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ORIGINAL PAPER

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Hammer crushers vs disk crushers: the influence of working temperature on the quality and preservation of virgin olive oil

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Abstract An investigation was carried out using a hammer-crusher and a disk-crusher for olive paste preparation to evaluate the effects of different processing temperatures on the quality of the virgin olive oils obtained. The tests performed showed that hammer-crushing produces a more intense fragmentation of the olive pits than the disk-crusher, thus resulting in a more substantial increase in output temperature. Higher temperatures in the crusher during olive processing lead to a shorter preservation of the oils. All the analytical determinations performed also showed that the oils obtained from hammer-crushed pastes presented a greater degradation than those from disk-crushed pastes. These findings were further confirmed by the oven test results.

Keywords Hammer crusher · Disk crusher · Virgin olive oil · Olive crushing temperature · Oils shelf-life

Introduction

Recent studies [1, 2] have shown that the use of mechanical devices for olive crushing in the oil-milling industry determines a substantial difference between olive input temperature and paste output temperature with an increase from 4 to 10 °C. The temperature rise is due to the release of energy in the form of heat occurring during crushing of the pits and their fragments within a very short time in a few seconds, in fact [2]; the heat thus released is thought to be very high in a virtual micro-environment where it immediately spreads over the semi-liquid mass.

This phenomenon considerably influences the composition of the virgin olive oils thereby extracted as well as their preservation. Tests performed on hammer-crushed olives that had previously been refrigerated at about 6 °C have shown that the oils produced contain greater amounts of simple phenols even if the change in temperature was of the same extent but with a definitely much lower output temperature than hammer-crusher olives at room temperature [3]. The phenolic substances are considered responsible for influencing the shelf-life of the oils [4, 5, 6, 7].

The aim of this investigation was to evaluate the effects of temperature rise during olive crushing by comparing a hammer-crusher and a disk-crusher after resorting to significant mechanical solutions to reduce the temperature change and by achieving continuous cooling of the crushing chamber simulating a cavity wall chamber with a circulating coolant.

Materials and methods

Raw material. A homogeneous batch (about 200 kg) of olives of the *Coratina* cultivar was hand-picked in the optimal stage of semi-blackening, washed, de-leafed, and then divided into two equal portions which underwent crushing with two different units.

Crushers. A semi-industrial scale disk-crusher and hammer-crusher were used to process the olives; their crushing devices and rotational speeds adequately approximated those of the same types of machines used in the oil-milling industries.

In the *hammer-crusher* (Fig. 1) a vertically positioned slightly half-cone-shaped crushing chamber received a constant inflow of about 30 kg/h of olives from a hopper [8]. Three hammers positioned at 120° on a single plane and splined onto the shaft (ϕ=4 cm) of the motor were fixed inside the chamber. Thirty counterbeaters (height=5 mm) were embedded in the side of the chamber with an angle of 42° while the lower part of the chamber was covered by a grid with 65 holes (ϕ=5 mm). The greater basis of the crushing chamber constituted its lid (ϕ=15.7 cm) which was used to retrieve any paste left inside and to insert temperature sensors in different positions. The lid was also lined with 39 counterbeaters. Due to the slightly half-cone shape of the chamber, the olives fed into it were thrust not only against the sides of the chamber and their counterbeaters but also towards its greater basis

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Table 1 Technical characteristics of the hammer crusher

Grid	Half-cone angle (°) 42	Depth (cm) 5	Number of holes 65	Diameter of holes (mm) 5
Crushing chamber	Inner diameter (cm) 15	Outer diameter (cm) 15.7	Width (cm) 1	No. counterbeaters 30
Lid outer	Inner diameter (cm) 15.7	Outer diameter (cm) 16.7	Width (cm) 1	No. counterbeaters 39
Hammers (fixed)	No. 3	Rotor diameter (cm) 4	Width arm (cm) 1	Width utensil (cm) 1
Asynchronous motor	Maximum absorption (A) 7	Maximum power (kW) 1.1	cos φ 0.97	Angular velocity (rpm) 2850

Table 2 Technical characteristics of the toothed disk crusher

Rotor	Outer diameter (cm)	Average width teeth (cm)	Number teeth
Outer ring	17	0.6	26
Middle ring	12	1	13
Inner ring	7.5	2.5	4
Lid	Outer diameter (cm)	Average width teeth (cm)	Number teeth
Outer ring	14.5	0.8	22
Inner ring	10.0	1.0	11
Motor	Maximum absorption (A)	Maximum power (kW)	Angular velocity (rpm)
Asynchronous	5	1.1	2700

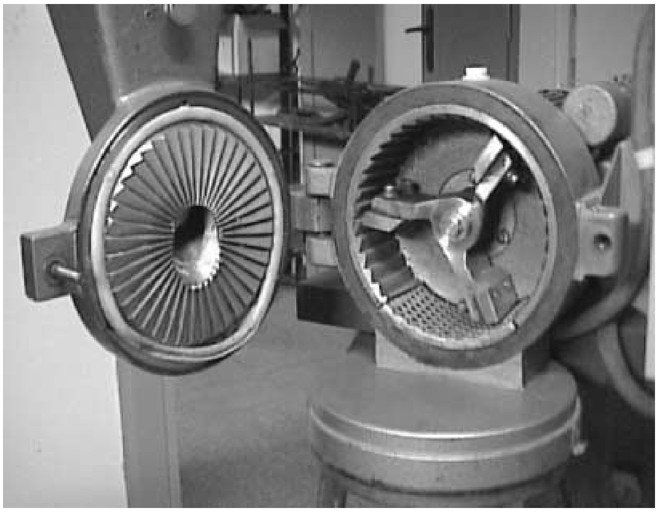

Fig. 1 Hammer crusher

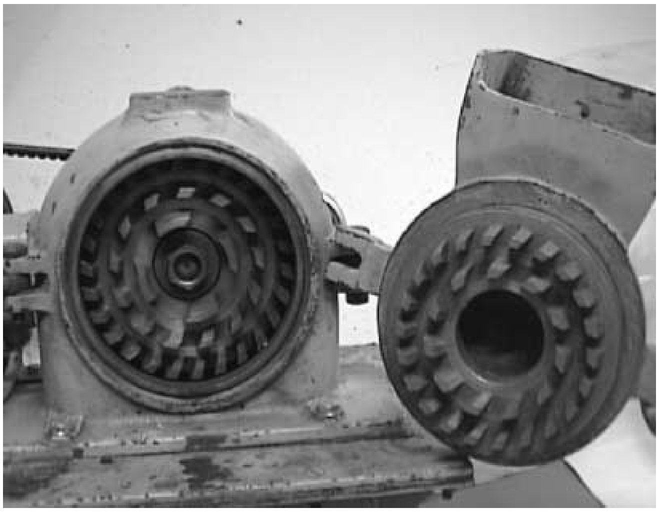

Fig. 2 Toothed disk crusher

with its counterbeaters. This system produced more efficient crushing of the drupes by the hammers; without this set-up, because of the small size of the machine and due to fact that the surface for heat exchange is greater than the internal volume, the effect induced by the temperature would have been smaller and the results difficult to interpret. Table 1 contains all the technical characteristics of the unit described.

The *toothed disk-crusher* used in the tests (Fig. 2) was also equipped with a small hopper ensuring a constant inflow of about 40 kg/h of olives. The unit consisted of an internal rotor directly splined onto the shaft of the motor and presenting three rings of prism-shaped picks with cutting edges 2 cm in length and 6 mm in width. The lid was lined with two rings of picks with cutting edges of the same length and width (Table 2) and was used to position several temperature probes in different positions. The paste fell out freely since there was no grid.

In each of the crushers the outside of the crushing chamber was surrounded by a long cooling coil containing a coolant coming from a thermostat refrigerator set at a range of –10 to –20 °C; the cooling coil was coated with insulating foam to minimize heat exchange with the outside. This system ensured continuous cooling of the crushing chamber. Temperatures were recorded by three thermocouples: the first was placed inside the chamber, the second on the hopper feeder, and the third at the outlet for the ground paste. Readings from the three probes were acquired in real-time and at a frequency of 5 s by a data-processing system connected to a personal computer. The olives were continuously fed into the machines at the highest flow rate.

Oil extraction. The olive paste obtained during each test with the two crushers was directly submitted to centrifugation in a basket centrifuge with an inner diameter of 19 cm of the bowl and a rotational speed of 2700 rev/min.

Thus, the crushing system was the only factor of difference between the two types of oil.

Measurement of olive stone size. Computation of the mechanical energy provided to grind the olives and, subsequently, the average rise in temperature produced was performed on the basis of the mechanical characteristics of the crushers described above and of the physical and mechanical characteristics of the drupes. By applying the results of a theoretical and experimental investigation of the problem of local and average rises in paste temperature during crushing, the relation between the diameter of each pit fragment and the amount of energy E (relative to the unit mass) required to crush an unbroken stone [9] is found:

$$E / W_i = \left(\frac{D_r}{D_2}\right)^{1/2} - \left(\frac{D_r}{D_1}\right)^{1/2} \tag{1}$$

where D_r is the reference diameter equal to 0.1 mm, D_1 is the original diameter of the pit, D_2 the diameter of the fragment considered, and W_i is a constant which is equal to approximately 40 J/g for more resistant agricultural substances. Since the original diameter D_1 is much higher than the reference value, the second term in Eq. (1) may be disregarded:

$$E = W_i \left(\frac{D_r}{D_2}\right)^{1/2}. \tag{2}$$

However, Eq. (2) is applicable when the pit is broken down into fragments having the same diameter D_2; generally it is necessary to calculate the average energy value by resorting to the size distribution of the pit:

$$\overline{E} = W_i \int_{-\infty}^{+\infty} \left(\frac{D_r}{D}\right)^{1/2} \varphi(D)\, dD. \tag{3}$$

Moreover, by working out the heat balance in the crushing system, the temperature rise due to the transformation of this mechanical energy into thermal energy may be computed:

$$T_m - T_e = \frac{M_n}{M_o} \frac{\overline{E} Q_o}{h S}. \tag{4}$$

All the stone fragments were separated from the softer parts of the olives by decanting the unsifted olive paste after it had been appropriately diluted it with water and separated. The portion thus obtained was dried in a ventilated oven at 60 °C and was sifted into different size groups by means of punched-plate screens with mesh sizes of 0.75, 1.00, 1.40, 1.70, 2.00, 2.36, 3.35, and 4.00 mm.

Analytical determinations of extracted oils. Acidity, peroxide value, and coefficient of specific extinction at 232 and 270 nm (K_{232} and K_{270}) were measured for each oil sample as per EC Regulation no. 2568/91 [10] and amendments and additions thereof. Chlorophyll pigment was determined according to the AOCS method [11]. The phenolic compounds were evaluated with the method described in Caponio et al. [12]; the results were expressed as mg of phenolic compounds (represented as gallic acid) per kg of oil. Resistance to oxidation of the oils was evaluated using the Rancimat method at 120 °C under an air flow of 20 l/h and the relevant results were expressed as induction time (h).

Results and discussion

Figure 3 shows the results regarding stone sizes and that in both cases the distributions are normal. Perusal of the data reported evidence that, under the experimental conditions described above, the mechanical thrust exerted by the hammer-crusher is stronger than that of the disk-crusher since the size of the stone fragments produced by the former is smaller than that obtained by the latter. On the basis of the distributions obtained (see Eq. 3) the mechanical energy conveyed to the drupes during grinding and, subsequently, the increase in temperature produced may also be computed (see Eq. 4). Table 3 itemizes the mean values and the standard deviations of the two distributions together with the mean specific energies for the two crushers.

Table 4 shows the results of the analytical determinations performed on the oils extracted from the hammer-crushed olives and from the disk-crushed olives at different processing temperatures. The mean values obtained with the results of three tests are reported in the table for each determination

As may be observed with both processing modalities, the temperature rise caused by the olive-crushing procedure remains practically constant even if the temperature approximates the room temperature as could be expected from having constant temperature and flow. What is worthy of notice is that hammer-crushing of the olives caused a substantially higher rise in the output paste tem-

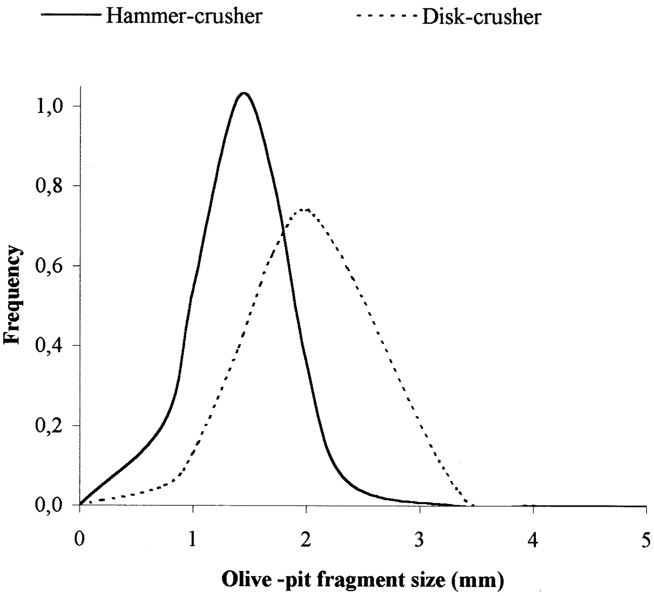

Fig. 3 Olive pit fragment sizes in the pastes obtained with the two crushing systems

Table 3 Characteristics of the distribution of pit sizes

Type of crusher	Average value (mm)	Standard deviation (mm)	Mean specific energy (J/g)
Hammers	1.44	0.39	11.94
Toothed disks	2.00	0.54	8.47

Table 4 Quality analytical characteristics of oil extracted

Test	Crusher temperature (°C)	Paste temperature (°C)	Free fatty acids (%)	Peroxide value (meq/kg)	K_{232}	K_{270}	Induction time h at 120 °C	Total phenols (mg/kg)	Chlorophyll (mg/kg)
Toothed disc crusher									
a	8	12	0.22	6.8	1.318	0.148	20.5	466	7.8
b	10	14	0.25	6.7	1.325	0.164	20.4	464	15.9
c	15	18	0.24	6.9	1.365	0.176	20.3	481	20.0
Hammer crusher									
A	8	14	0.28	10.2	1.346	0.173	20.3	462	44.6
B	10	16	0.30	11.0	1.360	0.178	18.9	455	40.5
C	15	20	0.33	11.4	1.391	0.180	18.7	453	32.8

Table 5 Oil submitted to accelerated auto-oxidation (60 °C in the dark): peroxide value

Test	Crusher temperature (°C)	Paste temperature (°C)	Sampling (days)										
			0	5	10	15	25	35	50	65	80	95	110
Toothed disc crusher													
a	8	12	6.8	10.6	13.4	20.0	24.0	31.5	33.2	37.2	44.4	46.3	50.3
b	10	14	6.7	11.4	13.7	20.1	27.6	32.8	35.6	39.5	46.4	53.8	58.5
c	15	18	6.9	12.6	13.5	23.5	26.5	36.2	36.9	37.2	48.6	57.4	66.6
Hammer crusher													
A	8	14	10.2	13.9	15.0	29.5	35.6	40.8	39.5	43.4	56.0	61.1	106.0
B	10	16	11.0	15.1	20.7	29.7	36.4	40.2	48.4	44.9	58.1	66.4	124.0
C	15	20	11.4	15.8	21.7	33.0	38.2	43.4	49.5	46.6	59.4	67.2	136.0

perature than did disk-crushing. This may be ascribed to the more intensive stone crushing action produced by the hammer-crusher which inevitably has a major impact on the quality and preservation of the oil. The occurrence of such a phenomenon is also supported by the fact that the rise in temperature is directly proportional to the mechanical energy required for fracturing the stones in the two systems (Table 3); see Eq. (4).

As for the routine analyses, the amounts of free fatty acids presented no particular correlation with the temperature of the crusher and of the output paste; the highest values were registered in the oils obtained from hammer-crushed olives and were very low ranging from 0.22 to 0.33%. Conversely, the peroxides value and the spectrophotometric constants appeared to be correlated with the temperature of olive processing since a rise in the initial temperature in the crusher was accompanied by a concomitant general and constant increase in their values. Processing with the hammer-crusher also determined a higher level of oxidation in the oil than did the use of the toothed disk-crusher: the mean value of peroxides in the oils from hammer-crushed olives was 10.9 as compared to a mean value of 6.8 in the oils from disk-crushed olives. The spectrophotometric constants showed mean values of 1.366 (oils from hammer-crushing) and 1.337 (oils from disk-crushing) for K_{232} and 0.177 (hammer-crushing) and 0.163 (disk-crushing) for K_{270}. The findings related to the different temperatures in each crusher show that rises in crusher temperature corresponded to slightly but consistently greater values of the parameters mentioned, especially of K_{232} and K_{270}, while the increases in peroxide values were less substantial.

The induction times of the oils measured at 120 °C with the Rancimat method tended to diminish slightly when the initial temperature of the crusher increased; the decrease was more substantial with hammer-crushing than with disk-crushing. As higher temperatures were reached, resistance to oxidation fell from 20.3 to 18.7 h with the hammer-crusher while with the disk-crusher it decreased only from 20.5 to 20.3 h.

The amounts of total phenols (ranging from 453 to 481 mg/kg of oil) in the oils obtained from either process did not change substantially as the temperatures of the machines increased; they also showed good agreement with the Rancimat results, which further substantiates the correlation existing between the two parameters [12, 13, 14].

Conversely the amounts of chlorophylls clearly differed based on the type of crusher used and on the temperature reached during processing. The oils produced with hammer-crushing had a greater chlorophyll content and were thus greener than the oils obtained after disk-crushing; the mean chlorophyll content was about two-fold greater in the former than in the latter: 39.3 and 14.6 mg/kg of oil, respectively. Although a deep green color is a good organoleptic characteristic of virgin olive oils, great amounts of chlorophyll have a pro-oxidant effect in the light and reduce the shelf-life of oils. Also to

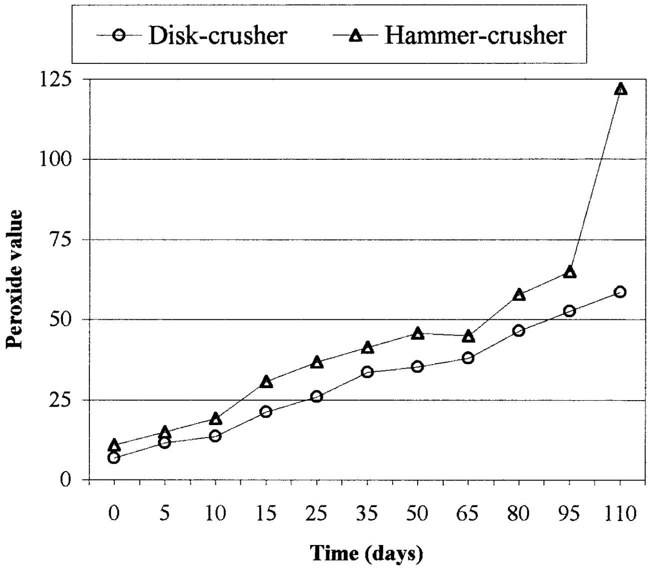

Fig. 4 Accelerated auto-oxidation (60 °C in the dark) of the oils extracted from disk-crushed olive pastes and hammer-crushed olive pastes: mean peroxide values of the three tests performed at different temperatures

be noted is that the amounts of chlorophylls change as the temperatures of the crushers change: they definitely increase when the temperature rises during disk-crushing while they decrease during hammer-crushing without however dropping to values as low as the highest levels registered in the oils from disk-crushing.

Disruption and smashing of the olive cell structure by means of hammer-crushing is already complete at the lower working temperatures of the machine while this is obviously not the case with the disk-crusher.

Table 5 shows the results of the oven test concerning the number of peroxides measured in the oils obtained using the two types of crusher for olive paste preparation. The values were registered periodically, throughout 110 days, and clearly showed the same differences as the basic analyses did regarding the state of oxidation of the oils and the corresponding resistance to oxidation. The oils extracted from the hammer-crushed pastes proved to deteriorate more rapidly with the thermostat treatment at 60 °C and in the dark. The oils obtained after disk-crushing, instead, had a consistently lower number of peroxides. These differences are more clearly depicted in the diagram of Fig. 4 which reports the mean number of peroxides registered in the oils examined in the three tests performed at different crusher temperatures. There also appears to be a homogenous (consistent) difference in the resistance to oxidation considered as a function of the crushers' working temperatures since (Fig. 5) higher olive crushing temperature during olive crushing was observed to bring about greater oxidative degradation of the oils.

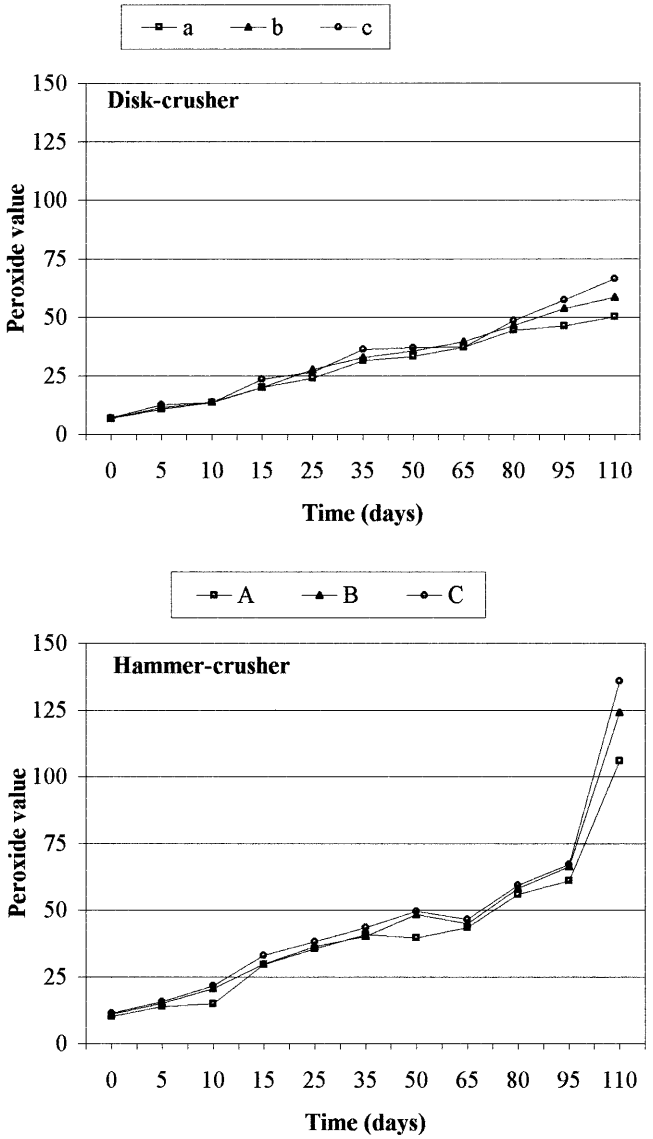

Fig. 5 Peroxide values in the oils obtained from disk-crushed pastes and from hammer-crushed pastes as a function of the different processing temperatures. Crusher temperature/paste temperature: a=8 °C/12 °C; b=10 °C/14 °C; c=15 °C/18 °C; A=8 °C/14 °C; B=10 °C/16 °C; C=15 °C/20 °C

Conclusions

The tests carried out at different temperatures during *hammer-crushing* and *disk-crushing* of olives provided useful information on the effects of different olive paste preparation modalities on the quality of oils:

- Under the experimental conditions used in this investigation, the hammer-crusher produced a more intense mechanical action on the drupes than did the toothed disk-crusher.
- The finer fragmentation of the olive pit thus obtained led to a greater increase in temperature of the paste.

- On the basis of the analyses carried out, the use of a hammer-crusher caused a greater auto-oxidation of the oil – irrespective of its deeper color – than did the disk-crusher.
- The increase in temperature during crushing – with both the disk and the hammer – seemed to be directly correlated with the peroxide value and the spectrophotometric constants of the oil extracted.
- The oven test confirmed the differences reported with the basic analyses concerning the more rapid oxidative degradation occurring in the oils from hammer-crushed paste than in those from disk-crushed pastes.

Overall, the results obtained suggest that the temperatures reached during fast olive crushing – either with traditional *hammer-crushers* or with *disk-crushers* – influence the quality and preservation of oils and that oils are more susceptible to auto-oxidation if they are produced with a hammer-crusher than with a disk-crusher. In conclusion it seems appropriate to improve the design of mechanical olive crushers in order to promote a more rapid dispersion in the environment of the thermal energy developed.

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