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Flower and fruit development of a low-chill peach, 'KU-PP2' in plastic houses with and without heating

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Abstract

Although 'KU-PP2', a low-chill peach cultivar, was released for high-quality peach production under forcing culture, the performance of 'KU-PP2' trees under forcing conditions has yet to be determined. In this study, we investigated the spring phenology, fruit development, and fruit quality of 'KU-PP2' in a heated plastic house compared with the same traits in an unheated plastic house and open field conditions. We found that the forcing conditions accelerated the spring phenology and harvest period of 'KU-PP2'. Heated conditions shortened the number of days from dormancy release to blooming and the length of the fruit development period, resulting in the blooming of flowers in late February, with fruit begin harvested as early as mid-May, which was notably earlier than blooming and fruit harvest under natural conditions by 4 and 6 weeks, respectively. Similarly, the unheated conditions accelerated the time to blooming and harvest by up to 3 and 4 weeks, respectively compared with the open field conditions. However, although the fruit produced by trees raised in the heated plastic house could be harvested at an earlier date, the amount of fuel used for the heating system was 50 L per tree, which could be prohibitively expensive for commercial production. Although the fruit growth pattern did not differ significantly between the forcing and natural conditions, the rate of fruit growth at stages S1 and S2 was higher in the heated plastic house than that under the other assessed conditions. Furthermore, the size and quality of fruit obtained under forcing conditions were slightly larger and superior, respectively, than those of fruit produced under natural conditions. Moreover, we found no evidence of split-pits under the forcing conditions. The findings of this study accordingly indicate that cultivation of the low-chill peach 'KU-PP2' under forcing conditions is conducive to a notably earlier harvest of fresh peaches. These observations advance our current understanding of the flowering, fruit development, and fruit production of low-chill peaches under forcing conditions.

Key words: Chilling requirement, peach production, protected agriculture, *Prunus persica*

Introduction

Under natural conditions, the harvesting season of Japanese peaches commences in May with early ripening cultivars and continues until late August or early September (Kubota, 2006). In Japan, fresh peach production peaks in July and August, coinciding with the melon, watermelon, and grape harvest seasons. Consequently, the price of peaches tends to fall notably when numerous other fruit types are available for purchase on the market. For example, in 2019, the unit price for peaches in the early season (May) approached 35 USD/kg but subsequently plummeted to 5 USD/kg during the peak season (Jul to Aug) (Japan Government Statistics, 2019). To overcome such price depreciation, peach trees can be cultivated in heated plastic houses to shorten the time to harvest, thereby enabling the production of fruit at a very early stage in the season, when fresh peaches grown under natural conditions are unavailable or are in very limited supply. Hence, at this time, the demand for fresh peaches is very high and these accordingly command a high market price, which is beneficial for growers (Maneethon, 2007).

The peach cultivar 'KU-PP2' [*Prunus persica* (Bastch) L.] was developed as part of the Low-chill Peach Breeding Program at Kagawa University and is derived from a cross between the low-chill peach 'Tropic Snow' (white pulp) and the Japanese high-chill peach 'Hikawa Hakuho' (white pulp). 'KU-PP2' is a yellow-fleshed peach with a low-chilling requirement (400-500 chilling hours) that produces excellent yields, high fruit quality and facilitates an early harvest (Manabe *et al*., 2015). It has been released for use in areas with mild winters, particularly in forcing culture systems to prolong the harvest season of a fresh peach in southwest Japan. A lower chilling requirement indicates that peach cultivars require less chill-hour accumulation to break dormancy, thereby enabling flowering in mid- to late winter (Topp *et al*., 2008). Exposure to chilling temperature enables low-chill peach cultivars to restore growth capacity. Nevertheless, bud growth could still be retarded by low mid- to late winter temperatures. Thus, warm temperatures are required to promote budburst in spring (Fadón *et al*., 2020). Consequently, by raising 'KU-PP2' under forcing culture conditions, growers can achieve a more advanced harvest season by adopting an earlier onset of forcing. However, high temperatures can have the effect on prolonging the flowering period and tend to have an adverse effect on the development of reproductive organs, pollen germination, and fruit-set in peach trees (Kozai *et al*., 2004). Accordingly, the prevention of excessive heating is necessary to ensure normal flower development and fruit production under forcing culture conditions.

The cost of fuel used for the heating system is one of the most strategically important of all costs in protected agriculture production (Canakci *et al*., 2013), and in this regard, early-season peach production is dependent on a sufficiently high temperature within the plastic house that are favourable with respect budburst and flowering. Consequently, energy consumption is an important consideration and the efficient management of energy usage is a key factor determining the success of fruit production strategies under forcing culture. Accordingly, in this study, we sought to assess the performance of 'KU-PP2' trees under forcing conditions with and without a heating system, evaluate the effect of forcing conditions on budburst, reproductive organ development, flowering, and fruit quality compared with these traits observed under natural conditions.

Materials and methods

Plant materials: In this investigation, we studied the budburst, flowering and fruit ripening of 'KU-PP2', a recently developed low-chill peach cultivar, as well as trees grown in natural conditions over the past two seasons (2016/2017 and 2017/2018). The plastic houses used for this purpose were 6 m wide, 12 m long, and 3.5 m high with an area of 72 m^2. Eight healthy five-year-old 'KU-PP2' plants were grown at the Faculty of Agriculture, Kagawa University (Japan: 34°27′N, 134°12′E). All plants were grafted onto a low-chill peach rootstock. Automated drip irrigation was set up for both conditions (once a day in the morning). A pipe frame structure was covered with a polyvinyl chloride (PVC) film and heated to 26 January 2017, chilling hours reached 850 h. On 12 May 2017, the PVC film was removed after harvest. Heating and ventilation systems were set according to the instructions for forcing Japanese high-chill cultivars into growth (Kagawa, 1998; Table 1). Unheated plastic house cultivation of 'KU-PP2' was evaluated in the 2017/2018 season. The pipe frame was covered with PVC film from January 8th, 2018, to harvest on May 25th, 2018. The ventilation system was set at 30 °C during the investigation. Temperature measurements were made 1.5 m above the ground surface by using a thermo-recorder.

Table 1. The temperatures of heating and ventilation system from the onset of heating to the harvest period in a heated plastic house for full heating in the season 2016/2017 season

Stages of development	Temperature (°C)		
	Heating system		Ventilation system
	Day[a]	Night[a]	
From the onset of heating to flowering	15	7	25
From flowering to petal fall	18	10	25
First half of fruit growth	20	13	28
Final half of fruit growth	22	16	30
From red coloring	24	18	30

[a] Daytime and nighttime were from 09:00 to 17:00 and 17:00 to 09:00, respectively.

Budburst, flowering, pollen germinability, and fruit-set assessments: Budbreak and flowering were monitored at 3-day intervals on the current-year shoots, which were randomly selected from the canopy of 'KU-PP2' trees. The number of floral and leaf buds on these shoots was also recorded and used to calculate the percentages of budburst and flowering on each shoot. The appearance of calyces or bracts on floral and leaf bud scales was considered to be indicative of budburst. The blooming of flowers was defined as the date when 50 % of the flowers had opened, and during full bloom, we collected 20 flowers from trees under forcing and natural conditions. The weight and size (width, length of pistil, and width of ovary) of these flowers were measured, and pollen grains were collected to determine pollen germinability. Pollen grains were cultured on an artificial medium containing 10 % sucrose and 1 % agar and incubated at 25 °C for 3 h. Fruit-set was evaluated after the final period of natural fruit drop (three weeks after full bloom). All opened flowers on the marked shoots were recorded and approximately 4 weeks after full bloom, the developing peach fruits on the same shoots were counted to estimate the fruit-set. The fruit-set rate was calculated using the following formula and expressed as the number of developing fruits per opened flower.

$$\text{Fruit set rate (\%)} = \left(\frac{\text{Number of developing fruits}}{\text{Number of opened flowers}}\right) \times 100$$

After fruit-set evaluation, the 'KU-PP2' peach trees were thinned by hand to leave gaps of 10 to 15 cm between fruit.

Fruit development and quality index evaluation: On each tree, we monitored the growth of 10 marked fruits by measuring the increase in fruit diameter from 1 week after flower blooming. At commercial maturity, 10 fruits per condition were collected and weighed, for each of which we obtained measurements of cheek-to-cheek diameter, suture-to-opposite-side diameter, and fruit length using a digital caliper. The fruit development period (FDP), defined as the time from full bloom to the first commercial harvest, and the date of harvest was also recorded. Flesh firmness was measured from two fruit sides using a manual penetrometer with a 4.5-mm tip, and total soluble solids (TSS) and titratable acid (TA) were assayed in fruit juice. TSS was measured using a digital refractometer (PR-101α; Atago Co. Ltd., Japan) and expressed as degree Brix (°Brix), TA was analyzed by titrating 5 mL of juice samples with 0.05 mol L^{-1} NaOH using an Acidity Titrator (TA-72; DKK-TOA Co. Ltd., Japan) and expressed as malic acid equivalents (g L^{-1} of malic acid). The percentage extent of over-color was rated visually under fluorescent light according to a scale from 1 (none) to 9 (hiding ground color) (Giovannini *et al.*, 2013).

Statistical analysis: Data were analyzed with an independent sample *t*-test using the Statistical Analysis System (SAS) University Edition software (SAS Institute Inc., Cary, NC). Percentage data were arcsine transformed prior to statistical analysis.

Results

In Kagawa prefecture, which is located in southwest Japan, the winter begins in December and continues until the end of February. In the 2016/2017 and 2017/2018 seasons, the average daily temperatures during this period were 7.3 and 5.3 °C with ranges of 2.3 to 13.2 °C and 0.9 to 10.5 °C, respectively. In the spring (March to May) of both growing seasons, the average temperature was approximately 15.3 °C, with a range of 5 °C to 25.1 °C (Japan Meteorological Agency, 2020). Fig. 1 shows the mean daytime and night-time temperatures under forcing conditions and in an open field at Kagawa university from the onset of heating to the end of the experiment when the fruits of 'KU-PP2' in the open field were harvested. The plastic houses contained 14 mature trees and were covered by PVC film in late January. The PVC film was removed in mid-May. The amount of fuel used for the heating system was 50 L per tree.

Spring phenology, flower characteristics and harvest period: In both assessed seasons, budburst, flowering and harvesting periods of 'KU-PP2' peach trees were also accelerated by forcing culture (Table 2). During the 2016/2017 season, the budburst, full bloom, and harvest of 'KU-PP2' under forcing with heating occurred earlier than under natural conditions by 30, 32 and 42

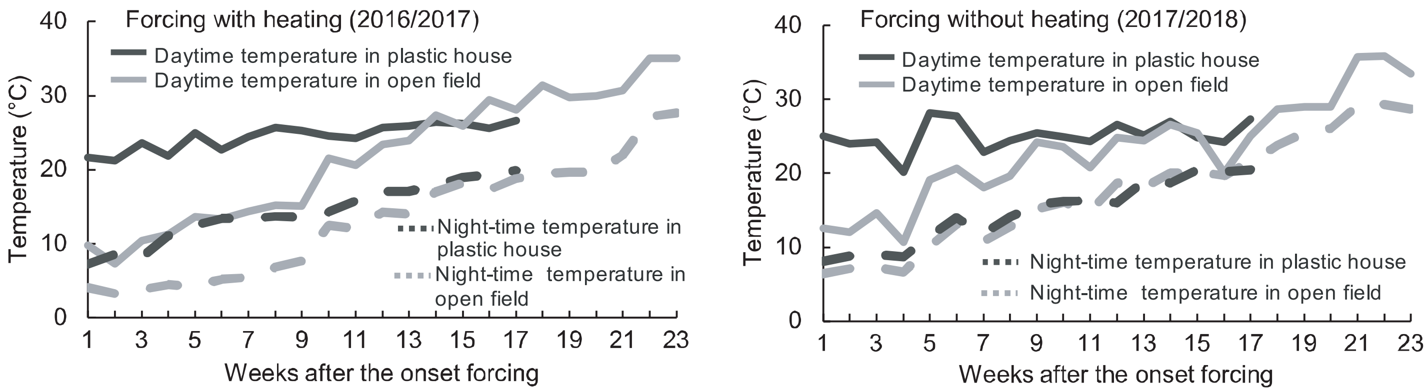

Fig. 1. The average of daytime (09:00-17:00) and night-time (17:00-09:00) temperature in plastic houses with and without heating and in an open field at the research field of the Faculty of Agriculture, Kagawa University, Japan during the experimental period (late January to late June) in the 2016/2017 and 2017/2018 growth seasons.

days, respectively. In the heated house, the floral and leaf budburst commenced 2 weeks after the onset of heating (29 January 2017) and blooming commenced 10 days thereafter. The average dates of the first commercial harvest enforced with heating and open field conditions were 12 May and 23 June 2017, respectively. The period from full bloom to the harvest of 'KU-PP2' trees (FDP) was shortened by heating, whereas no significant difference was detected in the FDP of trees cultivated under unheated and natural conditions (Table 2).

Likewise, the bud break, flower blooming, and harvest period of 'KU-PP2' peach trees under forcing conditions without heating (2017/2018) occurred earlier than those under open field conditions (Table 2). Forcing conditions were initiated on 12 January 2018, with budburst and full blooming occurring 12 and 45 days subsequent to the onset of forcing, respectively. Compared with trees grown in the open field, the plastic house without heating accelerated budburst, flowering, and harvesting by 38, 20 and 55 days, respectively.

The morphological characteristics of reproductive organs, budburst rate, and fruit-set are shown in Table 3. We detected significant differences in the size of reproductive organs, pollen germination rate, and fruit-set of trees cultivated under forced and natural conditions. In the plastic houses with and without heating, both the pistil length and ovary width of flowers were greater than those of flowers under natural conditions. Similarly, pollen germinability and the rate of fruit-set were higher in plastic houses than under open field conditions. However, although the rate of fruit-set in the heated plastic house was higher than that under natural conditions (season 2016/2017), no significant difference was detected in the fruit-set recorded in the unheated house and in the open field (season 2017/2018). In contrast, the flower weight and budburst rate of 'KU-PP2' trees in the plastic houses and open fields were found to be comparable.

Fruit development and fruit quality: The results indicated that the heated plastic house accelerated the early stage of fruit development and shortened the FDP of 'KU-PP2' peaches. The average FDP of fruit under forced conditions with heating was 79 days, which was 10 days shorter than that under open field conditions. In contrast, we detected no significant differences in either the fruit development or the FDP of 'KU-PP2' trees cultivated under forcing without heating and natural conditions. In both assessed seasons, the 'KU-PP2' fruits produced by

Table 2. Effect of forcing conditions with and without heating on budburst, full bloom and harvesting of 'KU-PP2' peach trees compared with natural conditions in the 2016/2017 and 2017/2018 growth seasons.

Season	Cultivation	The date of				Days from	
		Onset of forcing	Budburst	Full bloom^z	Harvest	Onset of forcing to blooming	Blooming to harvest
2016/2017	Open field	-	15 Mar	26 Mar	23 Jun	-	89
	Forcing with heating	29 Jan	13 Feb (30)^y	22 Feb(32)	12 May(42)	24	79
t-test		-	-	-	-	-	*
2017/2018	Open field	-	03 Mar	18 Mar	19 Jun	-	93
	Forcing without heating	12 Jan	24 Jan (38)	26 Feb(20)	25 May(25)	45	91
t-test		-	-	-	-	-	ns

Values are presented as means. ^{y} Values in parentheses indicate the number of days advanced under forcing culture.
^{z} Full bloom was defined as the date when 50 % of the flowers had opened. * and ns denote the significance level at $p \leq 0.05$ and non-significance, respectively.

Table 3. The percentage budburst, flower characteristics and fruit-set of 'KU-PP2' peach trees under forcing conditions with or without heating and open field conditions in the 2016/2017 and 2017/2018 growth seasons.

Season	Cultivation	Bud burst rate (%)	Flower weight (g)	Pistil length (mm)	Ovary width (mm)	Pollen germination (%)	Fruit-set rate (%)
2016/2017	Open field	85	0.3122	13.65	1.24	52.3	32.8
	Forcing with heating	82	0.3203	15.84	1.62	61.4	52.7
t-test		ns	ns	*	*	*	*
2017/2018	Open field	81	0.3378	11.24	1.13	64.5	49.1
	Forcing without heating	80	0.3514	13.49	1.71	67.1	50.7
t-test		ns	ns	*	*	ns	ns

Values are presented as means and were analyzed using an independent sample *t*-test. * and ns denote the significance level at $p \leq 0.05$ and non-significance, respectively.

trees under natural and forcing conditions exhibited a double sigmoidal growth pattern (Fig. 2), with the fruit development curve commencing after full bloom and growth occurring during three phases (S1-S3). During stage S1, there was a rapid increase in fruit diameter until 5 weeks after blooming, which was followed by a more gradual increase over 3 weeks during the second phase (S2). During the final phase (S3), however, the fruit diameter again underwent an exponential increase until 1 week prior to harvesting, at which time the final fruit size was attained. Although similar patterns of fruit growth were observed under forced and open field conditions, we found that the diameter of the fruits in the heated plastic house underwent a significantly greater increase during the early stage (S1) of development (Fig. 2).

Plant forcing conditions almost always support increases in fruit morphology and chemical composition (Table 4). Fruit weight and TSS were significantly higher than those found in the open field while forcing had no significant influence on TA and flesh firmness. Also, growing 'KU-PP2' fruit in a plastic house can help to prevent the splitpit phenomenon. Approximately 30% of the 'KU-PP2' fruits had split pits under natural conditions, but we found no sign of the fruit splitting in the plastic house with or without a heating system.

Discussion

In order to break dormancy, temperate fruit trees require a certain accumulated period of low temperatures, after which warmer temperatures are necessary to promote budburst and flowering (Perry, 1971; Fadón *et al*., 2015; Guerra and Rodrigo, 2015). When the chilling requirement has been fulfilled, a higher temperature is the principal driving force triggering spring phenology (Fadón *et al*., 2020), and consistent with this pattern, we found the budburst of 'KU-PP2' peach trees under forcing conditions in late January or early and bloom in late February, which was notably earlier than the same events in open conditions. During January and February, the average air temperature in the open field ranged from 0.9 to 13.2 °C, whereas that in the plastic house ranged from 7 to 28 °C.

Forcing conditions accelerated the phenological sequence during spring and fruit maturation for the 'KU-PP2' trees, resulting in a harvest time 4 to 6 weeks earlier than for trees grown in the open field. Similarly, previous studies have demonstrated that cultivation of the low-chill peach 'KU-PP1' in forcing culture enables the harvesting of fruit with superior quality at an earlier date than that of commercial peach cultivars (Beppu *et al*., 2015; Beppu *et al*., 2016). According to Dennis (2000), peach fruits exposed to higher temperatures develop more quickly and have a shorter fruit development period (FDP) than those exposed to lower temperatures, resulting in an early maturation.

We also found that the pollen germinability and fruit-set rate of 'KU-PP2' under forcing conditions were greater than those of trees cultivated in the open field, indicating that conditions in the plastic house during blooming and fruit-set (around 20 °C with high humidity) are suitable for pollen germination and fertilization. In this regard, Weinbaum *et al*. (1986) examined the effects of low to high temperatures (1-34 °C) on the pollen viability and germination in peaches and found that at low temperatures (11-12 °C), pollen viability and germination were low with a long germination period, whereas high temperatures (30-34 °C) were found to have detrimental effect on pollen germination and reproductive organs. The highest pollen viability and germinability and the most rapid germination were observed at temperatures of between 20 and 23 °C.

For trees cultivated in the heated plastic house, there was a typically shorter duration from the onset of forcing to budburst and FDP than those grown in the plastic house without heating.

Table 4. The fruit characteristics, fruit quality, and split-pits percentage of 'KU-PP2' peach trees under forcing conditions with or without heating and open field conditions in the 2016/2017 and 2017/2018 growth seasons

Season	Cultivation	Fruit weight (g)	Fruit size (mm) Cheek	Suture	Length	TSS (°Brix)	TA ($g\ L^{-1}$)	Firmness (N)	Split-pits (%)
2016/2017	Open field	165.2	67.9	65.9	52.8	10.0	0.23	0.22	32.4
	Forcing with heating	225.8	76.4	73.2	71.9	12.6	0.21	0.19	0
t-test		*	*	*	*	*	ns	ns	*
2017/2018	Open field	178.1	68.1	71.9	65.4	11.8	0.21	0.20	39.8
	Forcing without heating	199.3	69.5	72.2	64.1	12.1	0.19	0.23	0
t-test		*	ns	ns	ns	*	ns	ns	*

Values are presented as means and were analyzed using an independent sample *t*-test.* and ns denote the significance level at $p \leq 0.05$ and non-significance, respectively.

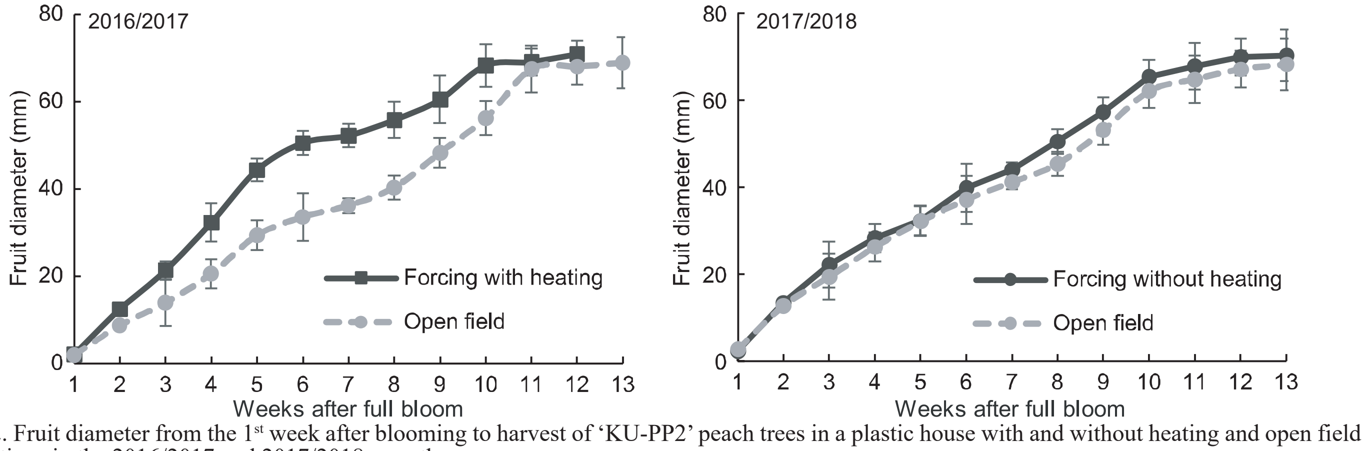

Fig. 2. Fruit diameter from the 1st week after blooming to harvest of 'KU-PP2' peach trees in a plastic house with and without heating and open field conditions in the 2016/2017 and 2017/2018 growth seasons.

Warm temperatures, once the cooling requirements are met, play an important role in stimulating spring phenological development, the resumption of growth, and metabolic activity. In this regard, several studies have established that elevated temperatures promote the earlier budburst, leafing, and flowering of temperate fruit trees (Chmielewski *et al*., 2004; Lu *et al*., 2005; Guédon and Legave, 2008; Caffarra and Eccel, 2011). Notably, in this context, Chmielewski and Rötzer (2001), who analyzed meteorological data across Europe for the period 1969-1998, found that an increase in annual mean temperature advanced the flowering date by 7 days/°C. Furthermore, temperature influences fruit development rate and maturation date, with high temperatures tending to increase the fruit growth rate and accelerate fruit maturity in many plants (Suzuki *et al*., 1995; Adams *et al*., 2001; Topp *et al*., 2008). As a result, the FDP of fruits that develop in warmer conditions is shorter than that of fruits that develop in cooler conditions.

The pit-splitting phenomenon observed in peaches can probably be attributed to excessive precipitation, nitrogen fertilization, and thinning (Warmund, 2016; Liu and Ma, 2017). In the present study, we found that pit-splitting in the 'KU-PP2' peach cultivar occurred only in the fruit produced in the open field, which we suspect could be ascribed to excessive seasonal rainfall. At our research field site, total precipitation prior to the 'KU-PP2' harvest period (April - June) in the 2016/2017 and 2017/2018 seasons was 158 and 266 mm, respectively.

In conclusion, the results of this study suggest that growing low-chill peach cultivars under forced conditions has the potential to produce high-quality fruit early in the season. The quality of fresh peaches at this time of the year is satisfactory, and the product is suitable for both local markets and distant regions in which ripe peaches are unavailable. Although the spring phenological events and fruit maturation of 'KU-PP2' under heated conditions occur earlier than those in a plastic house without heating and under open field conditions, the high fuel costs associated with heating currently represent a barrier to precluding commercial production.

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