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PERFORMANCE OF WATER COOLING FOR RADIATION HEAT FLUX FUEL STORAGE TANK

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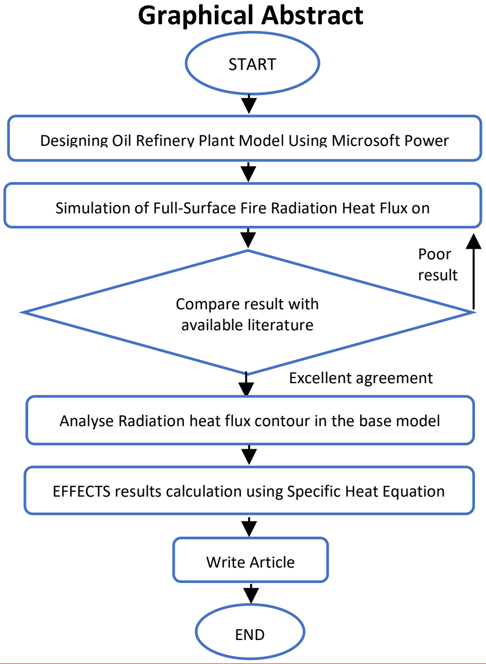
Graphical Abstract



Abstract

Full-surface fire on fuel storage tank emits high radiation heat transfer. As a fire protection strategy, the water curtain cooling system is activated to reduce the temperature on the adjacent tank surface. Therefore, the present work predicts and analyses the radiation heat flux and the maximum flame temperature of different types of fuels. Further, this analyses the effect of fuel total mass on radiation heat flux and maximum flame temperature and observes the effect of distance between two tanks on radiation heat flux distribution. The relationship between water cooling flow rate and outlet water temperature that absorbed radiation heat flux has been studied. The study has been conducted by using the Consequence modeling software trial version. The modeling setup of the tank is 17 m in height with 65 m inner diameter, and the meteorological data used are 5.4 m/s wind speed with north wind direction at atmospheric pressure in order to imitate the worst-case fire scenario. The results reveal that the gasoline fuel emitted the highest heat flux value of 11.03 kW/m^2 and the raw gasoline sample emits the lowest heat flux value of 9.14 kW/m^2. Furthermore, the total mass of the fuel shows no effect on the maximum flame temperature of 958.51°C. According to the findings, the critical tank distancing is 36 m and thus the appropriate tank distancing of 40 m is highly recommended by the standard. The result shows that the water cooling rate of 4.1 lpm/m^2 is an excellent practice of water cooling to cool down the temperature of the fuel tank which is exposed to radiation heat flux.

Keywords: Fire; Fuel storage tank; Heat flux, Radiation, Water cooling

1.0 INTRODUCTION

Oil and gas industries especially oil refining plants, necessitate well-planned passive and active fire protection provisions to prevent fire occurrence and mitigate any fire incidents. The probability of fire accidents still exists, whether as a result of system failure, human error, or a natural disaster, despite the implementation of all active and passive fire protection techniques.

Jet fire, pool fire, rim seal fire, and full-surface tank fire are a few of the fire situations that could happen in a gasoline storage tank [1-2]. Among these fire situations, full-surface tank fire typically causes a significant amount of fuel to burn. This kind of fire could have devastating effects and cause significant losses for both the plant owner and its stakeholders. There are a few big examples documented where full-surface tank fires had occurred in the past in Malaysia as well as worldwide [2-5]. Particularly in full-surface tank fires, the major component of heat is transferred by thermal radiation [6]. According to the analysis of the American Petroleum Institute, 6 % of fires are generated by radiation [7-8].

Placing water spray cooling system on the surface of the tanks adjacent to the fire is one of the effective strategies that is used to limit fire spread in hydrocarbon storage tanks farm. Also, this enables optimizing the spacing between the tanks in tank farms. However, while studying the suitable rate of application, many factors should be taken into consideration such as the rate of heat transfer required to be absorbed, the maximum allowable temperature of the system, the cooling water application method, efficiency, and the age of the system [2, 6, 8-9].

In addition, the establishment of complex considerations and resources is necessary for the experimental examination of fire propagation in medium and large storage tanks. As a result, few experimental studies had been conducted in the past and several oil refining plants practiced with this kind of cooling system are not highly efficient. In this sense, numerical analysis gives the great opportunity of studying the comprehensive details of this kind of cooling system. Hence, it is highly essential to design and analyse these systems using numerical models prior to the implementation. Several researchers have designed many fire mitigation models using cooling water in many applications.

The computer model developed by NIST (National Institute of Standards and Technology) was utilized to examine the necessary cooling water pressure, velocity, and application rates, to comply with standards NFPA15 (Standard for Water Spray Fixed Systems for Fire Protection) [2, 10]. Further, modeling and simulation studies were utilized to provide some recommendations for the suppression and mitigation of fire in storage tanks [11]. Several studies were carried out on thermal radiation effects and equations were derived by previous researchers [12-14]. Further, the computational results showed an excellent agreement with the experimental outcomes of later investigations [15-16].

Numerical simulations have been used in codes for many engineering applications including aerospace [17], microelectronic [18], heat transfer [19], thermal comfort [20], oil and gas industries [21], etc. For oil and gas CFD application, the SFPE (Society of Fire Protection Engineers) handbook of fire protection engineering [2, 21] employed several fuel types to mimic various types of fire and determine certain attributes linked to fire characteristics, such as soot generation and fire radiation. Premixed turbulent combustion and fire plumes were also studied using modeling techniques. Further, Fire Dynamics Simulator (FDS) is used to calculate the rate of heat release from various fuel burns and forecast flame geometry, smoke generation, and the impact of smoke on radiation and other parameters. Moreover, the investigation and discussion of sprinkler systems for fire suppression using FDS were undertaken by NFPA 30 (Flammable and Combustible Liquids Code) [22].

Wen *et al*., (2007) simulated a medium-scale methanol pool fire and investigated the air entertainment of the flame and the accompanied vortices [23]. This study concluded that FDS was capable of reliably predicting the most important parameters of pool fires. Also, FDS has the advantages of hydraulic and heat transfer simulations as well as combustion and radiation simulations, which enables simulating fire and smoke formation, in addition to simulating sprinklers and fire suppression systems [2].

Ebrahim Zadeh *et al*., (2016) forecasted the burning rate and the heat release rate of a sizable ethanol pool fire by using the FDS tool [24]. This study revealed that the FDS had good agreement with the experimental data. Then, Ghasemi *et al*., (2017) numerically investigated the thermal radiation incident on a surface subjected to an adjacent tank using PHAST consequent analysis software [25]. While studying the full-surface fire, the pool diameter represented the flame diameter. Several equations were proposed in order to estimate the value of the mass burning rate of the fuel.

Later, Zhi Tang *et al*., (2018) presented the effect of a water spray on a fire-induced smoke layer inside a hood using CFD [26]. In this study, the authors discussed how the parameters of the water spray affect the downward smoke displacement caused by drag and cooling. A simulation model was designed by Saber *et al*., (2022) for the mitigation and propagation of fire in cylindrical hydrocarbon storage tanks using cooling water. This model has been simulated by considering the nature of the fuel, the speed and direction of the wind, the smoke effect and the nozzles distribution, and the number of segments on the target tank surface [27].

In numerous applications relating to fire propagation, smoke production and spread, thermal radiation from flames, and firefighting and mitigation, it was shown through the literature that FDS has demonstrated satisfactory accuracy and dependability [28].

Though there are many fire mitigation models including FDS and Consequence Analysis Software discussed for various kinds of fires in many applications, few were discussed on gasoline storage tanks. However full-surface tank fire scenarios are not discussed in many models. Hence, this study employs EFFECTS Consequence Analysis Software to analyse the numerical investigations of the performance of water cooling during the full-surface tank fire scenario in a radiation heat flux fuel storage tank using a fire safety quantitative risk assessment tool. The relationship between tank spacing and thermal radiation has been discussed at the end of the discussion.

2.0 METHODOLOGY

In the present study, a trial version of EFFECTS consequence modeling software called fire safety quantitative risk assessment tool, was designed to calculate and analyze the effects of seventy specific scenarios. The two-dimensional model of the tank farm model was developed by using Microsoft PowerPoint (PPT) software. Then the tank farm model used in the simulation is to imitate the weather and operating conditions in an oil refining plant in Malaysia.

With reference to Figure 1, the oil refinery plant model used in this research comprises one open structure gasoline processing facility for a gasoline refinery, a truck loading bay for loading or unloading, an office building with a main fire control room, water tank for active firefighting system, flare stack to burn excess gases, electrical sub-station for electrical supplies and two units of identical gasoline storage tanks. Further, the oil refining plant base model with 40-meter shell-to-shell tank spacing is illustrated with PPT gridlines in order to make sure that the spacing distance is properly placed.

The two gasoline storage tanks which are the key factors in this research are labeled as TK-01 and TK-02. In this study, it is assumed that the TK-02 gasoline storage tank is trapped with a full-surface tank fire and the other adjacent TK-01 gasoline storage tank is impinged by the heat flux from the fire scenario where both tanks have stored gasoline volumes of 36,500 metric tonnes. Both TK-01 and TK-02 gasoline storage tanks are identical in dimensions with outer tank shell height and inner tank height of 17 m and 16 m, respectively. Also, the corresponding outer diameter (OD) and inner diameter (ID) of these tanks are 67 m and 65 m.

Furthermore, the study was carried out for four different shell-to-shell tank spacing such as 10 m, 20 m, 40 m, and 60 m. GASOLINE, Raw Sample Gasoline, Winter Grade Gasoline Sample, and Summer Grade Gasoline Samples are used in each case to analyse this study. Then the modeled design is simulated using EFFECTS software for each scenario including the kind of fuels, quantity of fuels, and tank spacing.

In addition, the calculation methods and input process conditions considered in this work are tabulated in Table 1. In order to create the worst environment scenario, it is highly essential to consider the meteorological parameters and hence the meteorological and environmental data are also tabulated in Table 2.

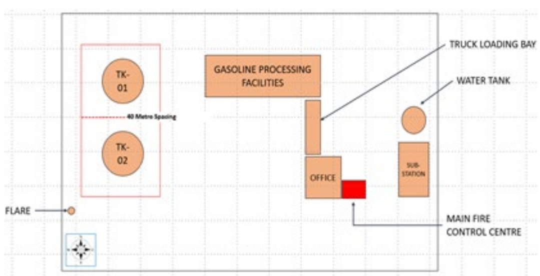


Figure 1 Base Model of Oil Refinery Plant

Table 1 Input Parameters of Calculation Method & Process

EFFECTS Modelling Input Parameters	Details
Type of Pool Calculation	Two Zone model Rew & Hulbert
Type of Pool Source	Instantaneous
Soot Definition	Calculate/Default
Type of Pool Shape	Circular
Max. Pool Surface Pool Fire	3,318 m^2
Height of the Confined Pool Above Ground	16 meter
Include Shielding at the Bottom Side Flame	Yes
Height of Shielding at Bottom Side Flame	1 meter

Table 2 Meteorological and Environmental Data [29]

EFFECTS Modelling Input Parameters	Details
The temperature of the Pool	25°C
Wind Speed & Direction at 10m Height	5.4 m/s from South
Ambient Temperature & Pressure	32°C & 1.015 bar
Ambient Relative Humidity	80.6%
Amount of CO_2 in the Atmosphere	0.0003

In order to justify the water cooling rate of 4.1 lpm/m2 which is applied to the adjacent tank, the outcomes of the simulation are verified using Specific Heat Formula equation shown in Eq. (1)[30]. In this case, it is assumed that the water properties are constant with temperature, and the radiation heat flux is constant on the tank surface. Further, the ΔT is calculated to analyze the amount of water that can be heated by the radiation heat flux generated at TK-02.

$$\frac{\dot{Q}}{A} = \dot{m} c_p \Delta T \qquad (1)$$

Where; $\frac{\dot{Q}}{A}$ is radiation heat flux in W/m^2, $\dot{m}$ is the mass flow rate of water in kg, c_p is the specific heat capacity of water in J/kgK, and ΔT is the temperature difference in K.

Due to the limitations in EFFECTS software, it is unable to determine the required water curtain cooling flow rate, the effect of fuel-burning rate, and time unsteady condition. In this case, the outlet water temperature is calculated using the Specific Heat Equation specified in Equation 1. Further, it is assumed that the water properties are constant with temperature, and the radiation heat flux is constant on the tank surface. Also, the water is supposed to be evaporated at the beginning of the cooling system activated.

2.1 Comparison with Previous Researcher's Result

Validation with experimental data is an important process in order to ensure that predicted results are reliable. However, it is extremely hard to obtain experimental data as the cost of the experiment is extremely expensive. Therefore, the study compares the present predicted data with the data presented by Feng Zhou (2019) on the Numerical Simulation of Thermal Radiation Distribution of Large-Scale Crude Oil Storage tanks using FDS has been considered [31]. The simulation model is set up with similar parameters which had been considered by Zhou (2019). In this comparison data, all input parameters are the same as Zhou (2019). The diameter and the height of the crude oil storage tank are 80 m and 21.88 m, respectively. The tank spacing and wind speed are set at 32 m and 10 m/s. In addition, the total mass released is 100,000 kg. According to the result from Zhou (2019), the highest radiation heat flux recorded at the adjacent tank wall is 28.78 kW/m^2. The highest radiation heat flux value generated by EFFECTS software is 24.19 kW/m^2, which is slightly lower compared to Zhou (2019), as presented in Figure 2. Hence, it is concluded that the outcomes of this study are comparable to FDS software.

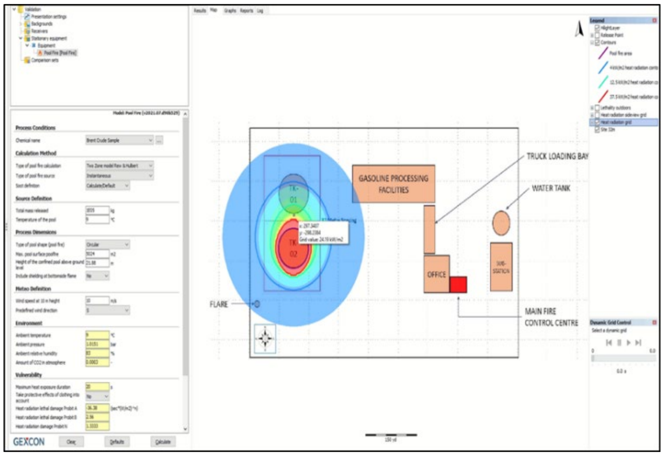


Figure 2 Predicted Result by EFFECTS for Comparison

3.0 RESULTS AND DISCUSSION

3.1 Radiation Heat Flux and Maximum Flame Temperature Using Different Fuels.

The radiation heat flux analysis is carried out for four types of fuels namely; GASOLINE, Raw Sample Gasoline, Summer Grade Gasoline Sample, and Winter Grade Gasoline Sample with an identical amount of total mass release of 36,500 metric tonnes. The tank spacing distance is set at 40 m as constant as recommended by NFPA 30 standard. The heat flux data is recorded on the TK-01 tank surface heat flux by EFFECTS software.

Figure 3 shows the bar chart for the highest radiation heat flux emitted by four different kinds of fuels. Based on the results obtained, the GASOLINE fuel emits the highest radiation heat flux, followed by Raw Sample Gasoline, Summer Grade Gasoline Sample, and Winter Grade Gasoline Sample. This phenomenon happens due to GASOLINE fuel having a higher molecular weight (115 kg/mol) than the other (97.709 kg/mol).

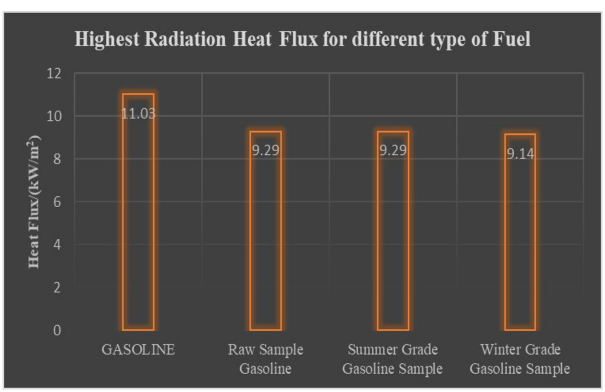


Figure 3 Variation of Highest Heat Flux for Different Kinds of Fuels

3.2 Maximum Flame Temperature Generated By Different Types And Quantities Of Fuels.

In order to analyze the radiation heat flux further, the bar chart for the maximum flame temperature of the full-surface fire scenario with all four kinds of fuels has been plotted as shown in Figure 4. The results reveal that the maximum flame temperature of all four fuels is apparently identical which is 958.51°C, even GASOLINE fuel produces the highest radiation heat flux.

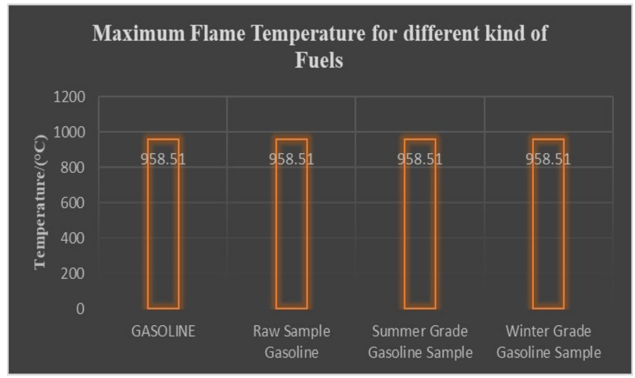


Figure 4 Plot of Maximum Flame Temperature with type of Fuels

Figure 5 analyses the maximum flame temperature for five different quantities of GASOLINE fuel. Similar to Figure 4, the maximum flame temperature of 958.51°C is reached in all five cases. Therefore, it is concluded that the types and quantity of fuel in the tank do not affect the maximum flame temperature.

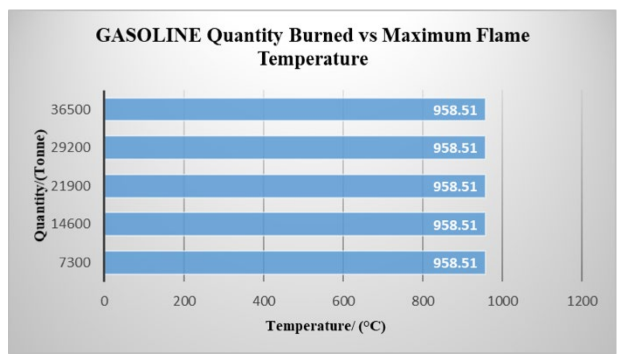


Figure 5 Bar Chart for GASOLINE Quantity Burned with Maximum Flame Temperature

3.3 Study of Tank Spacing Effect on Radiation Heat Flux Distribution

In addition to the active fire protection measures to prevent full-surface tank fire in TK-01, it is highly essential to consider passive fire protection measures as well. In this analysis, the highest heat flux reading on the TK-01 tank surface is recorded with different tank spacings based on GASOLINE as the chemical input. There are four tank spacing distances of 10 m, 20 m, 40 m, and 60 m has been taken in this study. Figure 6 shows the variation of the highest heat flux recorded on the TK-01 tank surface against the shell-to-shell spacing between TK-01 and TK-02 which is engaged with the tank surface fire scenario. According to NFPA 30 Table 22.4.2.1 [22], the minimum shell-to-shell tank spacing above ground required for floating roof tank is 1/6 diameter of the tank. In this analysis, the minimum tank spacing should be 10.83 m, and any tank spacing which is shorter than 10.83 m is considered non-compliance to NFPA 30 standard. Based on the results shown, the highest radiation heat flux value recorded is 40.64 kW/m^2 where a tank spacing distance of 10 m, and it is also a non-compliance tank spacing to NFPA 30 standard. The recorded least radiation heat flux is 6.86 kW/m^2 which occurred at the tank spacing of 60 m.

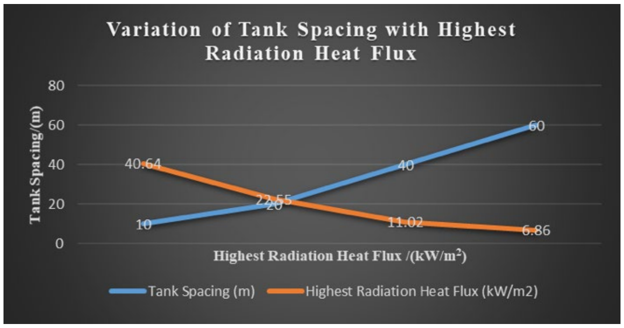


Figure 6 Variation of Tank Spacing with Highest Radiation Heat Flux

3.4 The Relationship between Water Cooling Flow Rate and Outlet Water Temperature which Absorbs Radiation Heat Flux

A water curtain spray system is used as an active fire protection to prevent the adjacent tank from being ignited due to radiation heat flux. Figure 7 illustrates the steady-state outlet water temperature of the water spray system for tank surface cooling for the highest heat fluxes generated by GASOLINE (11.03 kW/m^2) and Raw Sample Gasoline (9.29 kW/m^2).

According to Figure 7, the temperature is inversely proportional to both heat fluxes of 11.03 kW/m^2 and 9.29 kW/m^2. This reveals that the higher water flow rate induces to increase in the heat transfer coefficient and hence leads to reduce the temperature of the tank surface as well as the outlet water temperature. The highest predicted temperature is 183.3°C, which is produced by a heat flux of 11.03 kW/m^2 at a water cooling rate of 1 lpm/m^2. In addition, a heat flux of 9.29 kW/m^2 shows the lowest outlet water temperature of 38.1°C with a water cooling rate of 10.2 lpm/m^2.

Basically, water begins to boil and evaporate at a temperature of 100°C. As a result, the maximum water temperature at the outlet should be less than 100°C. when the temperature exceeds 100°C, the physical properties of water transform into hot steam, and the cooling system fails. Hence, it is critical to ensure the outlet water temperature which is less than the boiling point. According to Figure 7, the critical water cooling rate of Raw Sample Gasoline is 1.8 lpm/m^2 for the heat flux of 9.29 kW/m^2. Also, the critical water cooling rate of the GASOLINE Sample is 2.2 lpm/m^2 for the heat flux of 11.03 kW/m^2.

According to standard IP19 (Model Code of Safe Practice in the Petroleum Industry, Part 19) [32], it is mandated that all tanks should have a minimum water cooling rate of at least 2.0 lpm/m^2. However, it is risky to use a water cooling rate of 2.0 lpm/m^2 since it is very close to the critical water cooling rate and an outlet water temperature of 100°C. Further, the hot ambient temperature and wind speed are taken into account, and the best practice of water cooling rate in Malaysia is 4.1 lpm/m^2 as required by API RP 2030 (Guidelines for Application of Water Spray Systems for Fire Protection in the Petroleum Industry) standard [11].

Therefore, it is concluded that the optimum water cooling rate of 4.1 lpm/m^2 is applicable in this tank farm model as it is adequate to protect the TK-01 tank surface from heat flux impingement and avoid the TK-01 content to be ignited.

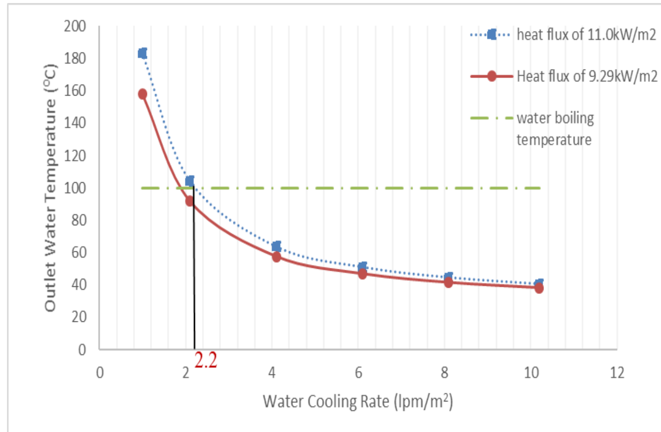


Figure 7 Variation of outlet water temperature with water cooling rate

4.0 CONCLUSION

The performance of water cooling for radiation heat flux fuel storage tanks is discussed in this present paper. Based on the analyses conducted, it is concluded that different types of fuels generate different values of radiation heat flux. The maximum radiation heat flux of 11.03 kW/m^2 is recorded for GASOLINE. According to the findings, the critical tank distancing is 36 m and thus the appropriate tank distancing of 40 m is highly recommended by the standard. In addition, the highest water cooling rates are highly effective on the adjacent tank surface in an active fire protection system. The result shows that the water cooling rate of 4.1 lpm/m^2 is an excellent practice of water cooling to cool down the temperature of the fuel tank which is exposed to radiation heat flux.

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