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Design and Analysis of Hydrogen Free Piston Linear Generator

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***Abstract*: A free-piston linear generator utilizes the power produced from hydrogen fuel and transmits it to the powertrain of a vehicle. In this study, a prototype FPLG, the two-stroke engines were developed and a linear generation system was incorporated in between the cylinders to get the electricity and the start of the engine as well. Venturi effect based on the Bernoulli principle was employed and the variable pressure and velocity conditions for different piston positions were studied. Nitrogen gas was provided in the bounce-back chamber for preventing striking of a piston to walls and having a smooth operation. Helical tubes with cooling water inside it were wounded around grooves provided in the wall thickness of the cylinder. This hypothesis focuses on the use of hydrogen as a power generation fuel which has been found to give higher combustion rates and effectively show improvements in power output and efficiency when employed at appropriate working conditions. A different type of engine design is introduced and some advancements in the structure of the combustion chamber are made for achieving high-performance characteristics.**

***Keywords*: Bernoulli principle, Free-piston engine, Hydrogen fuel, Linear generator, Two-stroke engine, Zero emissions.**

1. Introduction

Since the modernization of the automobile industry conventional crank-shaft engine has provided the world with a reliable mechanism for carrying all types of goods over long distances concerning fuel consumption and efficiency factors. There are different types of piston arrangements available at the present condition from in-line to the opposite piston for the generation of power. These two-stroke engines' linear motion of the piston is converted into a rotary motion of the crank. Due to mechanical linkages, there is a problem of frictional losses and eventually, it affects the output efficiency of the engine. The pollutants at the exhaust of these engines are harmful to humankind and the eco-system. The greenhouses gases and other harmful emissions are the major reasons for drastic climatic changes like global warming, acid rains melting of ice, etc. Given the fact that fossil fuels are depleting due to its regular usage, it has become very important that we shift towards a renewable source of energy as the fuel used by conventional engines ultimately leads to pollution. A better option would be to use hydrogen as a fuel for power generation as it is available in abundance and it leaves almost zero exhaust gases upon combustion.

2. Existing Design

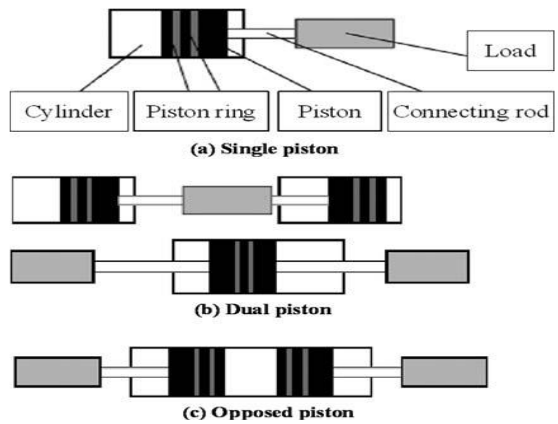

Fig. 1. Various free-piston configurations

- In a free-piston engine (FPE), piston motion is not restricted by any mechanical linkages whereas conventional engines have a slider-crank mechanism to convert piston linear motion into a rotary motion. The basic operating principle is similar to that of a conventional reciprocating engine i.e. the chemical energy of the fuel is transformed into mechanical energy employing linearly moving piston assembly. The main design concept is to utilize the minimum transformation of fuel's energy into electricity which is used by a linear generator. A two-stroke engine is usually used because it provides power stroke once per each stroke.
- The free-piston linear generator (FPLG) consists of one moving part that translates from TDC to BDC in the cylinder, this free-piston configuration allows the stroke length or compression ratio to vary almost instantaneously in between cycles and reliable compression ratio control enable the optimization of the compression ratio in different operation conditions, which is not possible with conventional crankshaft engines. Thus, a variety of alternative fuels can be applied to the engine without major hardware modifications.
- The piston in this engine consists of a permanent magnet and the stator winding of coils which revolves around the cylinder and there is a certain specified gap between the piston assembly and linear generator. When the piston is in translatory motion in the combustion chamber due to the motion there is the formation of flux across the magnetized

region leading to electromagnetic induction.

- Though there has been suggested so many free-piston configurations in the referred literature, many of them are only for the computational approaches before the demonstration or just for the introduction of their prototypes which are far from the completion of stable operation. That is because there are still many technical difficulties remained and this makes the goal for the stable and more efficient free-piston engine combustion hardly attainable. For an FPE generation system to be commercially available, it is strongly demanding to show high efficiency and stable operation apart from the low-cost benefit. In this study, a new thesis of FPE and a linear generator were tested with a computer-aided design for optimizing the process with higher efficiency and lower emissions than the conventional generation systems.

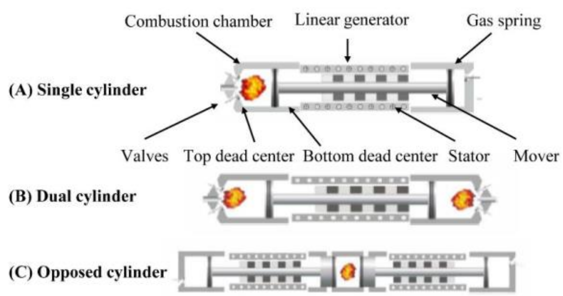

Fig. 2. Illustration of the principle of the free-piston linear generator

3. Proposed design

The proposed design has a capsule shape that is compact and has pressure withstanding ability. The proposed engine design has a diverging shape at both ends of the engine the purpose of this end is to ensure the bouncing of a piston in forwarding stroke so it will not collide at the end of the capsule. The combustion chamber shown in fig. [4] is a venturi shape chamber it is designed by the following Bernoulli's principle which helps the fuel-air mixture travel faster due to converging and diverging shape. Fig [3] shows the assembly of the capsule shape engine. There is two gas tank one of hydrogen(H_2) as fuel and another one of nitrogen (N_2) which acts as a coolant as well as supply to bounce chamber. The N_2 supply is to the end of the cylinder to push the piston forward. Around the engine, there is a helical tube that contains water as a medium which will help to maintain stable temperature during the working of the engine and help minimize the energy losses while the generation of electrical energy; the selection of helical coolant tubing which is implanted in design is based on the Joules-Lenz's law of heating. This helps to prevent the winding resistance from increasing and having a current loss. A piston is made up of hard insulating material to prevent any short-circuit in the chamber. The piston has an alternating magnetic pole ring fitted around it with a horizontal and vertical magnetic flux line which will then cut the winding across the engine.

A. *Working procedure of engine*

1. Hydrogen gas and the air are introduced into the cylinder via a nozzle from the air intake (via air filter) & due to nozzle affect its speed gets increased and thus a mixture of hydrogen gas and air (generally called as charge) is injected inside the combustion chamber.
2. A small amount of current from starter battery (generally of 12 V) is given to the coils and thus due to Electro-magnetic effect metallic core (i.e. Piston made of ferromagnetic material "Iron") gets in motion as magnetic force (F=BILSINα) is acting on it. And hence both pistons start reciprocating in the opposite direction and due to compression stroke performed by both the temperature of the piston of charge gets increased and thus the charge gets ignited.
3. After one cycle the current supply gets cut off from battery and piston start gaining higher RPM as per mass flow rate of air intake varies.
4. Then due to Iron core (i.e. piston) having reciprocating motion there is currently induced inside the coils as per Faraday's and Lenz's Laws and thus we start getting input in the form of induced current and this current is stored in capacitors or supplied to the powerhouses where it is directed for further use. It is also used to run the hub motor in case of an electric vehicle.
5. To cool the combustion chamber and for proper heat transfer helical drilled circular cross-sectional cooling tubes are also introduced in the capsule itself. Coolant like water is entered into the tube inside the cylinder through the radiator which is getting cooled by forced convection by from air sucked by cooling fans if required.
6. Venturi like convergent & divergent area is given in the design to maintain proper pressure requirements for combustion & nitrogen bouncing effect during the time of the collision.
7. For bounce back of piston when it moves from TDC to BDC (i.e. both the piston when moving in the opposite direction from the center to both fore-ends at the time of suction stroke) there comes a situation where they can collide with the walls of a capsule and thus to prevent this inert gas nitrogen is introduced in both the ends of capsule. Also, due to the eddy current effect induced in the cross-section of the piston (i.e. metallic core), this force acting on the piston opposes the motion of the core. During operation, if this core is reached at the extreme ends nitrogen gas prevailing in the chamber bounces it back towards the center and thus compression stroke gets started.
8. NLGI 2 grade grease is used in between piston (i.e. Iron core) and chamber walls to prevent it from material wear as well as to prevent the piston from corrosion. Additionally, this grease also acts as a coolant. This grease can form a protective film thereby, prevents mixing of charge with inert gas (N_2) along with the help

of compression rings & nylon O rings.

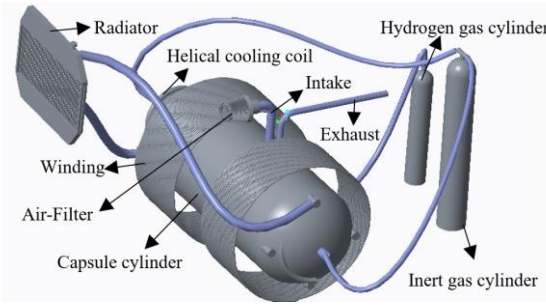

Fig. 3. Engine Assembly

The above fig. illustrates the entire assembly of the Hydrogen linear generator; in which the inert gas cylinder, as well as hydrogen gas cylinder, has a pressure regulator to maintain nitrogen gas and hydrogen gas flow in a certain range. the intake has an air filter attached to it to avoid unwanted dust particles into the combustion chamber. In this design, there is also a helical cooling tube that uses water as a medium to absorb and transfer the heat that generates in the combustion chamber due to the combustion of the Air-Fuel mixture to the radiator.

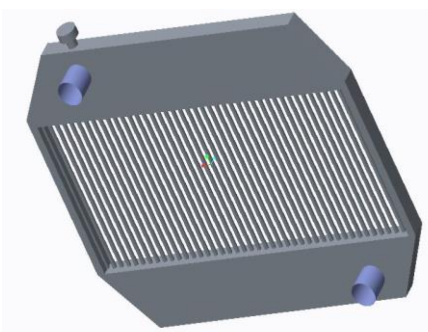

Fig. 4. Radiator

The work of the radiator is to exchange heat from the system that generates in the cylinder. It uses water medium to carry the heat from the cylinder to the radiator inlet; when the hot water enters into the radiator fins (made of aluminum) where atmospheric air absorbs the heat from the hot water and water with lower temperature is send back to the cylinder piping to repeat the cycle of cooling.

Fig. 5. Piston

The piston is made up of the ferromagnetic material (Iron) which has grooves at a few distances at both ends on which piston rings are fitted to avoid the inert gas and air-fuel mixture from mixing.

Fig. 6. Air Filter

An air filter is an important part of a car's intake system because it is through the air filter that the engine 'breathes.it usually made up of paper, cotton, metal, etc.

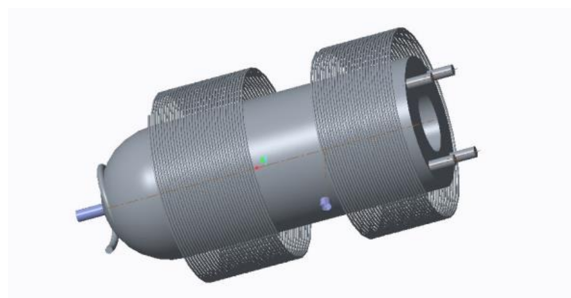

Fig. 7. Cylinder

The above figure shows the helical coil carrying water in tubes around the cylinder for cooling the combustion chamber while working.

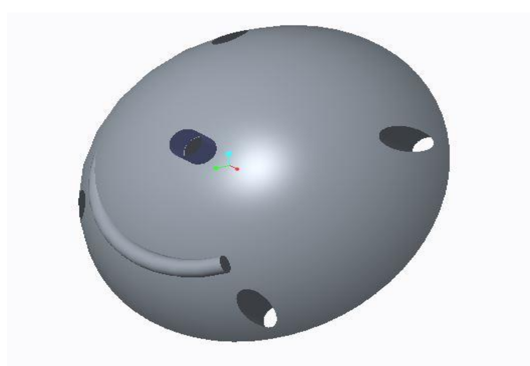

Fig. 8. Cylinder head

The cylinder head has one hole at the center from where the inert gas gets into the cylinder to push back the piston to forward stroke. the cylinder head is made up of graphite material to withstand the pressure.

Fig. 9. Hydrogen Gas Cylinder

It contains compressed hydrogen gas in the cylinder; Normally the hydrogen cylinder is red in color and has a pressure range from 30bar to 900bar.

Fig. 10. Inert gas cylinder

The above figure has compressed nitrogen gas in the cylinder; the Nitrogen cylinder is 5'and black in color. pressure in the cylinder is 151.687bar.

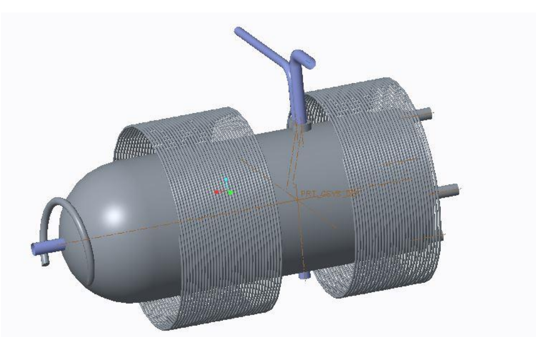

Fig. 11. Intake and Exhaust on a cylinder

4. Computer-Aided Engineering

To validate the design of piston and capsule to be safe for a certain life period use of FEA (Finite Element Analysis) is necessary and for this reason, we had used "Ansys Workbench 16.0" student version available

A. Static structural analysis of piston

As per the force application at the time of power stroke, boundary conditions are applied on the piston across longitudinal and lateral directions and hence, we had concluded that it is achieving Vorm Mises stress of 118.17 Mpa having and FOS (Factor of safety) of 3.62.

Force on piston top-F=p*A

$F=5 *10^3 * 0.25 =1.25*10^3$N

Material – Iron (Ferromagnetic)

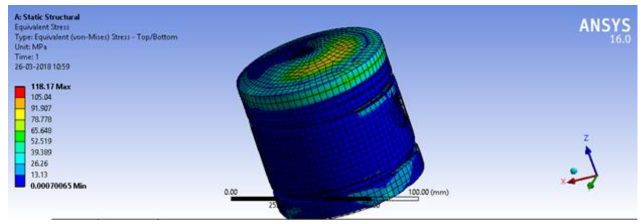

Fig. 12. Piston Analysis

B. Static structural analysis of capsule

The capsule is manufactured by Gray Cast Iron using the casting process. A capsule contains movable objects such as piston stress is induced inside the structure which is generally tensile in nature and also considering the working conditions the internal temperature reaches up to 900^0C or above due to this thermal expansion is probable and thus design virtual validation is necessary.

Properties of Outline Row 6: Cast

	A	B	C	D	E
1	Property	Value	Unit		
2	Density	7910	kg m^-3		
3	Isotropic Elasticity				
4	Derive from	Young's ...			
5	Young's Modulus	99000	MPa		
6	Poisson's Ratio	0.21			
7	Bulk Modulus	5.6897E+10	Pa		
8	Shear Modulus	4.0909E+10	Pa		
9	Field Variables				
10	Temperature	Yes			
11	Shear Angle	No			
12	Degradation Factor	No			
13	Tensile Yield Strength	330	MPa		
14	Compressive Yield Strength	570	MPa		
15	Tensile Ultimate Strength	430	MPa		
16	Compressive Ultimate Strength	570	MPa		

Fig. 13. Gray cast iron material properties

After meshing and applying boundary conditions to the model the analysis process was done in ANSYS 16.0 version. It computed the deflection concerning the boundary conditions applied then based on deflection stresses were calculated. Results are observed and consequently, changes are planned according to high-stress regions acquired. If the stresses are far from the permissible limits then variations such as a change in material, change in thickness of component or addition of ribs, etc. are made according to suitability. Maximum Von-mises stress according to the plot is 101.97 Mpa. The maximum value of stress is less than the yield stress of Gray Cast Iron (Sut=330), which results in a factor of safety greater than 1 (it is selected to be 3.25). While the Maximum deformation obtained is 0.0631 mm. This maximum deformation appears at the point which is subjected to maximum force. The above stress and deformation plots are used for selecting other materials and removing material for optimization.

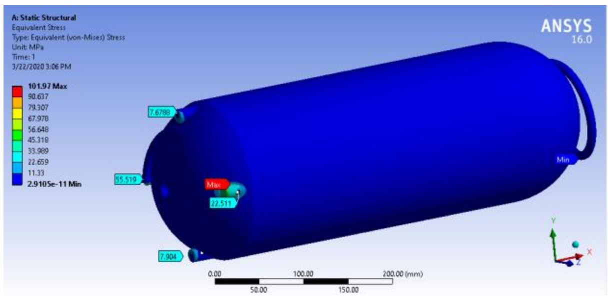

Fig. 14. Von Mises Stress

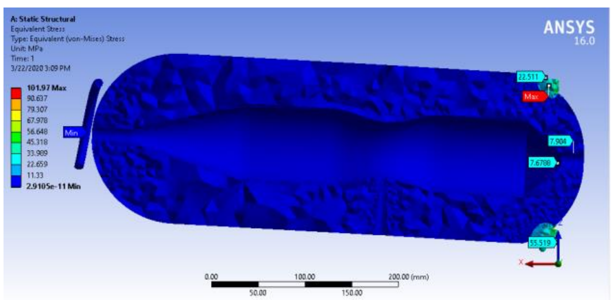

Fig. 15. Von Mises Stress (Cut section)

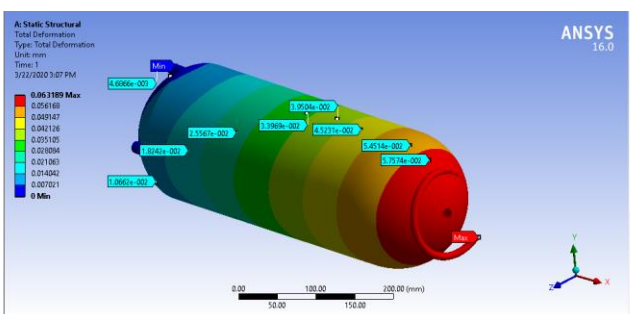

Fig. 16. Total deformation

5. Computational fluid dynamics

To validate the required pressure generation in venturi's convergent & divergent section for proper combustion and to maintain required minimum pressure for inert gasses CFD-Fluent Ansys solver version 16.0 is used.

A mass flow rate of charge from a nozzle is used as the input (ie m_f=0.75 kg/m^3). Also, introduce hydrogen as fluid passing through the enclosure.

Note: The mass flow rate is decided as per the dimensions of the input nozzle & intake manifold.

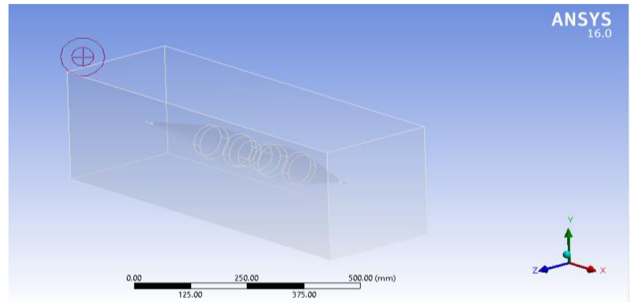

Fig. 17. Enclosure Formation (0.1m*0.25m*0.1m)

Meshing parameters:
Aspect Ratio =1.84 (avg)
Jacobian = 0.8
Element Quality = 0.88
Warping Factor = 0.00

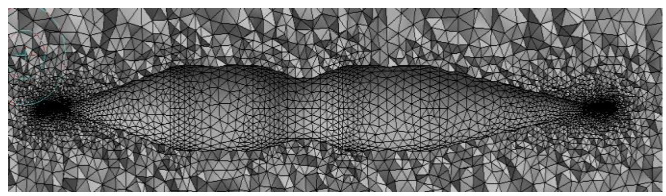

Fig. 18. Meshing

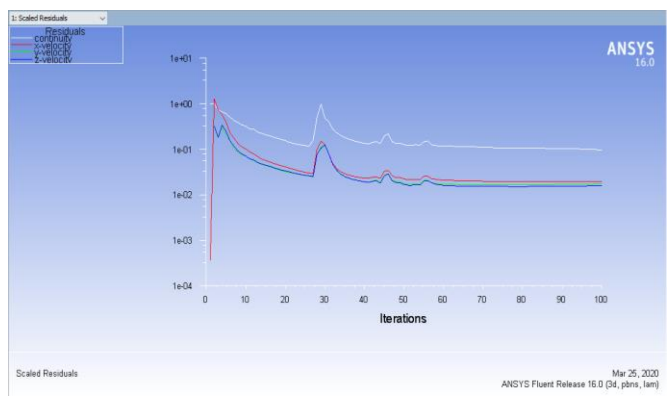

Fig. 19. Residuals

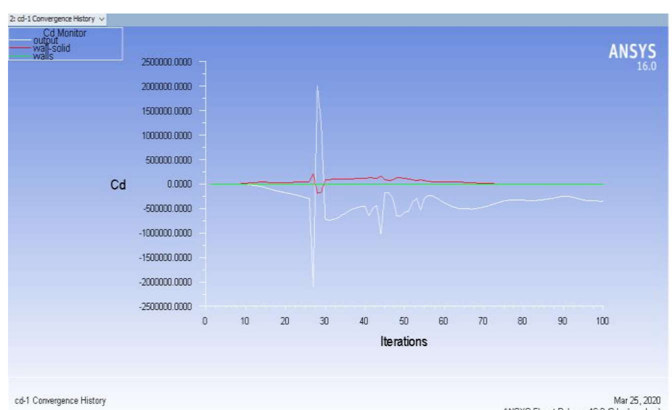

Fig. 20. Drag monitor

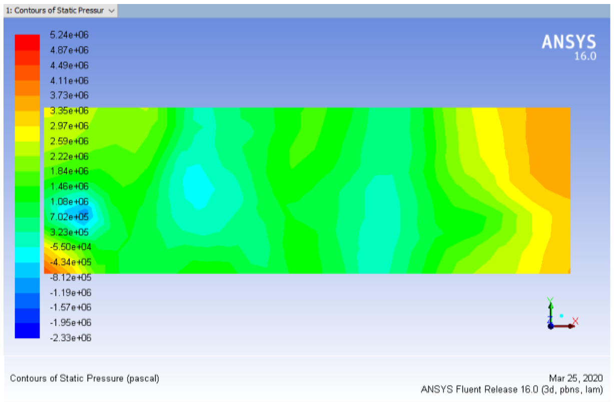

Fig. 21. Static Pressure

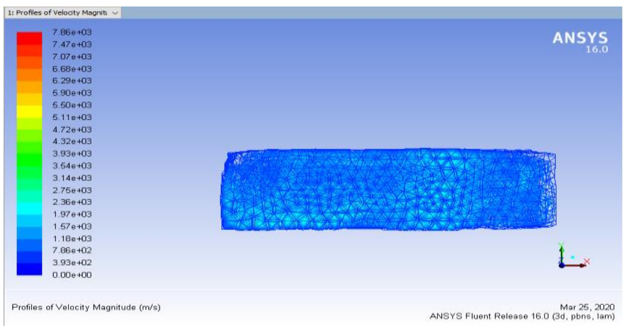

Fig. 22. Velocity

6. Conclusion and Future Scope

Free piston linear generator (FPLG) can be used as an alternative for the generation of electric power. FPLG system gives higher output power as compared to conventional crankshaft engines. It has more advantages over conventional engines like compact size, low production cost, lesser frictional losses, and easy manufacturing which will help achieve an optimized process in the automotive industry. Hydrogen fuel having low consumable and high availability can be used as an alternative to other conventional fuels like CNG, gasoline, solar panels or even battery cells. Considering its high power density with a variable compression ratio it has proven to be a simple and reliable method of power generation. By using hydrogen as a fuel in these type of engines it will help ensure almost zero-emission levels attributing to high burning rates of hydrogen gas.

In this thesis, a capsule-shaped, two-stroke opposing dual-piston engine is studied for its performance characteristics at high temperatures. The design was optimized for the selection of the material of various components and finding the maximum permissible stress conditions across the given boundaries. Although design analysis and simulation were done to validate the working of design theoretically, there is no experimental proof for the working of this system. The computational fluid dynamics (CFD) method was used to find out the pressure generation across various regions of the combustion chamber and fulfill the minimum pressure requirements of inert gas. Further experiments and case studies must be conducted to validate the results. Advanced studies will prove the efficiency, feasibility, and reliability of the engine in depth.

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