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Review

Use of Nano Fluids in Nuclear Technology: A Review

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Abstract. Nuclear energy is the most important source to produce electricity. The production processes are very important for reducing risks and increasing the efficiency. Nano-fluids also have the potential to transfer heat with improved thermo-physical properties which can be applicable in many devices for better performance. Advancement in nanotechnology develops new fluids which transfer heat called nano-fluids. So, for heat exchange in the core of nuclear reactors, nano-fluids are used because of their unique heat transfer properties. For significant improvement in properties, the modest concentration of nano-particles is required. Recent research is more about behaviour of nano-fluids to utilize their unique properties. Heat transfer property is very important for industrial applications, nuclear reactors, transportation, and electronics and also in biomedicine. Nano-fluid acts like smart fluid, where heat transfer property can be controlled. This review establishes a focus on the wide range of recent and future uses about nano-fluids, related to their improved properties of heat transfer that may be controllable and other specific properties of nano-fluids.

Keywords: nanotechnology, CHF, thermo-physical properties, nano-particles

Introduction

Nuclear energy is the most exciting origin of electricity. Those production processes which are based upon nuclear energy are very important for reduction of risks and to increase the efficiency (Pioro and Duffey, 2015). In nuclear reactors, water has great significance because it acts as coolant internally and neutron moderator externally, according to the type of nuclear reactor (Attia, 2015). Advancement in nanotechnology has produced new fluids that transfer heat through suspended nano-particles within them, are called nano-fluids (Singh and Gupta, 2016). Nano-fluids are basically suspensions of nano-particles in base fluids (Saidur, *et al*., 2011). Nano-sized suspensions vary the convey and thermal turn over properties of the base fluids (Trisaksri and Wongwises, 2007). To exchange heat in the core of nuclear reactors, nano-fluids are used because of their unique heat transfer properties. In recent research, synthesis and application of nano-fluids is a very exciting area of study (Eapen *et al*., 2007; Li and Peterson, 2006; Hong, *et al*., 2005; Murshed, *et al*., 2005). Nano-fluids exhibit high thermal conductivity (Das *et al*., 2003; Eastaman *et al*., 2001; Xuan and Li, 2000; Lee *et al*., 1999; Wang *et al*., 1999; Eastman *et al*., 1996; Hamilton and Crosser, 1962) and other engrossed thermo-physical characteristics such as density Drew and Passman, 2006), thermal diffusivity (Hamilton and Crosser, 1962), viscosity (Brinkman, 1952) and conective heat transfer (Kim *et al*., 2004; Khanafer *et al*., 2003; Putra *et al*., 2003; Kang *et al*., 2001) coefficients as compared to other conventionally used base fluids (Wong and De Leon, 2017; Wei *et al*., 2010; Chen and Xie, 2009; Wei *et al*., 2009) because of its solid nano-sized suspended particles. The thermal conductivity of nano-fluids is varied by their size, shape, pH of suspended nano-particles, base fluid type and particles used for coating (Trisaksri and Wongwises, 2007). Other physical properties are also affected with thermal conductivity like temperature and volume (Philip and Shima, 2012; Wen *et al*., 2009; Wang and Mujumdar, 2007; Choi and Eastman, 1995). There is an improvement in thermal properties of nano-fluids due to addition of nano-particles and their aspect ratio (Wang *et al*., 2003). For significant improvement they require modest concentrations and proper dispersion of nano-particles. To utilize their unique properties, recent research is more focused on behaviour of nano-fluids. Contemporary work has analyzed that the 10 ppm concentration of nano-particles gives conductivity enhancement up to three times, so both have inverse relationship (Choi, 2009). Nano-fluids act like smart fluids, where change in heat transfer property can be controlled. This work focus wide range

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of recent and future usage of nano-fluids, related to their improved heat transfer properties that may be controlled and other specific properties (Wong and De Leon, 2010). Nano-fluids also have the significant heat transfer (Vassallo *et al*., 2004; Das *et al*., 2003a and b; You *et al*., 2003) properties (Gupta *et al*., 2017) with improved thermo-physical properties for high performance (Saidur *et al*., 2011). Recently available data shows that nano-fluids have high temperature invariant thermal conductivity which has less particle-concentrations as compared to those fluids which were used earlier which results in the better performance of nano-fluids in multiple applications (Tran and Lyons, 2007). Due to their best thermal efficiencies, nano-fluids has improved their performance in industrial applications (Wong and De Leon, 2010). For different applications, different properties of nano-fluids such as overcoming heating effects in power plants, micro-electronics and chemical processes (Khattak *et al*., 2016). Heat transfer property is significant for transportation applications also (Solangi *et al*., 2015). Nano-fluids have shown great potential as a new generation coolants in vehicle thermal management systems (Choi *et al*., 2008; Ollivier *et al*., 2006) chilling fluids (Leong *et al*., 2010), medicine industry (Yu *et al*., 2007) anti-bacterial activities (Hirota *et al*., 2010; Zhang *et al*., 2008), power production (Saidur *et al*., 2011; Elcock, 2007) creation of new sensors (Scott *et al*., 2008; Ying and Sun 1997), transmission systems (Tzeng *et al*., 2005), in nuclear reactors (Zarifi and Jahanfarnia, 2014), in hotness shift efficiencies of freezers, and in private refrigerators (Buongiorno *et al*., 2008). Table 1 highlights previously reported characteristics of different types of nano-fluids.

Nuclear reactors and nano-fluids. Kim *et al*. 2017 and (Lake *et al*., 2017) at (MIT) have studied the involvement of nano-fluids in nuclear applications to enhance the efficiency of those nuclear reactors in which water is used as coolant and ejection of heat is limited (Murray and Holbert, 2014). Use of nano-fluids as coolant would be used in other emergency cooling situations, so they can quickly cool heating surfaces to improve safety issues. In nuclear reactors, nano-fluids involve in water movement, operating in the core. Nano-fluids are also involved in safety system in the core of the nuclear reactor. Recently used nuclear reactors can maintain themselves at critical temperatures where phase distinction is disappeared. Due to this, their heating efficiencies become lowered. Some difficulties related to the use of nano-fluids in nuclear systems include the unpredictable results about total aggregate of nano-particles that take evaporating vapors away to a certain distance. To dispose off nano-fluids effectively is also one of the main concerns in today's world (George *et al*., 2014). It is recently addressed that nano-fluid coolants in BWR cause erosion in nuclear power plants. Present work has also examined the appreciable improvement in the CHF could be attained by developing the outer layer of reactors with nano-fluids. CHF might be enhanced by improving morphological properties of depositing film. Heating of nano-fluids is the simplest way to achieve upgrade top (George *et al*., 2015). Nano-fluids play significant role in various interesting applications of nuclear power plants (Bai *et al*., 2018). There is a poor understanding about efficiency of nano-fluids, paradigmatic reactor requirements and suitability of the nano-fluids with acquired materials of the reactors (Bhogare and Kothawale, 2013). Exchange in heat efficiencies is also controllable through advancement in nanotechnology. But in heat exchangers, size, quantity and type of nano-particles matters. As a result, the heat exchangers increases the efficiency of heat transfer of cold water and converts it to hot water as well as maintains their temperature for long duration (Xie *et al*., 2010). Nano-particles that can be effective include the following substances Al_2O, SiO_2, TiO_2, AlO_3, CeO_2 and CuO. Nano-fluids also develop by using colloidal suspensions of nano-composites in water and show a significant improvement in the boiling CHF with less concentrations of nano-particles. During pool boiling, behaviour of gold nano-fluids is also studied by using experimental techniques (Bhogare and Kothawale, 2013).

Recently researchers have developed new technologies, which show that the characteristics of nano-fluids also change with their heat transfer and transport properties. These new technologies may provide us with good facilities for future use. Due to change in thermo-physical properties of nano-fluids, we can transfer heat for free heat conversion and temperature profiles can also be changed. This may be 2-D narrow vertical layer. Different coolants which were used in nuclear reactors could select this type of configuration. Consequently, this shows that no significant changes are taking place for free heat conversions, but only temperature profiles change (Kim *et al*., 2009). Experimental results related to boiling heat transfer of nano-fluids are still poor because of the limited data provided. So, there is no

Table 1.

Nano-fluids type	Previously reported properties	References
Cu/water	Xuan *et al*. provided innovative study on the convective thermal variation of nano-fluids which showed good hotness capability compared to pure H_2O.	(Xuan and Li, 2003)
Al_2O_3/water and CuO/water	Heris *et al*. studied laminar flow of nano-fluids with specific physio-thermal properties and showed exciting heat transfer coefficients with increase in volume of nano-particles.	(Heris *et al*., 2006)
CNT	Ding *et al*. examined heat transfer in a tube having diameter up to 4.5 mm from its inner side. These findings reveal that coefficients of heat transfer and thermal conductivity have direct relationship.	(Ding *et al*., 2006)
Au/water and Al_2O_3/petroleum	Venerus *et al*. reported the artificial Rayleigh scattering method to calculate therma l conduction of gold/water and aluminum oxide /petroleum nano-fluids and found that level of thermally conductive properties of these nano-fluids does not depend upon temperature.	(Venerus *et al*., 2006)
SiC/DI	Lee *et al*. presented experimental investigations about thermo-physical attributes of Silicon Carbide/Deionized water nano-fluids for high temperature heat varying implementations. Viscosity of these nano-fluids is directly proportional to volume fraction of particles and inversely proportional to the temperature.	(Lee *et al*., 2011)
Al_2O_3/water	Ho *et al*. determined the cooling outcomes of Cu micro-channel by applying enforced convection and produced nano-fluids by TiO_2 nano-particles.	(Ho *et al*., 2010)
TiO_2/water	Murshed *et al*. experimental analysis revealed that thermal conduction of TiO_2/water nano-fluids at ordinary conditions give improved thermal conductivity up to 30%.	(Murshed *et al*., 2005)
SnO_2/ DI	Habibzadeh *et al*. studied that change in relative surface area gives significant improvement in heat transfer applications and suspension stability of SnO_2/DI nano-fluids.	(Habibzadeh *et al*., 2010)
$Cu/C_4H_{10}O_3$	Nikkam *et al*. reported heat transfer applications of $Cu/C_4H_{10}O_3$ nano-fluids.	(Nikkam *et al*., 2014)
Ag /water	Munkhbayar *et al*. analysed the stability and thermally conductive properties of Ag/H_2O nano-fluids which show higher thermal conductivity as compared to those nano-fluids which had been produced at 40 °C.	(Munkhbayar *et al*., 2013)

proper understanding of the thermal behavior of nano-fluids related to boiling heat transfer. For proper understanding about boiling of nano-fluids, detailed investigations should be conducted. It is also known that boiling phenomenon is affected by surface properties like roughness, contamination and wet ability of the surface. This review have a focus on only one parameter which is roughness of the surface. Wen *et al*. (2009) also studied the relation between surface and nano-fluids (Wang and Mujumdar, 2008). These findings also show that nano-fluids technology may provide new interesting opportunities in the development of coolants on the basis of nanotechnology for the variety of innovating applications in engineering and medical fields. Nano-fluids are also called the fluids which are used to transfer heat. Liquid-fluoride-salt were developed to enhance the efficiency heat transfer to electricity. These fluids were used to enhance efficiency of solar power towers. It works on temperature range of 700°C to 850°C. Helium gas is used as working substance. To transfer heat from the core of the reactor, nitrogen gas may also be used. These types of advancements can provide the opportunities in the development of technology and nuclear power tower (Forsberg *et al*., 2007). In real life applications, CHF is used in nucleate boiling, nucleate boiling is another method to transfer heat from nuclear systems. To enhance performance economically; their properties can be changed. With the usage of nano-fluids at boiling critical heat flux may provide 20% energy in power plants. It is beneficial in that sense, for CHF, any change in design is not required. Nano-composites are also beneficial because they don't change their neutronic performance (Buongiorno *et al*., 2008). Recent research observed that decrease in heat transfer up to 20% in base fluid caused an increase in CHF. This increase in CHF varies with the size of nano-particles. A surface deposition occurred that is found to be the source of the altered boiling curves. Moreover, it was also observed that wetting is not the solitary origin of the improvement in

CHF (Jackson, 2007). Investigators studied that the CNTs synthetic suspension oils have elevated improvement in thermally conductive properties compared to CNTs $C_2H_6O_2$ suspensions (Liu *et al*., 2005). Recent studies reveal that G-IV consortium provides unique production system for nuclear power plants. These systems require reactors and their fuel-cycle facilities. Researchers have a plan to contribute to VHTR and SFR because of their good adventure with these systems (Ebadian and Lin, 2011). From recent research, performance of different materials like graphite increases by using neutrons. Due to this behavior of different fuels, their efficiency can be enhanced by using actinides at minute levels. Recycling of different fuels can also be made possible due to this (Dresselhaus and Thomas, 2001). Heat is removed from the core of nuclear reactor under specific conditions to determine its feasibility (Abram and Ion, 2008). Nowadays our society faces different challenges because of energy crisis. There are Some other applications of nano-fluids in nuclear reactors, in which several accidents occurs such as core of the nuclear reactors melts and re-locates to rear part of the reactor carrier. If these issues are present, it should be advantageous to maintain the melted propellant within the container by extracting the decomposed heat from the barrier of the container. Presence of CHF restricted this operation externally, but recent findings showed usage of nano-fluids enhanced the internal retentivity of nuclear power plants up to 40% (Al-Zareer *et al*., 2017). Mostly those nuclear systems in which water is used as coolant have limited data related to CHF, but these difficulties are solved with the passage of time, by using nano-fluids instead of water. Use of nano-fluids improves the CHF of a coolant and safety issues of nuclear systems are also resolved due to this. (Barber *et al*., 2011).

Types of nuclear reactors. Nuclear reactor systems include Light water reactor (LWR), pressurised water reactor (PWR), and Boiling water reactor (BWR) (Bai *et al*., 2018).

After research on Nuclear research reactor, fundamental results showed that PWR have many fruitful applications. Nuclear reactors use water as coolant and a neutron moderator which is classified according to the type of water which is being used.

Light water reactor (LWR). Different types of nuclear power reactors use different materials to transfer heat or act as coolant. In recent decades, LWR used for power generation purposes. Those reactors which use H_2O under high pressure act as reactor coolant. Recent studies reveal reactors which are operated at high critical temperature. In LWR, two types of coolant loops are present, one of them is primary and other is called secondary loop. At ultra-high pressure, primary loop of coolant flows in the core of the reactor where it maintains their liquid phase then it transfers this heat to their secondary loop which changes it from liquid to vapors and finally it is transferred to the turbines. Molten metals may also be used for this purpose. It is said that light water is also used as cooling agent for those reactors which use thermal energy. Light water is available at a lower cost and is widely used in nuclear power plants. This type of reactor uses enriched uranium (Wong and De Leon, 2010). Schematic diagram of LWR is shown in Fig. 1.

Heavy water reactor (HWR). It is a kind of thermal nuclear reactors that uses heavy water (D_2O) which is made from deuterium instead of hydrogen + normal oxygen (Chopkar *et al*., 2006). As compared to light water, heavy water is the most efficient coolant and acts as a good moderator. HWR uses natural uranium (Ebadian and Lin, 2011). Fig. 2 presents working principle of HWR.

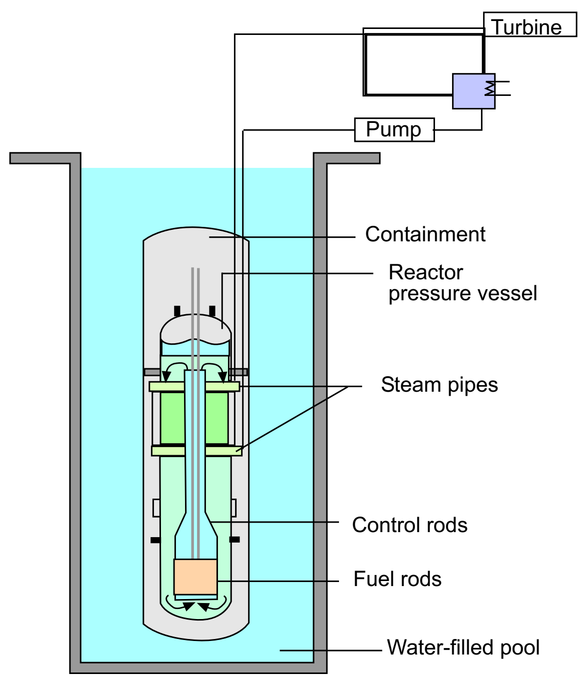

Fig. 1. Schematic of light water reactor (LWR). (Reactorhttps://en.wikipedia.org/wiki/Light-water_reactor).

Boiling water reactor (BWR). Mostly, various types of reactors use same coolant but with different mechanisms. In BWR, coolant has contrasting phase transitions and changes into steam inside the reactor (Routbort *et al*., 2006). Like LWR, boiling water reactors use ordinary water as coolant (Shen *et al*., 2008) but phase transitions take place in reactor's center and H_2O changes into gas which finally pumps directly towards turbine which gives power to the electrical generators. In other words it is said that nano-fluids have potential to improve heat transfer applications (Buongiorno and Hu, 2009). Fig. 3 represents the schematic illustration of BWR.

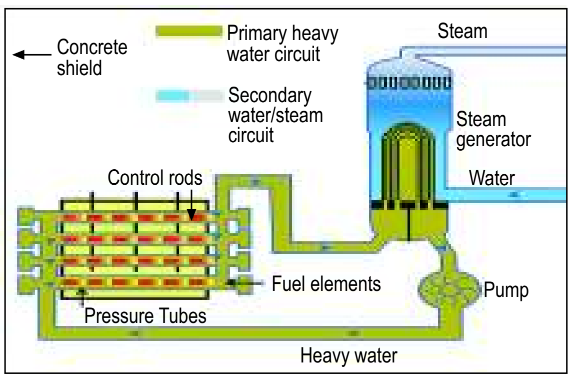

Fig. 2. Working principle of heavy water reactor (HWR) system. (reactorhttps://www.researchgate.net/figure/2-A-complete-schematic-of-the-CANDU-R-nuclear-reactor-Image-taken-from-4-with-the_fig2_315081975).

Pressurised water reactor (PWR). Figure 3 shows the main parts of PWR. In this process, steam is produced between fuel rods and water. These vapors are unable to cover the surface of fuel rods so they conduct very less amount of heat. To overcome this drawback, water is replaced by nano-fluids. By using nano-fluids instead of H_2O, shaft of the reactor is also covered with nano-particles like Al_2O_3, which carry recently created fizz away and avert the emergence of vapors around the rod which significantly increases the CHF (Wu and Zhao, 2013). The schematic representation of PWR is shown in Fig. 4.

Liquid metal cooled reactors. Another type of nuclear reactors like liquid metal cooled reactors use sodium in molten form. Other metals are also used for this purpose according to their physical and chemical properties. Firstly mercury is used as coolant in nuclear fast reactors. Gases like CO_2 and He can also be used for cooling. Liquid lead and other compounds containing carbon and hydrogen can also be used as coolant. H_2O and Na in liquid form is commonly used as nuclear coolant (Buongiorno *et al*., 2008). Development in the designs of water-cooled reactor to enhance several properties, safety issues and to improve it for future use. For the development of nuclear reactors, thermal-hydraulics is the major concern. This works very efficiently at low temperatures. It is also suitable for reverse condensation. The phase transition is easy as compare to other heat transfer mechanisms. There is an

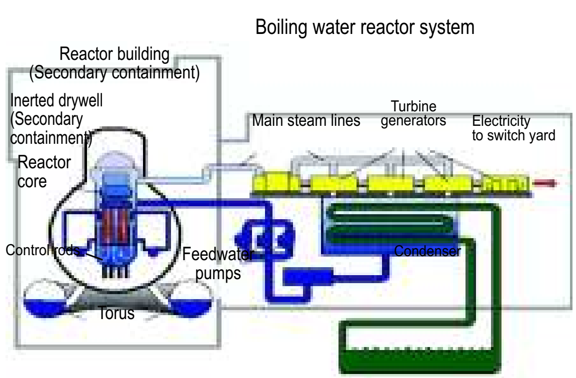

Fig. 3. Schematic diagram of boiling water reactor (BWR). (Reactorhttp://www.nucleartourist.com/type/bwr.htm).

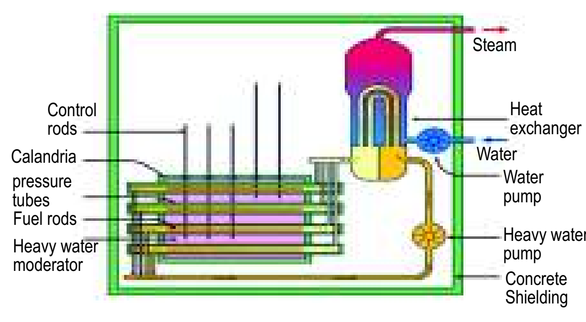

Fig. 4. Schematic figure of pressurized water reactor (PWR). (Reactorhttps:// nuclearstreet. com/nuclear-power-plants/w/nuclear_power_plants/320.pressurized-heavy-water-reactor-phwr).

advancement taking place in these applications due to nanotechnology. Since different improvements in nuclear systems in terms of advanced nuclear thermal-hydraulics are useful for future (Bang and Jeong, 2011).

Coolant loops could also be used for that purpose, so chain of two loops in which one coolant loop used for radioactive materials which are used there. With the passage of time, molten metals which is in liquid form replaced with molten salts. For good efficiency, those coolant materials could work at low vapor pressure and high temperatures. In that way, inner strength of the core of the reactor also increases. For that kind of coolant designs of the reactors also changes, so cores of the reactors are smaller in size with less complicated piping systems and their efficiency is also so good (Buongiorno and Hu, 2009).

Nano-fluids as coolant. Present research also reveals the nature of nano-fluids to act as a coolant (Senthilraja *et al*., 2010). To improve cooling effects nano-fluids are used.

- Usage of nano-fluids as coolants gives smaller size.
- Due to higher efficiency less amount of fluid would be used.
- Argonne researchers, Singh et al., have found that those nano-fluids which have high thermal conductivity reduces aerodynamic drag and save approximately five percent fuel (Routbort *et al*., 2006).
- One of the major benefits of nano-fluids is that it reduces friction, parasitic losses, and saving fuel up to six percent and greater saving would be obtained in the future.
- Different radiators designed in such a way that materials which used as coolants flow in it and due to nano-fluids material loss taking place. So erosion of radiator materials depends on weight. Frictional losses would also be examined by reducing weight.
- Different finding shows that by using nano-fluids, no erosion is present. Basically those nano-fluids made from base fluid have minimum erosion (Wong and De Leon, 2017).

Shen *et al*. (2008) examined the properties of dry and wet minimum quantity lubrication (MQL) grinding process. To improve roughness of the surface and other losses, water-based alumina and diamond nano-fluids are used instead of water. As compare to wet grinding, dry grinding process could lower heating process and recent findings also improves erosion rate. Future research findings shows that nano-fluids with base nano-particles containing alumina and metal oxides. This work would help in cooling process, to design engines and other heat generating systems related to nano-fluids (Shen *et al*., 2008). In future, designing of engines also depends on cooling properties of nano-fluids that will be able to operate at optimum temperatures and have significant output. According to requirement of nano-fluids, those engines were designed which should have smaller components, low weightage which allow them for betterment in erosion process which also save fuel, money and clean environment (Ramesh and Prabhu, 2011).

Future directions. Nano-fluids are gaining a rapid pace in nuclear reactors as a coolant. Their heat transfer properties and other unique properties seems to be suitable for many new industrial applications. With the passage of time, properties of nano-fluids improved because of the introduction of nanotechnology. Recent findings of research explained the rapid results of nano-particles which enhance the properties of nano-fluids. Researchers should find out all results about different attributes of nano-particles used in nano-fluids as coolant such as oxides of silicon and aluminum and also have the understanding relative to core designs of nuclear reactors. Different technologies with unique properties of nano-fluids such as hotness shift etc. New nano-technological investigations can play a vital role in advance applications of nano-fluids to explore use of new nano-particles.

Conclusion

It is demonstrated that nano-particles have high potential to overcome all the problems observed in the past in the field of nuclear power plants. Nano-fluids act as smart fluid for efficient cooling as well as used in other applications. Nano-particles can be explored to control properties of nano-fluids such as heat transfer properties. For enhancement in the properties of nano-fluids to improve cooling performance in different nuclear reactor's core, nano-fluid suspensions with different oxides have been used and the outputs results are helpful for new applications in this field. Future of nano-particles in nano-fluids for cooling in reactor's core seems to be at great pace.

Conflict of Interest. The authors declare no conflict of interest.

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