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GAS FLARING IN NIGERIA: ESTIMATING THE MAGNITUDE OF HEAT LIBERATED FROM FLARE SITES IN NIGERIA'S PETROLEUM FIELDS

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ABSTRACT

For the purpose of enhancing energy management, this study explores the thermodynamics' fundamentals as the tools and methods of estimating the annual quantities of heat liberated to the surrounding environment by gas flaring in Nigeria's petroleum fields. Many approaches are available for evaluating the heat released from gas flaring. This work reviews the specific-heat-capacity and the enthalpy-change approaches to evaluating heat liberation. The enthalpy-change-computational approach is applied in this work because it is less cumbersome than the specific-heat-capacity approach. In applying the enthalpy-change approach, a step-by-step computational procedure is employed to enhance the presentation and guide the reader from one aspect to the next. To this end, the average molecular weight of Nigeria's natural gas is computed from its constituents. The average density of Nigeria's natural gas is calculated from its components. Also, the total enthalpy change for Nigeria's natural gas is estimated using the enthalpy-change approach. Subsequently, on the basis of the official-gas-flare statistics and the total enthalpy change calculated, the annual quantities of heat liberated to the environment are estimated using the thermodynamics' equations reviewed in the work. The significance of these computational outcomes lies in the disclosure of the massive quantities of heat liberated from gas flaring in Nigeria. The magnitude and trend of the quantity of heat liberated from gas flaring are discussed within the context of the theoretical framework. It is expected that the result from this study will contribute towards the elimination of gas flaring in Nigeria's petroleum fields and also enhance energy management.

Keywords: Gas flaring, estimating, thermodynamics' fundamentals, heat liberated, enthalpy-change-computational approach, natural-gas components.

NOTATIONS

Symbol	Description	Units
a	Rate of density change over temperature rise	$kgm^{-3}K^{-1}$
C_p	Specific heat capacity of natural gas components	$kJkmol^{-1}K^{-1}$
C_{pa}	Specific heat capacity of the natural gas component	$kJkmol^{-1}K^{-1}$
C_{Pb}	Specific heat capacity of the natural gas component	$kJkmol^{-1}K^{-1}$
C_{pc}	Specific heat capacity of the natural gas component	$kJkmol^{-1}K^{-1}$
C_{pm}	Mean molar heat capacity of the natural gas component	$kJkmol^{-1}K^{-1}$
ΔH	Enthalpy change from gas flaring	GJ
m	Mass of the ideal gas mixture	kg
n	Number of moles of natural gas in a known volume	-

P	Atmospheric pressure in gas flare environment	kNm^{-2}
Q	Heat Liberated from gas flaring	GJ
R	Universal gas constant ($8.314\ kJ.kgmol^{-1}K^{-1}$)	$kJkmol^{-1}K^{-1}$
T	Gas flare temperature (1500K)	K
T_o	Ambient air temperature (298K)	K
V	Volume of flared natural gas (natural gas)	m^3
W_a	Molecular weight of the natural gas component	kgmol
W_b	Molecular weight of the natural gas component	kgmol
W_c	Molecular weight of the natural gas component	kgmol
W_m	Mean molecular weight of the natural gas component	$kg.(kgmol)^{-1}$
Y_a	Mole fraction of the natural gas component	
Y_b	Mole fraction of the natural gas component	
Y_c	Mole fraction of the natural gas component	
ρ	Density of the natural gas mixture of gas flare temperature	kgm^{-3}
ρ_o	Density of the natural gas mixture at ambient air temperature	kgm^{-3}

INTRODUCTION

Energy generation and supply to industrial, commercial and domestic consumers are the bedrock/cornerstone of economic development and industrialization of any nation. A significant proportion of the world's energy comes from the heat energy released from combustion of fossil fuels. While some of the heat energy liberated will be applied directly for heating purposes, others can be utilized only when transformed into mechanical work, electrical energy and other forms of energy by means of heat engines and generators.

Heat engines are any devices or machineries that transform heat energy into mechanical energy. Mbah and Aneke [1999:171] categorize heat engines into two types, (a) the internal combustion engines which include the gas turbine engine, the diesel engine, the gasoline engine and jet engine; (b) the external combustion engines which include the steam power plant and the steam locomotive engine usually applied for marine and rail transport.

Despite the availability of heat engines and other devices that can convert chemical energy in fossil fuels into other forms of useful and utilizable energy, Nigeria's flares a significant amount of natural gas to waste with attendant heat pollution to the surrounding environment. Oguejiofor [2006:1370-1371] shows that inspite of the emergence of various gas utilization projects, Nigeria still flares about 50 percent of her natural gas production. This is a source of worry and challenge for energy management in Nigeria. Incidentally, energy management in this context entails the planning, organizing, directing and controlling of the resource for energy generation and supply to industrial, commercial and domestic consumers.

Therefore, to provide the data and information relevant for proper energy management in Nigeria, this work will delve into the estimation of the quantity of heat pollution from relentless gas flaring in Nigeria's petroleum fields. With the proven gas reserves of about 187 trillion cubic feet (5.30 trillion cubic metres), official statistics showed that on the average Nigeria flares about 50 percent of its gas production. Gas flaring in Nigeria has over the years of petroleum production attracted technical, economic and political attentions because of its wasteful and environmental implications. The Federal Government of Nigeria (FGN) has set December 31, 2010, as the date to end gas flaring. The previous deadlines of January 1, and December 31st 2008, are shifted because of the incompletion of projects meant to utilize gas and eliminate flaring. Interestingly, thermodynamics provides the equations interrelating the properties of the components of natural gas with measurable parameters from which the heat released from gas flaring can be estimated.

To this end, this report will be presented under the following objects:
a). Examination of composition of Nigeria's natural gas and the assumptions necessary for the estimation.
b). Theoretical framework for the study.
c). Method of numerical computation.
d). Results and discussion.
e). Concluding remarks.

COMPOSITION OF NATURAL GAS AND COMPUTATIONAL ASSUMPTIONS

Composition of Nigeria's natural gas

Natural gas is a mixture of hydrocarbon gases and the hydrocarbons belong to the paraffin group. The groups that have 1 to 4 carbon atoms ($C_1 - C_4$) occur as gases, while the groups having 5 to 7 carbons ($C_5 - C_7$) exist as liquid at surface conditions, but may also exist as vapours in natural gas.

Wami [2006:16] explains that natural gas is classified into two broad categories, dry and wet natural gas. While the wet natural gas contains condensable hydrocarbons like propane, butane and other heavier hydrocarbons, the dry natural gas does not contain economically recoverable amounts of condensable hydrocarbon. Wet natural gas is produced from geological formations containing crude oil, and it is called associated natural gas. This is the type of gas presently being flared in Nigeria.

Table 2-1 shows the average composition of Nigeria's natural gas or flare gas constituents in mole percent. In some oil fields methane which is the chief constituent of natural gas (flare gas) is as high as 94.3 percent, while in others it is as low as 65.9 percent.

Table 2-1: Average Composition Mole Percent of Natural Gas in Nigeria

Symbol	**Name**	**Formula**	**Average Composition (mole Percent)**
C_1	Methane	CH_4	85.82
C_2	Ethane	C_2H_6	6.46
C_3	Propane	C_3H_8	2.71
iC_4	Iso-butane	C_4H_{10}	1.25
nC_4	Normal-butane	C_4H_{10}	0.92
iC_5	Iso-pentane	C_5H_{12}	0.42
nC_5	Normal-pentane	C_5H_{12}	0.28
C_6	Hexane	C_6H_{14}	0.16
C_{7+}	Heptane	C_7H_{16}	0.26
N_2	Nitrogen	N_2	0.41 (Impurity)
CO_2	Carbondioxide	CO_2	1.16 (Impurity)
H_2S (ppm)	Hydrogen sulphide	H_2S	<0.15 (Impurity)

Source: Compiled from SPDC (1999)

Computational Assumptions

The quantification of heat evolution from gas flaring will be a tedious computation. In order to facilitate the computation, the following simplifying assumptions will be made:

(a) Natural gas is taken to be in the ideal state. Therefore the variations of the densities of the natural gas constituents with temperature are assumed to be negligible. However the variations of the specific heat capacity of the component of the natural gas with temperature are assumed to be significant, and therefore
$C_p = A + BT + CT^2$.

(b) The hydrogen sulphide (H_2S) impurity in natural gas is taken to have negligible impact on the heat released to the surrounding environment, because its composition is less than 0.51 parts per million (<0.51ppm).

(c) The flare stations and their surrounding environment are taken to be diathermal, thereby allowing the exchange of heat energy. That is $dQ \neq 0$.

(d) The flaring process is assumed to take place at constant atmospheric pressure (Isobaric process), whereby $dP = 0$.

(e) The average ambient air temperature is taken to be 25^0C (298K), while the flare station operates at 1500K.

(f) Gas flaring is assumed to accomplish complete combustion and maximum heat evolution from the process.

THEORETICAL FRAMEWORK

The theoretical framework reviews and presents the relevant equations for computing the heat liberated from gas flaring; and also it searches for the hints about the magnitude of heat evolution from flaring.

Smith and Van Ness [1987:65] give the equation of constant pressure (isobaric) process, or open air process heating for one kmole of an ideal gas as:

$$\Delta H = Q = \int C_p dT \qquad \ldots (1)$$

Owing to temperature dependence of C_p, Smith and Van Ness [1987:108] express the empirical equation for an ideal gas as:

$$\frac{C_p}{R} = A + BT + CT^2 + DT^{-2} \qquad \ldots (2)$$

Where either C or D is zero depending on the gas considered. Since the ratio C_p/R is dimensionless the units of C_p are governed by the choice of R. The choice of the unit of R is indicated in the Notation Section. Values of the constants A, B and C are applicable in the range of 300-1500K and are given by Smith and Van Ness [1987:109] for a number of common organic and inorganic gases.

The expression that will be applied in evaluating the specific heat capacities of the components of natural gas is obtained by the rearrangement of eqn (2) as:

$$C_p = R(A + BT + CT^2) \qquad \ldots (3)$$

The molar heat capacity of the mixture in the ideal gas state is expressed by Sinnott [1999:71], Himmelblau [1989:379] and Smith and Van Ness [1987:13] as:

$$C_{Pm} = Y_a C_{Pa} + Y_b C_{Pb} + Y_c C_{Pc} + \quad \ldots \qquad \ldots (4)$$

Therefore eqn (4) will be applied for computing the weighted average per kmole of the heat capacities of natural gas components.

By extension of eqn (4), the expression for calculating the kmole weighted average of the molecular weight of natural gas components will be:

$$W_m = \sum_{i=a}^{n} Y_i W_i \qquad \ldots (5)$$

Or, $$W_m = Y_a W_a + Y_b W_b + Y_c W_c + \quad \ldots \qquad \ldots (6)$$

Hummelblau [1989:250] gives the density expression for ideal gas as:

$$\rho_o = \frac{m}{V} = \frac{PW_m}{RT_o} \qquad \dots (7)$$

Where the symbols are defined in the Notation Section. Because density depends on temperature, Hummelblau [1989:81] expresses density as a linear function of temperature, such as:

$$\rho = \rho_o + aT_o \qquad \dots (8)$$

Where the variables are defined in the Notation Section. Thus it could be deduced from eqn (7) that the density of the ideal gas mixture at the gas flare temperature is:

$$\rho = \frac{PW_m}{RT} \qquad \dots (9)$$

T, being the operating temperature of flare station.

Onukwuli [2001:65] illustrates that the number of moles in a known gas volume can be given by:

$$n = \frac{\rho_o V}{W_m} \qquad \dots (10)$$

And Mbah and Aneke [1999:80] shows that the quantity of heat can be estimated with the following expression:

$$Q = n\Delta H = nC_{Pm}\Delta T \qquad \dots (11)$$

All the equations above are harnessed from various sources for estimating on annual basis the magnitude of heat liberated from gas flare furnaces in Nigeria's petroleum fields.

The Shell Petroleum Development Company (SPDC) of Nigeria [1996:1] discloses that the energy available from Nigeria's flared gas is prodigious, equivalent to one quarter of France's gas requirements. Also SPDC [1996:1] reports that a total of some two billion standard cubic feet per day (scf/d),representing more than 95 percent of associated gas production is flared, which is estimated to be about a quarter of the gas the world flares and vents. Daily Independent Editorial [2007:B4] reports that 45.8 billion kiloWatts of heat is generated into the atmosphere as a result of daily flaring of about 1.8 billion standard cubic feet (scf) of gas. Interestingly, this provides a clue as to the magnitude of heat dissipated from gas flaring furnaces.

METHOD OF COMPUTATION

The thermodynamic-property evaluations were accomplished by the following steps. The first was the use of eqn (6) in the calculation of the average molecular weight of Nigeria's natural gas. Secondly, the calculations of the average density of Nigeria's natural gas at the gas flare temperature of 1500K by using eqn (9). Third, the calculation of the enthalpy change of natural gas using the tabulated enthalpy values in Appendix D of Hummelblau [1996:656-659]. Fourth, the computation of moles of flared natural gas by using eqn (10). Fifth, the application of eqn (11) in the estimation of the quantity of heat given out by gas flaring to the surrounding environment.

Table 4.1: Computation of average molecular weight of gas from Nigeria

Computational tool: Eqn (6) Basis: 100kgmol of natural gas			
Component i	Y_i (kgmol %)	W_i (kg)	Y_iW_i (kg.kgmol)
C_1	85.82	16.04	1376.55
C_2	6.46	30.07	194.25
C_3	2.71	44.09	119.48
iC_4	1.25	58.12	72.65
nC_4	0.92	58.12	53.47
iC_5	0.42	72.15	30.30
nC_5	0.28	72.15	20.20
C_6	0.16	86.17	13.79
C_{7+}	0.26	100.20	26.05
N_2	0.41	28.02	11.49
CO_2	1.16	44.01	51.05
H_2S	0.15	34.08	5.11
$\sum_{i=a}^{n} Y_i W_i$			= 1974.39
Average mole weight (W_m) = $\frac{\sum_{i=a}^{n} Y_i W_i}{\text{Basis}} = \frac{1974.39}{100} = 19.74\text{kg.kgmol}^{-1}$			

Table 4.2: Computation of average density of gas from Nigeria

Computational tools: Eqn (9) and eqn (7)

Data:

T_o = 298K; W_m = 19.74kg.kgmol^{-1}; R = 8.314kJ.kgmol^{-1}K^{-1};

T = 1500K; P = 1atm = 1.013 x 10^5 Nm^{-2} = 1.013 x 10^2 KNm^{-2}

$$\rho = \frac{PW_m}{RT} = \frac{(1.013 \text{ x} 10^2)(19.74)}{(8.314)(1500)} = 0.160 \text{ kgm}^{-3}$$

and $$\rho_o = \frac{PW_m}{RT} = \frac{(1.013 \text{ x} 10^2)(19.74)}{(8.314)(298)} = 0.807 \text{kgm}^{-3}$$

Table 4.3: Computation of the enthalpy change of gas from Nigeria

Computational tool: $\Delta H = H_{1500K} - H_{298K}$

Basis: Tabulated enthalpy values in Appendix D of Himmelbau [1996:656-659]

Component i	H at 1500k (kJ.kgmol^{-1})	H at 298K (kJ.kgmol^{-1})	ΔH (kJ.kgmol^{-1})
C_1	79,244	879	78,365
C_2	133,678	1,277	132,401
C_3	190,581	1,771	188,810
iC_4	247,650	2,394	245.256
nC_4	248,571	2,328	246,243
iC_5	304,595	2,976	301,619
nC_5	304,595	2,976	301,619
C_6	361,539	3,563	357,976
C_{7+}	409,352	3,651	413,003
N_2	39,145	728	38,417
CO_2	62,676	912	61,764
H_2S	52,802	845	51,957
$\Sigma\Delta$H =			2,417,430kJ.kgmol^{-1} 2.4 GJ.kgmol^{-1}

Table 4.4: Computation of the moles of flared gas and quantity of heat liberated

Computational tools: Eqns (10) and (11)

Basis: Annual volumes of flared gas obtained from NNPC[2002:45] and Federal Bureau of statistics [2006:322]

Year	Flared gas Volume, V. (000,000 m^3)	Moles of flared gas (n)	Heat liberated n$\Sigma\Delta$H (000GJ)
1965	2,733	111,729,027	268,150
1966	2,692	110,052,888	264,127
1967	2,532	103,511,854	248,429
1968	1,311	53,595,593	128,629
1969	4,062	166,060,486	398,545
1970	7,957	325,293,769	780,705

1971	12,790	522,873,860	1,254,897
1972	16,848	688,770,821	1,653,050
1973	21,487	878,419,909	2,108,208
1974	26,776	1,094,641,945	2,627,141
1975	18,333	749,479,787	1,798,752
1976	20,617	842,853,040	2,022,847
1977	20,952	856,548,328	2,055,716
1978	19,440	794,735,562	1,907,365
1979	26,073	1,065,902,280	2,558,166
1980	22,214	908,140,730	2,179,538
1981	13,470	550,673,252	1,321,616
1982	11,940	488,124,620	1,171,499
1983	11,948	488,451,672	1,172,284
1984	12,813	523,814,134	1,257,154
1985	13,922	569,151,672	1,365,964
1986	13,917	568,947,265	1,365,473
1987	12,194	498,508,511	1,196,420
1988	14,740	602,592,705	1,446,223
1989	18,784	767,917,325	1,843,002
1990	22,410	916,153,495	2,198,768
1991	24,660	1,008,136,778	2,419,528
1992	24,575	1,004,661,854	2,411,189
1993	25,770	1,053,515,198	2,528,437
1994	26,910	1,100,120,061	2,640,288
1995	26,986	1,103,227,052	2,647,745
1996	26,590	1,087,037,994	2,608,891
1997	24,234	990,721,277	2,377,731
1998	23,632	966,110,638	2,318,666
1999	22,362	914,191,185	2,194,059
2000	24,255	991,579,787	2,379,792
2001	26,759	1,093,946,960	2,625,473
2002	24,836	1,015,331,915	2,436,797
2003	23,943	978,824,772	2,349,180
2004	25,091	1,025,756,687	2,461,816
2005	23,003	940,396,201	2,256,951

DISCUSSION

Discussion about magnitude of heat evolution

The annual quantities of heat liberated from gas flaring are massive and awesome numbers in the magnitude of millions of Giga Joules (GJ). These magnitudes may have informed SPDC statement that the energy available from Nigeria's flared gas is prodigious, equivalent to one quarter of France's gas requirements. Unfortunately, the release of these annual magnitudes of heat (See Table 4.4) into the environment is not an eco-friendly approach to petroleum production and also it is wasteful of the valuable energy resources.

Heat engines were described earlier in this report as machineries that transform heat energy into mechanical work. The massive amounts of heat energy (see Table 4.4) lost to wasteful gas flaring in Nigeria could serve numerous sizes of heat engines that would benefit Nigeria's drive for rapid industrialization and economic development through the transformation of heat energy into mechanical work that result in electricity generation and locomotion for rail and marine transportation.

Discussion about the trend of heat evolution

Since the moles of flared gas and the quantities of heat liberated from the flare gas are time-series data, ranging from 1965 to 2005, they are graphed respectively in order to derive some meaningful discussion about their trends.

Figure 5.1: Plot of Moles of flared gas versus time (1965-2005)

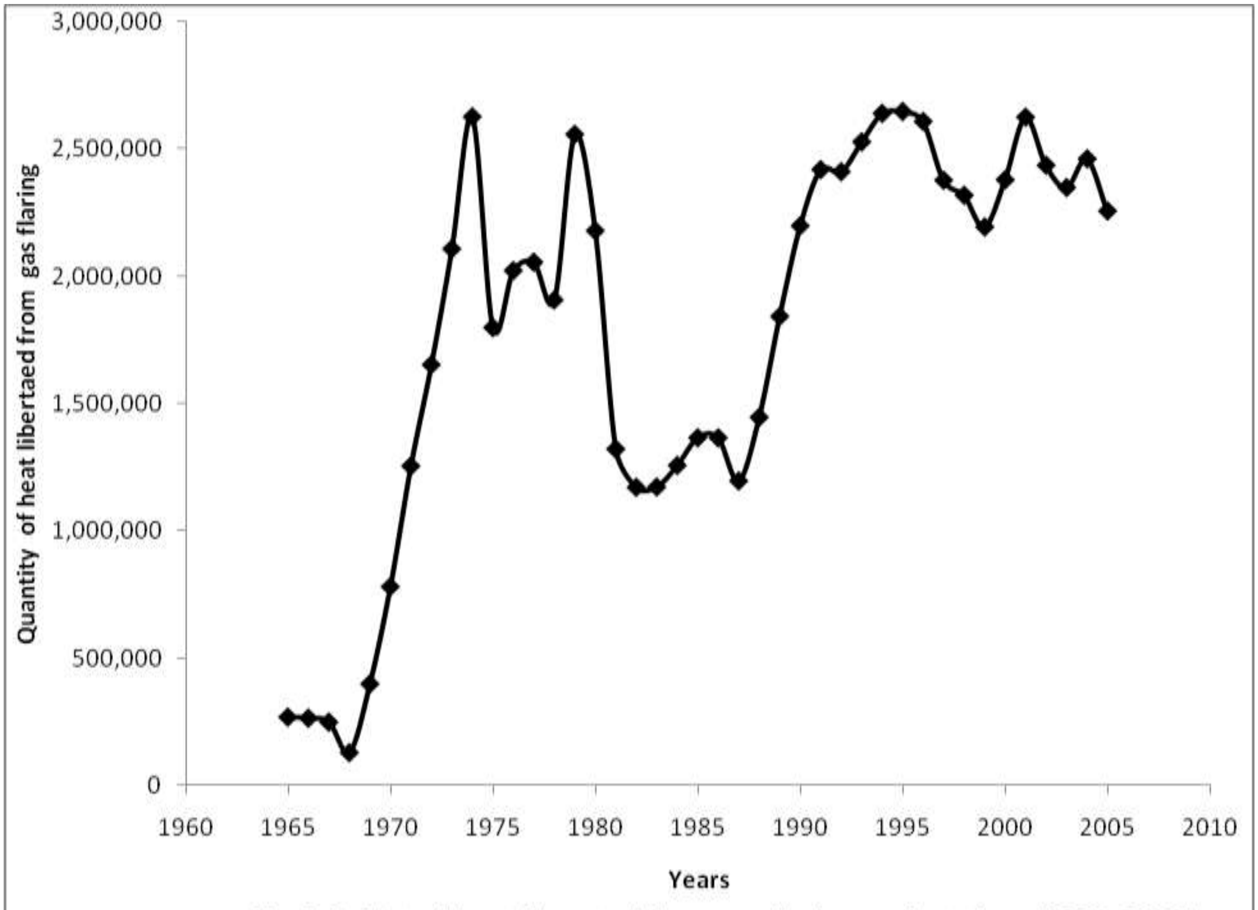

Fig. 5.2: Plot of heat liberated from gas flaring against time (1965-2005)

These graphs, Figures 5.1 and 5.2 depict erratic-growth trends in the number of moles of flared gas (Figure 5.1) and the quantities of heat liberated from gas flaring (Figure 5.2). However, on the average it could be written that Figure 5.1 portrays steady growth in the number of moles of flared gas over the years under study (1965-2005). Also, for Figure 5.2 it could be said that on the average the quantities of heat liberated from gas flaring rose progressively over the years, 1965 – 2005, attaining the peak of 2,468 million GJ in 1995 and the least of 128 million GJ in 1968(See Figure 5.2)

Discussion about estimation Of heat evolution

Eqn(11) indicates that the heat liberated from gas flaring (Q) may be estimated from two approaches; the enthalpy ($n\Delta H$) approach and the specific heat capacity ($nC_{Pm}\Delta T$) approach. This work estimated Q from the enthalpy ($n\Delta H$) approach because it is an easier approach. However, since the enthalpy term, $n\Delta H$ equates the specific heat capacity term, $nC_{pm}\Delta T$, estimating Q from $nC_{pm}\Delta T$ approach may not likely produce any significant difference in the quantities of heat (Q) evolved from gas flaring.

To minimize the loss of significant numbers through approximations in the rounding up of numbers, the Q computed were raised to exponent three as 000GJ of heat liberated. While for the number of moles, n, only the decimals were rounded up to whole numbers.

CONCLUSION

The estimation of the quantities of heat liberated from gas flaring sites are direct measurements of the thermal pollution and waste in Nigeria's petroleum fields. These annual quantities of heat pollution are on the average, progressive in trend from 1965 to 2005; and no doubt they are sources of discomfort to human and plant lives in the Nigerian hydrocarbon fields. It is believed that the magnitudes of heat evolution from gas flaring impact negatively on the entire eco-system in the Nigerian petroleum fields.

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