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PUBLICATION TYPE

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COVERAGE

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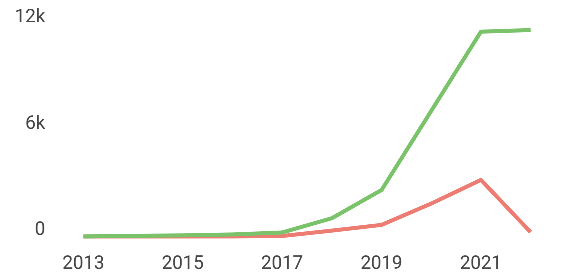

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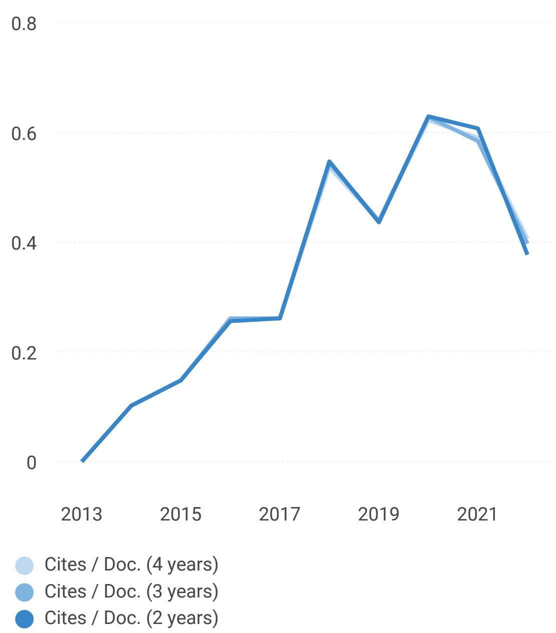

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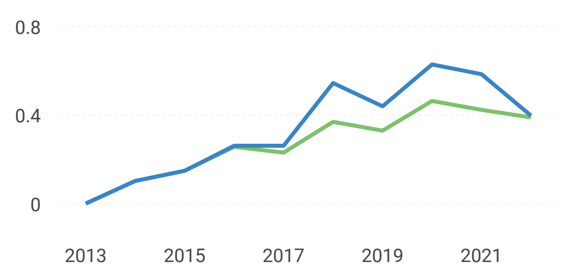

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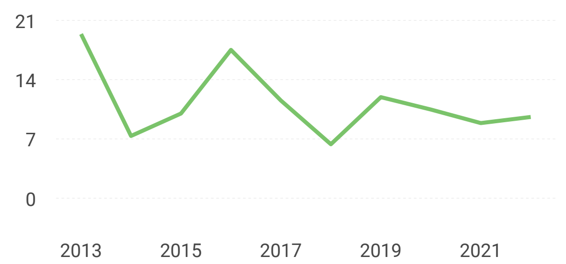

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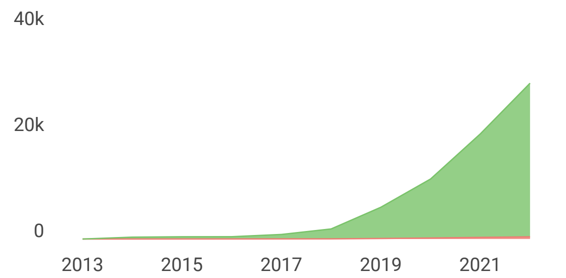

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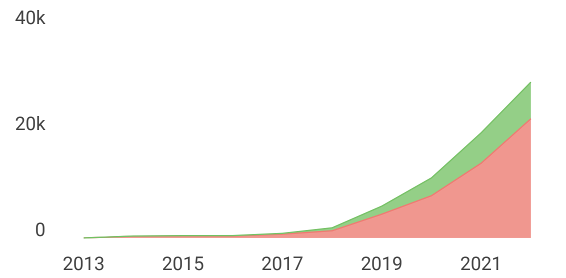

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An experimental investigation on CCFL characteristics during gas/low surface tension liquid counter-current two-phase flow in a small-scaling PWR hot leg typical geometry

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Abstract. A sharp increase in world energy demands which further results in another large progress in the development of nuclear energy establishes comprehensive developments on corresponding mitigation studies. Therefore, as a scenario of accident called LOCA is fundamentally considered, the related phenomena, i.e., the counter-current flow followed by flooding in the primary circuit of PWR, is of a great importance. The present work investigates characteristics of the flooding during a pair of gas/low surface tension liquid counter-current two-phase flow in a complex conduit representing a down-scaled of PWR hot leg typical geometry. Visual observations were obviously carried out to observe the flow phenomenology, while flow parameters were frequently varied. A typical result reveals that the gas flow rate to initiate the flooding decreases with the increase of liquid flow rate. Moreover, exhibiting locations of the onset called locus, a front flooding tends to occur during relatively low liquid flow rates while the higher liquid flow rates exhibit another flooding namely rear flooding. Accordingly, the present investigation provides a package of valuable information on a particular understanding towards the flooding characteristics to overcome the efforts on promoting safety managements on the operation of nuclear power plants..

1 Introduction

The issue of climate change, becoming a catalyst for the utilization of energy sources, as well as a sharp increase in world energy demands, results on another large progress on developments of nuclear energy. However, this source is considered as an environmentally

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friendly energy which has capability to reduce greenhouse gas emissions [1]. This obviously implies the requirement of comprehensive studies on corresponding mitigation procedures. As both communal and environmental safety issues lead to the implications during operations of nuclear power plants, scenarios of various accidents during the operational of nuclear power plants, for an instance loss of coolant accident (LOCA), are specifically considered.

During LOCA, amount of steam flows counter-currently to condensate. This counter-current two-phase flow is only stable at certain conditions, and limited by the onset of flooding (counter-current flow limitation/CCFL), then followed by both partial delivery and zero liquid penetration (ZLP), respectively [2]. Herein, ZLP may contribute to the failure on core cooling mechanisms. As the corresponding phenomena are of a great importance, investigations on the basis of theoretical analyses, mathematical modelling, numerical simulations, and also experimental works have been widely reported [3]. Therefore, predicting CCFL is one of the most critical issues in nuclear safety evaluation [4].

On the basis of experimental investigations, studies on the basis of visualizations have been largely introduced [2,5-8] through detailed identifications of the obtained flow structures. Here, the mechanisms leading to flooding have been visually observed and supported by signal characterizations obtained by physical measurements such as pressures [9,10] as well as phasic fractions [11]. Subsequently, through these visual observations, CCFL has been largely reported to be characterized through a curve representing the phasic superficial velocity when the transition is initiated, well-known as CCFL characteristic curves.

During numerous studies of factors influencing the CCFL characteristics, effects of channel geometry have been widely reported as the dominant variable to be investigated, whereas effects of physical properties of working fluids have also been proposed, but in a rather small portion [12]. However, the operation of the real nuclear power plants involves dynamic characteristics in the fluid physical properties since it is relatively accompanied by both heat and mass transfers during the flow. Furthermore, the dynamic change in the liquid temperature and the system pressure corresponds the change in the surface tension between the phase, which further affects the momentum transfer. Therefore, the scaling on the fluid properties, for an instance the surface tension, exhibits the opportunity to enhance the database on CCFL characteristics as well as the scaling of channel geometry.

The aforementioned brief literature surveys imply that comprehensive knowledge through obviously visual observations enhances the suitability to describe an understanding during either the mechanism leading to CCFL or the location of the onset. Therefore, the present work provides valuable information related a particular understanding on the flooding characteristics. It properly supports the efforts to either promote the safety management in the operation of nuclear power plant or overcome the environmental impact assessments and managements through further developments of both mechanistic models and validations for computational fluid dynamics.

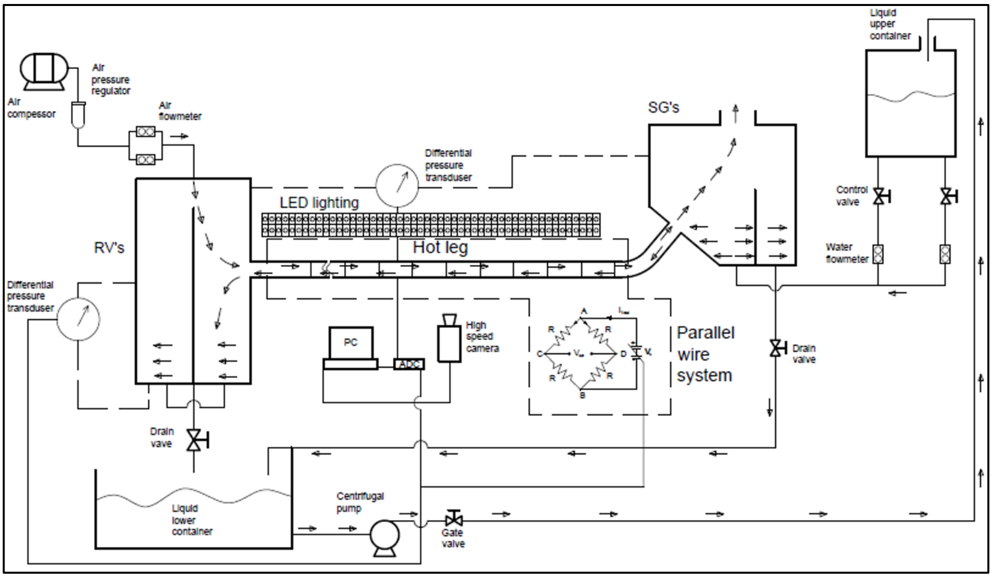

Fig. 1. A schematic diagram of the experimental apparatus.

2 Methodology

The experiments were carried out during a research framework to investigate the characteristics of counter-current flow in a small-scale facility representing a down-scaled model of German-Konvoi PWR primary circuit [9-12,13,14]. The experiment apparatus, which is schematically depicted in Figure 1, has been particularly developed in the Laboratory of Fluid Mechanics and Heat Transfers of Universitas Gadjah Mada, Indonesia. Details of construction of the facility, comprising the fluid supply and lighting systems, and also experimental procedures including the measurement techniques are described by previous reports [9-12,13]. Therefore, in the present reports only the test section is briefly explained in the following.

A test section which represents a 1/30 scaled-down of PWR typical geometry as depicted in Figure 2 was utilized. It is made of transparent acrylic resin to overcome visual observations, and has an internal diameter of 25.4 mm with a 635 mm of characteristic length. Along the horizontal part of the test section, 10 pairs of parallel wire array probes were arranged to acquire the instantaneous interfacial fluctuations during the experiments.

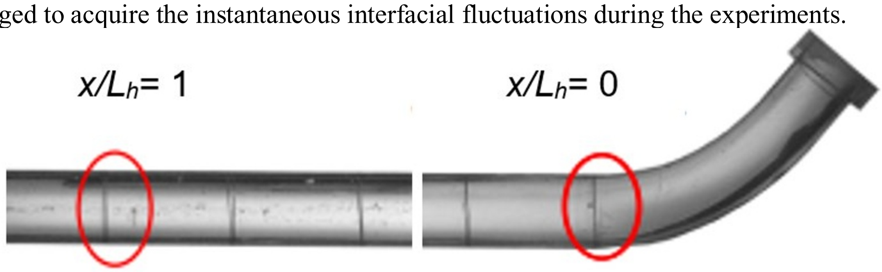

Fig. 2. A photograph of the test section [14].

In addition, particular information of physical properties of the tested fluids at an ambient condition are listed in Table 1. Furthermore, measurements of the density, viscosity and surface tension of the test liquids were particular carried out before and after the experiments. Herein, a gaseous phase utilized air from a unit of reciprocating air compressor, while amount

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of an aqueous solution was used as the liquid phase. To decrease the static surface tension of the test liquid, amount of butanol was mixed to distilled water by 5% total volume of the solution.

Table 1. Physical properties of the test fluids.

Fluid	Density (kg/m^3)	Viscosity (kg/m.s)	Surface tension (N/m)
Air (assumed)	1.15	1.87×10^{-5}	-
Distilled water + 5% Butanol	961	9.51×10^{-4}	0.041

Moreover, Table 2 provides a set of information of an experimental matrix. Herein, two types of experimental run were carried out during a constant flow rate of both the liquid and gas, respectively. Under a constant liquid flow rate, QL= 24 gallons per hour (gph), the gas flow rate is stepwise increased by an increment of 5 liters per minute (lpm). It was conducted until the flooding is initiated, and continued to a point in which the liquid does not penetrate the RVs, i.e. ZLP.

On the other hand, during a constant gas flow rate, the air was supplied under the flow condition of QG= 30 liters per minute (lpm). Here, the liquid flow rate was increased by an increment of 2 gph in which an almost similar procedure of experiment was exhibited, but without the occurrence of ZLP.

Moreover, during two-phase flow, a flow parameter namely superficial velocity which assumes that a phase occupies the entire cross section has been considered as the most important variable to overcome developments of two-phase correlations, including CCFL correlations. Here, the phasic superficial velocity (J_k) is defined as the phase flow rate (Q_k) divided by the cross sectional area (A) of the channel. It is further formulated as written in Eq. (1).

$$J_k = \frac{Q_k}{A} \tag{1}$$

Additionally, since an experimental facility exhibits different in either channel geometries or fluid properties, scaling parameters were largely reported to be applied on the analyses during studies in counter-current flow [3]. Herein, a non-dimensional parameter introduced by Wallis [15] has been largely reported as a scaling function during studies in CCFL characteristics. Moreover, the phasic Wallis velocity (J_K^*), which is defined as the ratio of inertial to gravitational force, involves the density of liquid (ρ_L) as well as the gas (ρ_G), channel diameter (d) and gravitational acceleration (g). It is further formulated as written in Eq. (2).

$$J_K^* = J_K\sqrt{\frac{\rho_K}{gd(\rho_L - \rho_G)}} \tag{2}$$

Table 2. Experimental tested matrix.

ps (bar)	1					
$J_{L,c}$ (m/s)	0.05					
J_G (m/s)	0	1.2	…	CCFL	…	ZLP

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$J_{G,c}$ (m/s)	1.6					
J_L (m/s)	0.019	0.023	…	CCFL	…	0.086

3 Results and discussion

Figure 3 exhibits a typical series of visualization of the obtained interfacial-phasic structures during experiments. Here, the liquid flow rate was kept constant, Q_L= 24 gallons per hour (gph), while the gas flow rate was stepwise increased by a relatively small increment of 5 liters per hour (lpm). From the figure it can be seen that for relatively low gas flow rates, 5 lpm ≤ Q_G ≤ 20 lpm, stratified structures with a smooth interface are obtained. Here, an inertial dominated region, called supercritical flow, was observed in the riser and the bend. Meanwhile, another gravitational dominated region, called subcritical region, was noticed along the horizontal section. This change of region allows the occur the hydraulic jump (HJ) phenomenon.

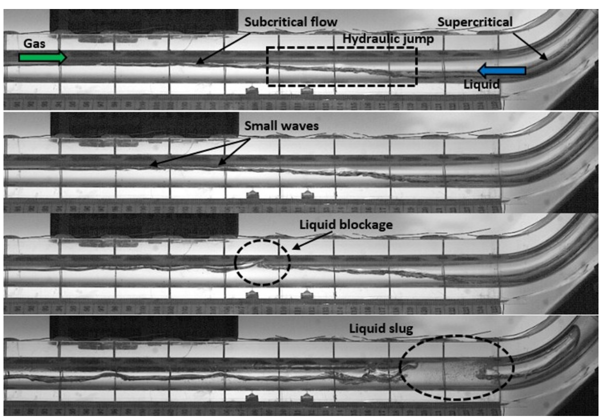

Fig. 3. Typically flow structures during experiments under the flow condition of Q_L= 24 gph.

An increase on the gas flow rate into Q_G= 25 lpm causes waves to be formed and propagate along the direction of liquid. As a result, relatively wavy interfaces are observed in which the location nearby the upper end of HJ invites a rather fluctuate interface than other locations along the subcritical region. Herein, as previously also reported by Prayitno et al. [16] during the liquid flow, the pressure of the liquid film decreases by the friction while the pressure difference of the interface increases. This leads to interface fluctuations as a compensation of the change in pressure difference on the fluid interface. Therefore, as time progresses, the interface between gas and liquid becomes unstable and waves appear. The instability of the interface boundary occurs due to the increasing friction of the gas and liquid interface.

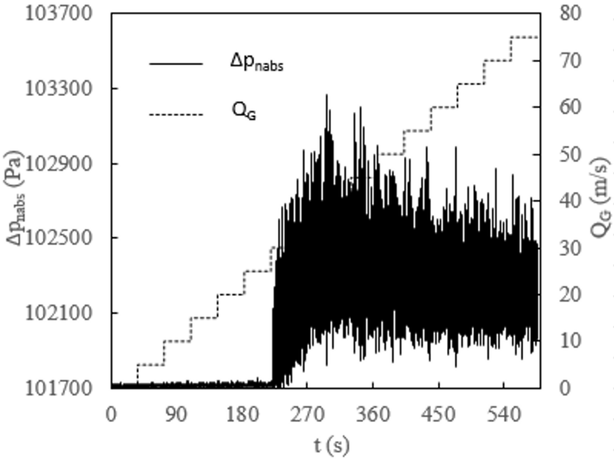

Fig. 4. A typical time-series of pressure fluctuations.

Subsequently, during the increase in gas flow rate at a constant liquid flow rate, the slip velocity increases. It causes the drag force increases. As reported by Zapke & Kroger [17], flooding relates to a phenomenon in which the weight of liquid is balanced by drag force in the direction of gas flow. Besides, the increase in wave height as its propagation may precede the flooding [5,6]. Therefore, it explains that a further increase in gas flow rate, Q_G= 30 lpm, results on a portion of liquid to block the entire channel cross section and initiates a slugging to start the flooding. The corresponding phenomena relates to a drastically increase on pressure fluctuations acquired through the pressure probes which are located on the RVs and SGs as typically shown in Figure 4.

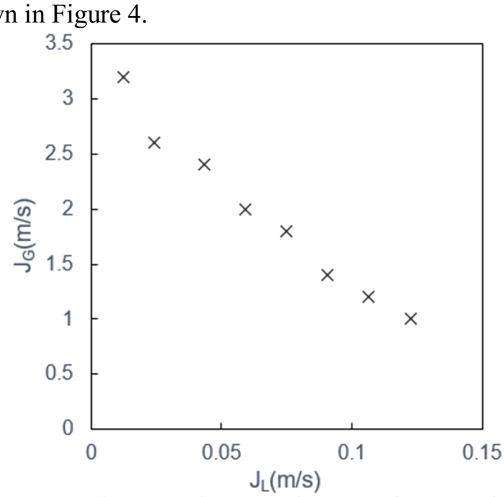

Fig. 5. A curve of CCFL characteristics in terms of phase superficial velocity.

Next, Figure 5 and 6 depict CCFL characteristics' curves in terms of both phasic superficial velocity and Wallis parameter, respectively. It can be seen in the figure that the curve has a decreasing trend describing that the gas flow rate to initiate the flooding monotonously declines with the increase of the liquid flow rate. Here, as also previously reported by Astyanto et al. [14,18], as the liquid flow rate increases, the liquid film thickness increases and causes a narrower area to be pass by the gas. The more the narrow the area left, the faster the liquid blockage is reached.

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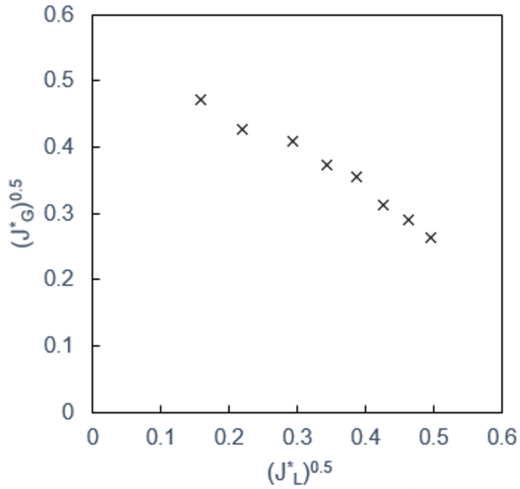

Fig. 6. A curve of CCFL characteristic curve in terms of phase Wallis velocity.

A visually distinguished typical flooding on the basis of the location of the occurrence of initial liquid blockage leading to slugging was reported by Badarudin et al. [19] as well as Deendarlianto et al. [5,6]. A couple type of flooding, namely the upper and rear flooding, by Deendarlianto et al. [5,6] was proposed during the flooding investigation in a straight geometry while front and rear flooding by Badarudin et al. [19] was observed during flooding in hot leg typical geometry. Here, applying the definition previously introduced, the front flooding is defined as the liquid blockage that initiates the flooding occurs at the half of characteristic length nearby the elbow while the rear flooding indicates the opposite location as described in Figure 7.

From the figure it is clearly noticed that the front flooding occurs at low liquid flow rates, while the relatively higher liquid flow rates exhibit the rear flooding. The visual observations reveal that these phenomena correspond to the location in which the hydraulic jump (HJ) occurs. As can also be seen in Figure 3, the upper end of HJ is found to coincide to the location of the onset of slugging. Herein, front flooding generally occurs in the middle of the horizontal pipe to the bend, while rear flooding occurs from the middle of the horizontal pipe to the liquid outlet.

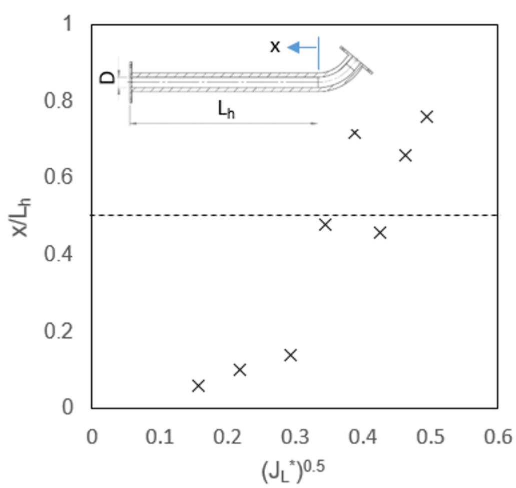

Fig. 7. Front flooding and rear flooding correspond to the liquid flow rate.

The authors are thankful to Dr. A. Badarudin, Dr. IGNB. Catrawedarma, Dr. S. Wijayanta, Dr(Cand). US. Dharma, Dr(Cand). H. Kusumaningsih, Eng. YV. Yoanita, Ms. CD. Rumiarti, and also all members of Multiphase Flow Research Group, Laboratory of Fluid Mechanics and Heat Transfers, Department of Mechanical and Industrial Engineering, Universitas Gadjah Mada for several brief discussions during either the facility installation or particular analyses. In addition, a better understanding on the flow phenomenology involves a Phantom Miro M310 Lab high speed camera as well as a partial funding of the experiment is well supported. Therefore, the author also acknowledges PT. Chevron Indonesia and Sanata Dharma Foundation for the proper opportunities, respectively.

4 Concluding remarks

An experimental-based study covering CCFL characteristics during a pair of gas/low surface tension liquid counter-current two-phase flow in a complex conduit representing a down-scaled of PWR hot leg typical geometry was carried out. Visual observations were obviously conducted to observe the flow phenomenology, while flow parameters were varied. A typical result reveals that the gas flow rate to initiate the flooding decreases with the increase of the liquid flow rate. Furthermore, exhibiting locations of the liquid blockage, a front flooding tends to occur during relatively low liquid flow rates while a rear flooding seems to correspond to higher liquid flow rates. Accordingly, the present study provides a number of valuable knowledge on particular understanding on CCFL characteristics to supports the effort on promoting safety managements in the operation of nuclear power plants.

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