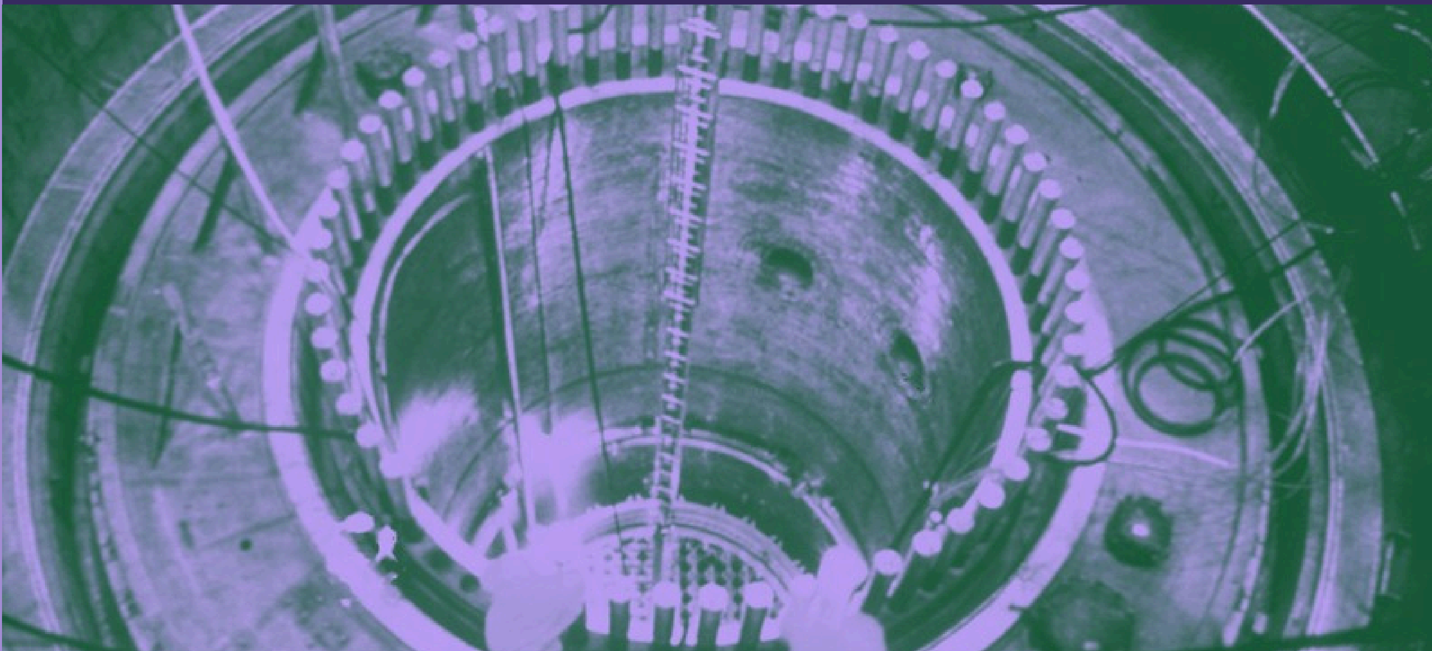

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ABOUT WEPLANET

WePlanet is a network of grassroots charitable organisations driven by science-based solutions to climate change, biodiversity collapse and the need to eliminate poverty.

WePlanet was founded in 2022. The start-up of our activities has been made possible by membership fees and donations as well as very welcome contributions from the Rodel Foundation, Quadrature Climate Foundation, The Dreamery Foundation, Founders Pledge and the Anthropocene Institute. WePlanet neither solicits nor accepts corporate funding.

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