Nuclear Power Without Radioactive Waste – The Promise of Lunar Helium-3

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Abstract

It is possible to generate nuclear power without the production of radioactive waste or radioactive material that can escape the reactor in case of an accident. The key lies in controlling the fusion of third-generation fuels containing ^{3}He. This will not be an easy task because there are both physics and economic issues to face, but it is a goal worth pursuing in the 21st century. The main physics issue is the proof that the D^{3}He reaction can be maintained in an economical manner and later this must also be demonstrated for the more difficult ^{3}He^{3}He reaction. The second issue is the location of large, economical ^{3}He reserves. One approach to the physics problem is to use an inertial electrostatic confinement (IEC) device. One possible solution to the resource issue has already been identified by the discovery that there is at least one million tonnes of ^{3}He on the Moon's surface.

Introduction

The impending world energy crisis of 21st century will require innovative solutions and massive action if we are to avoid a collapse of the Earth's economic system as we know it. Because of expanding populations, increased standards of living, and increasing aspirations in the developing nations, experts now predict that the Earth's energy supplies will have to expand by factors of 3 to 6 in the next 50-100 years.[1,2] It is widely understood that the 21st century will be the last one in which fossil fuels will play (or at least should play) a dominant role. As we move toward the middle of this century, liquid and gaseous fossil fuels will become scarce and more expensive while greenhouse gas emissions may limit the practical usefulness of coal. Hydroelectric facilities, already under fire from environmental activists, will not be able to expand fast enough to fill the gap and terrestrial renewable resources (geothermal, wind, solar, and biomass) will likely satisfy only local needs on an intermittent basis. Of the known energy sources available to society today, only nuclear energy in the form of fission or fusion can fill the enormous energy needs of the 21st century and beyond.

There is enough energy in fissionable material to satisfy the world's needs for hundreds of years if used in breeder reactors.[3] However, the fission industry (at least in the United States) is currently wrestling with the problem of long-lived nuclear waste and is essentially stymied by institutional problems and public acceptance. The use of first-generation thermonuclear fuels, based on the deuterium (D) and tritium (T) fuel cycle, can also provide the necessary energy for centuries to come but the economics of such systems is uncertain[4] and the DT fuels will only go part way towards solving the nuclear waste problem.

It is the objective of this paper to show that there is a solution to the world's energy dilemma that can eventually solve the current major problems facing nuclear energy. It will also be shown that this solution will allow future generations to enjoy the benefits of nuclear energy without the problems of long-lived nuclear waste or the risk of accidental release of radioactive materials.

Nuclear Issues Associated with Fission and Fusion Fuels

The fission industry in the United States has had a remarkable safety record over the past 35 years. Over 11 trillion-kilowatt hours has been generated[5] from 1965-1999, from the fission reaction in Equation 1, without any known fatality to the public. This has been accomplished at costs that are very competitive with fossil fuels even without requiring the carbon-based fuels to pay for the environmental damage that they produce.

Fissionable isotope + neutron →
Two fission products + approximately 2.5 neutrons (1)

$$^{235}U + {}^{0}n \rightarrow 2\ FP + 2.5\ {}^{0}n\ (\approx 1\ MeV)$$

However, there are critics who point to the lack of a national plan that would sequester the waste generated in the process of releasing nuclear energy currently besiege the fission industry. The main problem in the public's eyes appears to be the long time (hundreds to thousands of years) that the fission waste must be isolated from the biosphere. There is also a public fear of nuclear reactor malfunctions that would release radiation into the environment and cause evacuation of large numbers of the population. While the U. S. fission industry can point to a record that has successfully demonstrated that such accidents are extremely unlikely, events in other countries with less stringent safety regulations (e.g., the Chernobyl accident in the former Soviet Union) have kept such fears alive. Finally, there is the issue of proliferation associated with the production of weapons grade fissionable material in reactors. The possible use of enriched ^{235}U and the production of ^{239}Pu for military purposes has caused policy makers in the U. S. to ban the commercial reprocessing of the nuclear fuels which, in the long run, makes the nuclear waste problem even more severe.

Originally, it was expected that fusion reactors would solve the safety and societal problems associated with fission reactors. In the early 1950's, scientists began to investigate the use of the DT fuel cycle to release energy via the reaction described in Equation 2.

$$\text{deuterium} + \text{tritium} \rightarrow \text{neutron} + \text{helium}$$

$$^{2}H + {}^{3}H \rightarrow {}^{0}n\ (14.1\ \text{MeV}) + {}^{4}He\ (3.5\ \text{MeV}) \tag{2}$$

Throughout the 1960's and early 1970's, the main plasma physics issues were addressed and in the late 1970's and 1980's engineers attempted to design power plants that might be able to produce electricity from this reaction.[6] It was not long before it was realized that converting the kinetic energy of the 14.7 MeV neutron (which constitutes ≈ 80% of the total energy released) into a form that could make electricity was harder than expected. There were two reasons for this conclusion. First, the high-energy neutron was known to cause considerable damage to any structure surrounding the plasma, even more than the ≈ 1 MeV neutrons from a fission event. Even now, there still is not a generally accepted solution that would allow the fusion reactor chamber to survive more than a few years of operation before it would have to be replaced. The second difficulty was the fact that these same 14.1 MeV neutrons can produce large amounts of radioactivity. The magnitude of this effect can be appreciated when one remembers that in the fission process (which releases ≈ 200 MeV), there is one neutron produced for every 80 MeV of energy released. In DT fusion, there is one neutron produced for every 20 MeV released. The fusion neutrons can actually cause more than 14.1 MeV to be released when absorbed in the structure and coolant of the reactor. In other words, the DT reaction actually releases four times as many neutrons per unit of energy than a fission reactor.

Another first-generation fuel involves the fusion of deuterium alone. The DD reaction is described in Equation 3.

$$\begin{aligned} 2\ \text{deuterium} &\rightarrow \text{neutron} + \text{helium-3} \quad (50\%) \\ &\rightarrow \text{proton} + \text{tritium} \quad (50\%) \end{aligned}$$

$$\begin{aligned} D + D &\rightarrow {}^{0}n\ (2.5\ \text{MeV}) + {}^{3}He\ (0.8\ \text{MeV}) \\ &\rightarrow {}^{1}H\ (3\ \text{MeV}) + {}^{3}H\ (1\ \text{MeV}) \end{aligned} \tag{3}$$

In this reaction, approximately 35% of the energy is released as neutrons and there is only approximately 7 MeV of energy released per neutron.

Fortunately, other fusion fuel cycles do not release as many neutrons as the two first-generation fuels described in Equations 2 and 3. The so-called second-generation fusion fuel based on the D^3He cycle (Equation 4) emits no neutrons directly, but some of the D ions do react with each other to produce a few neutrons via Equation 3.

$$\text{deuterium} + \text{helium-3} \rightarrow \text{proton} + \text{helium-4}$$

$$D + {}^{3}He \rightarrow p\ (14.7\ \text{MeV}) + {}^{4}He\ (3.7\ \text{MeV}) \tag{4}$$

Depending on the type of fusion confinement approach used, the neutrons constitute approximately 1-5% of the total energy released.[7,8] The overall energy released can be as much as 1800 MeV per neutron in the D^3He cycle.

An even better situation exists with the third-generation fusion fuel cycle $^3He^3He$ described in Equation 5.

$$\text{Two helium-3} \rightarrow \text{two protons} + \text{helium-4}$$

$$^{3}He + {}^{3}He \rightarrow {}^{1}H + {}^{1}H + {}^{4}He\ \ (\text{total } 12.9\ \text{MeV}) \tag{5}$$

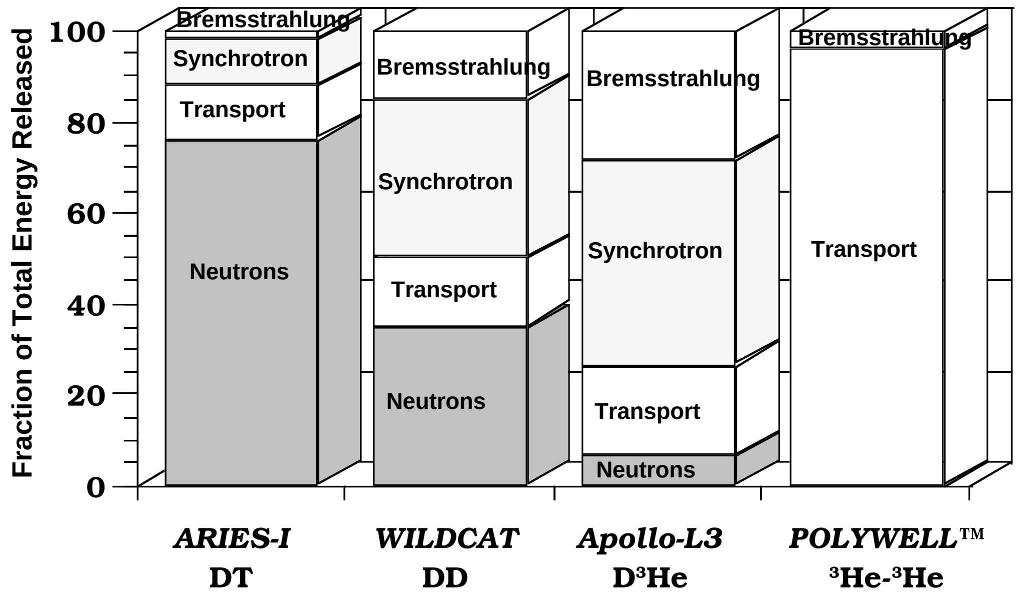

Figure 1. The fraction of energy released from the DT, DD, D^3He, and $^3He^3He$ fuel cycles is quite different. In the long run, those fuels that emit the least amount of neutrons will be favored if they can be used in economical systems.

The fact is that the $^3He^3He$ reaction produces no neutrons. There are no side reactions and neither the fuel nor its direct reaction products are radioactive. In a sense, it is the perfect nuclear reaction!

A summary of the fusion product energy release from the four fusion fuel cycles described above is given in Figure 1. The important part of this figure is the amount of energy released in neutrons: 80% in DT, 35% in DD, 1-5% in D^3He, and 0% in ^3He-^3He. Since the amount of radioactivity and radiation damage is directly proportional to the number of neutrons, it is clear why the second- and third-generation fusion fuel cycles are much preferred over the first-generation fuels.

Nuclear Waste Issues

There are two aspects of radioactive waste from nuclear systems that need to be considered: the half-life of the waste and the volume of waste generated per unit of useful energy produced. The fission products dominate the waste from a fission reactor while the waste from a fusion reactor is dominated by the neutron activation of the structural material (i.e., steel, vanadium, carbon, etc.). A summary of the waste from fission and fusion systems is summarized in Table 1. The level of waste has to do with the form in which it must be placed in the repository and the length of time that it must be monitored.[9,10] For example, Class A material can be buried within one meter from the surface with no container requirements and has to be monitored for no more than 100 years. Class C material must be buried deeper than five meters in a concrete vault and monitored for 500 years. All other material must be disposed of as deep geological waste in a facility such as Yucca Mountain. Obviously, the cost of disposal is highly non-linear with the class of waste.

A quick assessment of Table 1 reveals that fission waste will have to utilize all three classes of waste disposal sites and the relative cost will be ≈ 100 times more than DT fission facilities and as much as 1,000 times the cost of waste from D^3He systems.

If This Such a Good Idea, Why Hasn't It Been Done Before?

There are two main reasons that second- and third-generation fusion fuels have not been used extensively in the past:

1. The physics requirements of these fuels are much more difficult than the first-generation fuels.

2. Even if the second- and third-generation fuels could be used, there was no large resource of ^3He known before 1986.

Class of Waste	Relative Cost of Disposal	LWR Fission (once through)	DT (SiC)	D^3He (SiC)	$^3He^3He$ (SiC)
		Relative Volume of Operational Waste/GWe-y			
Class A	1	Several times the Class C waste	Several times the Class C waste	1	0
Class C	10	55	7	0	0
Deep Geological (Yucca Mountain)	1,000	3	0	0	0

Table 1. The relative cost of disposing of fusion waste (using SiC as structure) is considerably less than for Light Water Reactor fission waste. The class of waste is described in Reference 10.

A measure of the energy required to promote the various fusion reactions is given in Figure 2 where the product of the energy released times the reactivity is plotted as a function of the energy of particles as they collide with each other. It is clear that the DT reaction is the most reactive at the lowest energy and that is where practically all of the world's research is now currently directed.

The D^3He reaction requires approximately three times more energy to initiate and to operate in a power mode. The $^3He^3He$ reaction requires another factor of three to four to initiate and perhaps a factor of ten more energy to operate. While the D^3He power may be produced in a thermonuclear device such as a tokamak, the $^3He^3He$ fuels will clearly require a different confinement concept.

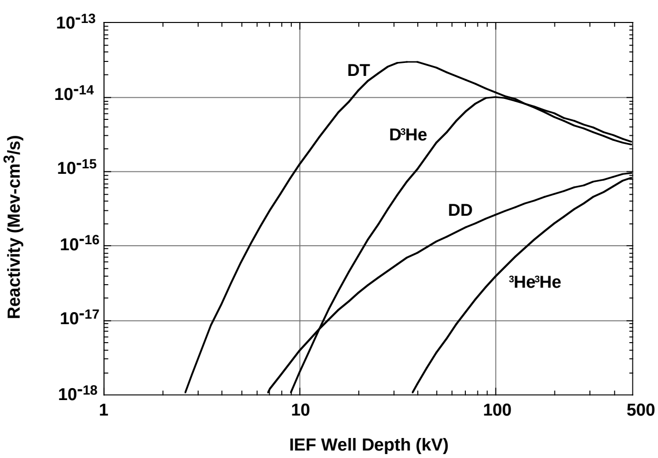

Figure 2. The DT fusion fuel cycle requires the least amount of energy and releases the most amount of energy when compared to the D^3He and $^3He^3He$ fuel cycles. However, the superior environmental features of the second- and third-generation fuels provide an incentive to develop those cycles.

For reasons outlined in previous papers[11-14], we have chosen to demonstrate the usefulness of the second- and third-generation fuels in a fusion fuel cycle in a device that relies on electrostatic confinement of the plasma as opposed to the traditional electromagnetic or inertial confinement schemes. This is not a new concept. Farnsworth[15], the inventor of television, first proposed the IEC device. Hirsch[16] first demonstrated the operation of an IEC device with DD and DT. Because of the higher energies needed to cause the D and ^3He to fuse, this concept is much more effective at providing high-energy ions than the tokamak or laser-driven devices around the world.

A schematic of the Wisconsin IEC facility[14] is shown in Figure 3 and a photo of the device operating at steady state is given in Figure 4. The basic idea of this approach is to surround an inner cathode charged to a negative potential of 50 kV or more with a larger spherical mesh globe that is positively charged. By mechanisms described elsewhere,[15,16,17] positively charged fuel ions are formed around the outer grid and accelerated inward by the large negative potential. When the inward streaming ions meet energetic ions from the opposite direction they can fuse, releasing energy or scatter and "climb" the potential hill on the other side and return to the center of the device. Obviously, the deeper the potential well, the higher the energy of the colliding ions and the higher the fusion rate.

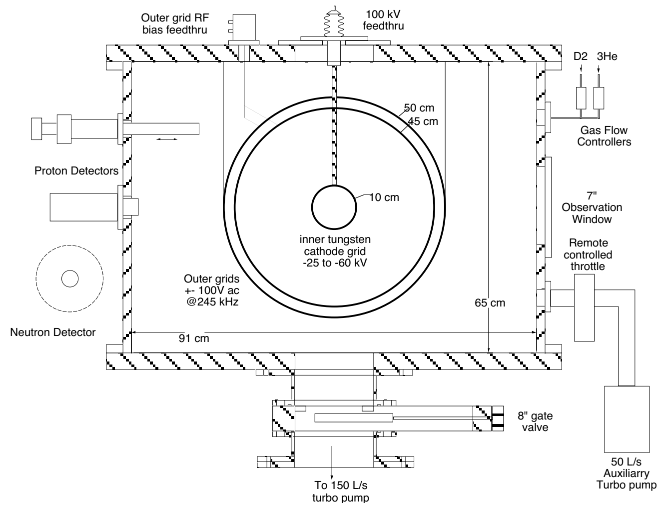

Figure 3. A schematic of the University of Wisconsin IEC device[14] shows the 10 cm diameter inner cathode surrounded by a 50 cm diameter anode. The inner cathode is negatively charged up to 75 kV which attracts the positively charged D^+ and $^3He^+$ (and $^3He^{++}$) formed at the anode by energetic electrons.

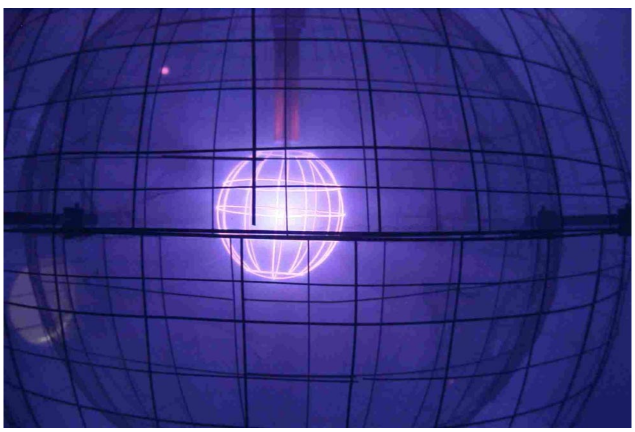

Figure 4. Photograph of a D-^{3}He plasma in the center of the Wisconsin IEC device. Currently fusion rates of nearly 3 x 10^6 per second at 55 kV and a current of 60 mA have been achieved.

Initially, the IEC device at Wisconsin was used to study the physics associated with electrostatic confinement. In those studies, a DD fuel was used and steady-state fusion reaction rates of ≈ 1 x 10^8 per second have been produced to date[14]. In late 1998, our attention switched to the D^{3}He cycle and an example of the progress made over the past two years is shown in Figure 5. The steady-state reaction rate has been increased nearly by a factor of 1,000 over that time. Use of higher accelerating potentials and more efficient cathode design should boost the fusion rate to levels where PET isotopes such as ^{15}O and ^{18}F can be made for commercial distribution[11-13]. It is hoped that the experience gained with the near-term devices will lead us into the next phase where electricity production can be investigated.

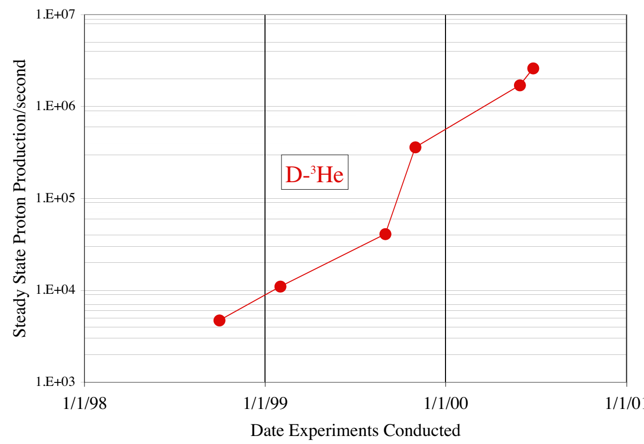

Figure 5. Progress in the steady-state production of D^{3}He fusion has been rapid as more is learned about the physics of IEC plasmas.

If the ^{3}He containing fuel cycles can be successfully demonstrated in the laboratory, one still must address the issue of ^{3}He resources. Nearly 15 years ago,[18] it was pointed out that while there are limited resources of ^{3}He on Earth, the Moon contains as much as a million tonnes of this isotope implanted in the lunar regolith by the solar wind. A measure of the potential impact of this resource on the Earth is the fact that as little as 150 tonnes of ^{3}He could supply the entire electrical needs of the world in the year 2000. Obviously, if such a fuel source could be economically extracted and brought to the Earth, our energy needs would be satisfied for perhaps a thousand years or more. Such an immense source of clean energy will take much more research to develop, but if the promise of nuclear energy without the associated problems of nuclear waste is achieved, then the Moon will become a strategic factor in the future of the Earth.

Observations on the Development of Fusion Energy in the 21st Century

If one accepts the need to develop nuclear energy to satisfy the needs of Earth's inhabitants in the 21st century and beyond, then it is reasonable to ask "How can one transition from the current fission nuclear economy to a future fusion economy and what would be the benefits of such a transition?" A detailed discussion of this important question is

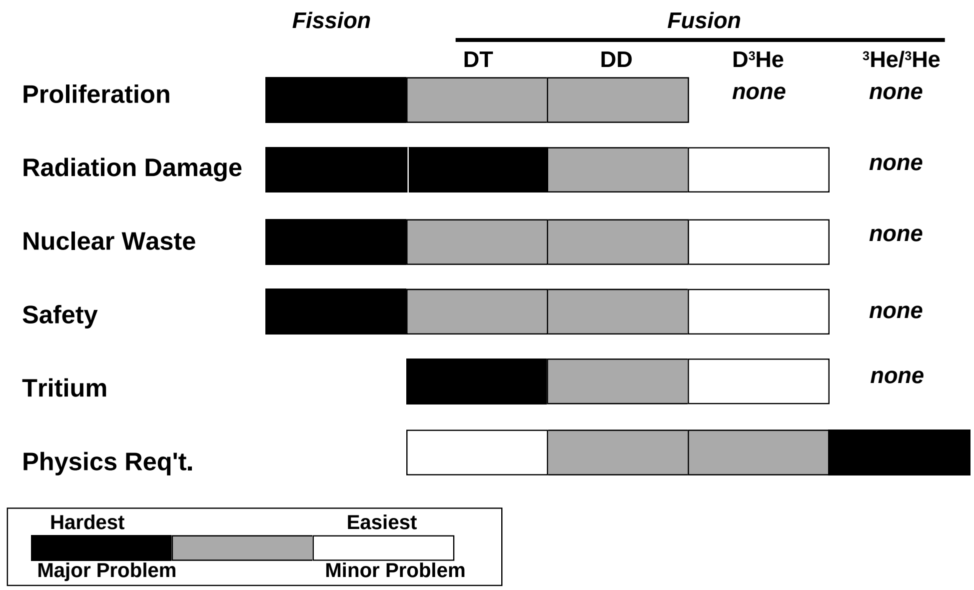

Figure 6. It is clear that a transition from current fission reactors to future first-, second-, and third-generation fusion fuels will greatly alleviate, or even eliminate some of the most serious concerns over nuclear power. However, these gains are purchased at the cost of solving more difficult plasma physics confinement problems.

beyond the scope of this paper but the general outline of an answer is summarized in Figure 6. For example, the level of concern over proliferation, nuclear waste, safety, and radiation damage to reactor components is very high in the case of fission reactors. This is not to say that the fission industry has not or cannot solve those problems, but it is clear that the public has concerns in those areas. If one moves to the first-generation fusion fuels, the issues of proliferation, nuclear waste, and safety are somewhat alleviated. However, the radiation damage issue is as difficult (or some would say even more difficult) to solve. One additional area of concern that is faced by first-generation fuels is the safe handling of large amounts of radioactive tritium.

Basically, the use of second-generation fuels (D^3He) eliminates the proliferation issue and the safety issues are greatly reduced. However, these advantages are purchased at the price of more difficult physics requirements. Finally, the move to the third-generation fuel ($^3He^3He$) completely removes the concerns over proliferation, radiation damage, nuclear waste, safety, and tritium. However, these benefits have to be balanced against the much more difficult physics requirements of this fuel cycle.

Conclusions

It is appropriate, as society enters a new millennium, to question how future generations will be able to sustain life on Earth while expanding into the solar system. One of the essential questions to answer is how will future generations find enough energy to avoid the economic and environmental collapse that could occur if fossil fuels become prohibitively expensive in the next 50-100 years. Presently, nuclear energy appears to be the only solution capable of sustaining society as we know it. There is a growing resistance, whether justified or not, to expansion of fission energy. Fusion energy represents an improvement over fission, if it can be shown to be economic, but the first-generation fuels (DT, DD) are very capital intensive because they generate large amounts of radioactive waste and must contain large amount of radioactive materials in a hostile environment. The second-generation fuels (D^3He) represent a tremendous improvement over the DT and DD cycles but face somewhat more difficult plasma physics requirements. Ultimately, the third-generation fusion fuels ($^3He^3He$) could remove the concern of the public over radioactive waste and releases of radioactivity during reactor malfunctions. This optimism must be balanced against much more challenging physics regimes compared to those for the first- and second-generation fusion fuels.

If one takes the long-range viewpoint, it is clear that some effort should be expended early in the 21st century to developing the third-generation fusion fuels. The ultimate payoff from such research could be the "pot of gold at the end of the rainbow", the production of clean, safe, economical, and long lasting nuclear energy without nuclear waste in the 21st century.

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