

COBEM-2017-2127

FAULT DETECTION ALGORITHM FOR TEMPERATURE SENSORS OF HOUSEHOLD REFRIGERATORS

Everton Machado
Alexsandro dos Santos Silveira
Alexandre Trofino
Claudio Melo

Federal University of Santa Catarina

everton@polo.ufsc.br, alex@polo.ufsc.br, alexandre.trofino@ufsc.br, claudio@polo.ufsc.br

Abstract. *This work presents a study and development of an innovative fault detection system for temperature sensors of household refrigerators. The proposed algorithm is based on the temperature difference between defrost and fresh food sensors and comparison with normal operating conditions. An experimental apparatus was designed to validate the fault detection method and a fault generation routine was developed in a computational ambient to modify the temperature signal in accordance to different types of faults found in real world. A set of experimental tests in several ambient temperature conditions were performed suggesting efficiency and reliability of the fault detection algorithm.*

Keywords: *Fault detection, household refrigeration, temperature sensors, offset faults*

1. INTRODUCTION

The increase of embedded control systems in household refrigerators has created a new concern about the correct functioning conditions of the sensors present in these products. Sensors are fundamental in every control systems, Isermann (2006), and faults in these elements can lead to a malfunctioning and even a total interrupting of refrigerator functioning.

For these reasons, fault detection schemes for refrigeration systems have been investigated and reported in the recent literature. Support data vector description (SVDD) and self-adaptive principal component analysis method (APCA) for detecting faults in chillers were presented in Zhao *et al.* and Hu *et al.*, respectively. Seo *et al.* evaluated a method based on refrigeration cycle to evaluate the occurrence of faults in household air conditioners. In spite of these results, there is a lack of works focused on household appliances, more specifically in household refrigerators.

The aim of this work is to evaluate an innovative algorithm for detecting offset faults in temperature sensors of household refrigerators using only sensors available in the original configuration of the product, i.e. no extra sensor is used in the proposed fault detection scheme.

2. EXPERIMENTAL SETUP

This work uses a single door household refrigerator with two temperature sensors. One of them (focus of this research), is responsible for controlling the compartment temperatures (freezer and fresh food), and the another one is a defrost terminator used to finish the defrost process. Figure 1 shows the temperature sensors location inside the refrigerator.



Figure 1. Sensors location inside the refrigerator: (1) Fresh food sensor; (2) Defrost sensor

The fresh food sensor is responsible for maintaining the compartments temperature under standard values, driving the compressor through an on/off controller present in the embedded system of the refrigerator. Being present on the temperature control loop, Fig. 2, fault in this sensor can lead the refrigerator ranging from small temperature variations to large ones degrading the system performance.

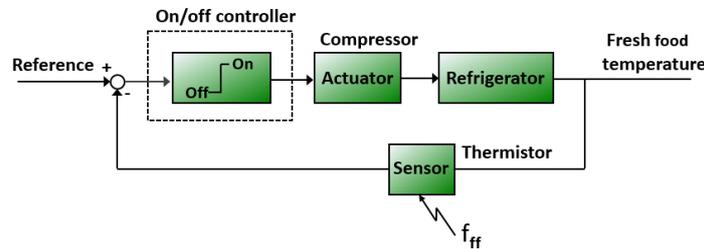


Figure 2. Temperature control loop

The experimental apparatus was designed with two main objectives: Firstly, a fault generator was programmed in Labview to generate offset faults in the fresh food sensor. This computational routine receives the temperature measurement and modify it emulating offset faults with different amplitudes.

The second objective is to make these emulated faults produce real faulty behaviors in the refrigerator. To this end, the on/off controller was reproduced in the same computational ambient of the fault generator. In this proposed configuration, the control system receives the faulty sensor and the compressor is driven by the data acquisition system through solid state relays. The defrost process was maintained under original logic. Figure 3 shows the experimental apparatus scheme.

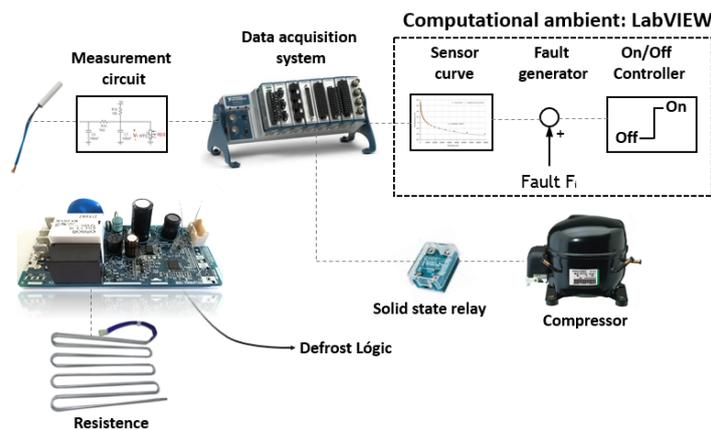


Figure 3. Experimental apparatus diagram

The LabVIEW application, Fig. 4, counts with the sensor curve fitted with the Stainhart-Hart equation, the on/off controller, the fault generator and fault detection algorithm proposed herein.

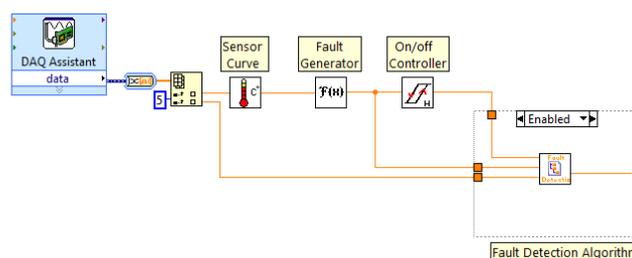


Figure 4. Labview application

Information about the status of the defrost process and door openings, usually available in a refrigerator, are obtained in this experimental apparatus by monitoring the electrical power. Furthermore, in order to verify the performance of the

proposed fault detection algorithm, t-type thermocouples were placed inside the refrigerator for evaluating the fresh food and freezer average temperatures in presence of faults.

3. FAULT DETECTION ALGORITHM

Based on preliminary tests, the difference between fresh food and defrost temperatures can be used to detect offset faults in household refrigerators. Figure 5 shows the detection algorithm scheme.

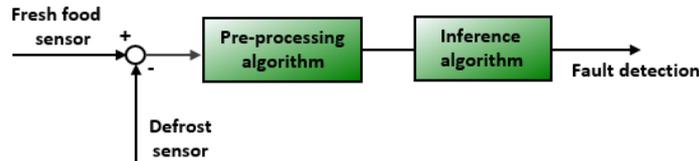


Figure 5. Fault detection algorithm scheme

The proposed fault detection method consists of a pre-processing algorithm that treat the information received from both, sensors and embedded system, of the refrigerator. This treated information is used as input to the inference algorithm that returns the status, faulty or not faulty, of the sensor. Subsections 3.1 and 3.2 discusses in details both pre-processing and inference algorithms implemented in this work.

3.1 Pre-processing algorithm

This algorithm is responsible for processing and organizing the information to be used by the inference system. The main rule for evaluating fault conditions uses the difference between fresh food and defrost sensors. Good functioning conditions have a pattern behavior that is changed when a fault occurs. Figure 6 shows a typical curve of the difference between fresh food and defrost sensors, here called "gap", obtained before and after a fault in the refrigerator sensor.

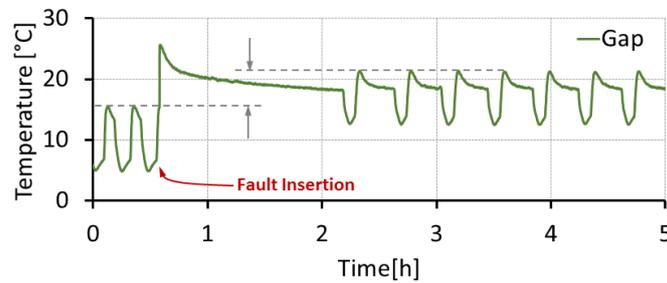


Figure 6. Defrost temperature reduction

The gap temperature taken in each sample time:

$$Gap = T_{ff} - T_{df} \quad (1)$$

where T_{ff} is the fresh food temperature and T_{df} is the defrost sensor temperature. The pre-processing algorithm calculates the average of the first thirty samples when the compressor is turned on:

$$\overline{Gap} = \frac{\sum_{i=1}^n Gap_i}{n} \quad (2)$$

When the compressor is turned off, the defrost sensor is evaluated. Two static functions (see Figure 5) are used to evaluate the defrost sensor. The predicted defrost sensor temperature \hat{T}_{ds} is related to the compressor run time and compared to the measured defrost sensor temperature. The \overline{Gap} is discarded when the predicted defrost temperature is out of a established threshold.

$$\hat{T}_{ds} = 0.172x^2 - 3.80x - 9.70 \quad \text{to } x \in [3, 11] \quad (3)$$

$$\hat{T}_{ds} = 0.0021x^2 - 0.25x - 28.4 \quad \text{to } x \in]11, 100] \quad (4)$$

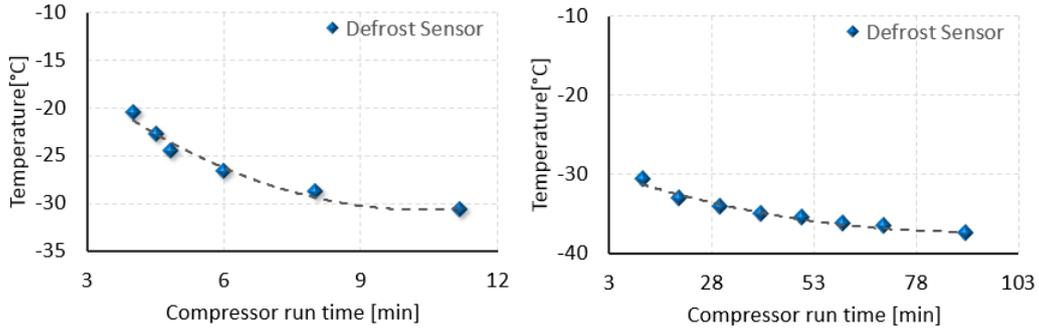


Figure 7. Static functions for defrost sensor evaluation

The average Gap (\overline{Gap}) is stored in a five-position array if no door openings has occurred in the middle of the period when the compressor is on. This array plays the role of a filter, reducing the influence of one sample in the detection process. The average and standard deviation of the array elements are calculated, Montgomery and Runger (2010):

$$\overline{Array} = \frac{\sum_{i=1}^n Array_i}{n} \quad (5)$$

$$\sigma = \frac{\sqrt{\sum_{i=1}^n (array_i - \overline{array})^2}}{n - 1} \quad (6)$$

Pseudocode 1 shows the pre-processing algorithm implemented in this work.

Algorithm 1 Pre-processing algorithm

```

1: procedure PRE-PROCESSING (time_on,  $T_{df}$ ,  $T_{ff}$ , door_status, compressor_status)
2:    $\alpha \leftarrow compressor\_status(k) - compressor\_status(k - 1)$ 
3:   if status_compressor = on then
4:      $i \leftarrow i + 1$ 
5:      $rtr \leftarrow (i * 10) / 60$  ▷ calculates the compressor run time
6:     if  $i < 30$  then
7:        $gap \leftarrow T_{ff} - T_{df}$ 
8:        $sum \leftarrow sum + gap$ 
9:        $avg \leftarrow sum / i$ 
10:    else if status_door = on then
11:       $flag \leftarrow 1$ 
12:    else if compressor_status = off and  $flag = 0$  and  $\alpha = 5$  then
13:      procedure DEFROST SENSOR EVALUATION(time_on) ▷ Procedure for evaluating the defrost sensor
14:      return df_status
15:      procedure INSERT INTO ARRAY(avg) ▷ Procedure for inserting the  $\overline{Gap}$  in the array and calculates the
16:      return array_avg, sd average and standard deviation of the elements
17:       $sum \leftarrow 0$ 
18:       $i \leftarrow 0$ 
19:       $flag \leftarrow 0$ 
20:       $avg \leftarrow 0$ 
21:    else if compressor_status = off and  $flag = 1$  and  $\alpha = 5$  then
22:       $sum \leftarrow 0$ 
23:       $i \leftarrow 0$ 
24:       $flag \leftarrow 0$ 
25:       $avg \leftarrow 0$ 
26:    return array_avg, sd, rtr, time_on, time_off ▷ Return the fault status

```

3.2 Inference

As essential part of every fault detection method, the inference algorithm is responsible for deciding if some specific behavior of the refrigerator is classified as a fault, Gertler (1998). The inference mechanism adopted in this work is based on expert systems with a set of rules observed experimentally suggesting the occurrence of faults.

The inference algorithm compares the data array average calculated in the pre-processing algorithm with a standard value obtained in a correct functioning condition (without presence of fault). Table 1 shows the reference values adopted in this work.

Table 1. Algorithm reference values.

Data array average [°C]	Threshold [°C]	Standard deviation
13.7	4.0	0.5

The inference algorithm is based on set of rules experimentally observed. The simplest rule present in all fault detection systems is the limit checking, being responsible for detecting high amplitude faults. Equation 7 represents this first rule.

$$-40^{\circ}C \leq T_{ff} \leq 70^{\circ}C \quad (7)$$

The fault detection algorithm uses the on/off cycle to load the array with \overline{gap} values. Conditions where the compressor do not turn off are evaluated from the filtered fresh food temperature variation, according to Eq. 8 and Eq. 9.

$$\Delta T = T_{ff}(k) - T_{ff}(k-1) \quad (8)$$

$$\Delta T_{filtered}(k) = \frac{1}{M} \sum_{i=0}^{M-1} \Delta T(k-i) \quad (9)$$

Additional rules as large time of turned off compressor and large period of time with compressor turned on are incorporated to the inference system.

Algorithm 2 Inference algorithm

```

1: procedure INFERENCE(time_on, time_off, array_avg, flag)
2:   if |(array_avg - 13, 7)| > 4.0 and sd < 0.5 then ▷ 13.7 is the array average standard and 4.0 is the threshold.
3:     fault ← 1
4:   else if time_off > 40 min then
5:     fault ← 1
6:   else if Tff > 70 or Tff < -40 then
7:     fault ← 1
8:   else if comp_rt > 80 min and flag = 0 and ΔTfiltered then
9:     fault ← 1
10:  else
11:    fault ← 0
12:  return fault

```

▷ Return the fault status

4. EXPERIMENTAL TESTS

In order to evaluate the efficiency and reliability of the algorithm, a set of tests in different ambient conditions (16°C, 25°C and 32°C) were performed. The tests consist in generating offset faults in both fresh food and defrost sensors as indicated in Tab. 2. The proposed algorithm uses both fresh food and defrost sensors in the detection process. The algorithm in turn, should detect only faults generated in the fresh food sensor since only these faults cause performance reduction in the refrigerator.

It was defined faults with sufficient amplitude to produce significant variations in the temperature compartments. The defrost sensor offsets were chosen to produce changes in the detection process and verify the sensitivity of the algorithm.

Correct and incorrect detections were adopted as performance criteria for evaluating the proposed algorithm. Incorrect detections in turn, were divided in false negatives and false positives, being the last one the worst result if it is considered that in this case an inexistent fault is detected. The detection speed is defined in this research as the elapsed time between the fault insertion and its detection by the algorithm was also defined as a metric in this work.

Table 2. Offset faults adopted in the experimental tests

Test	Defrost sensor [°C]	Fresh food sensor [°C]	Expected result
1	+3.0	0.0	No Fault
2	-3.0	0.0	No Fault
3	+6.0	0.0	No Fault
4	-3.0	0.0	No Fault
5	0.0	+5.0	Fault
6	0.0	+10.0	Fault
7	0.0	-5.0	Fault
8	0.0	-10.0	Fault

5. RESULTS

Figure 8 shows a detection process when a -5°C offset fault is introduced in the fresh food sensor. Note that the detection time is approximately one hour in this specific test.

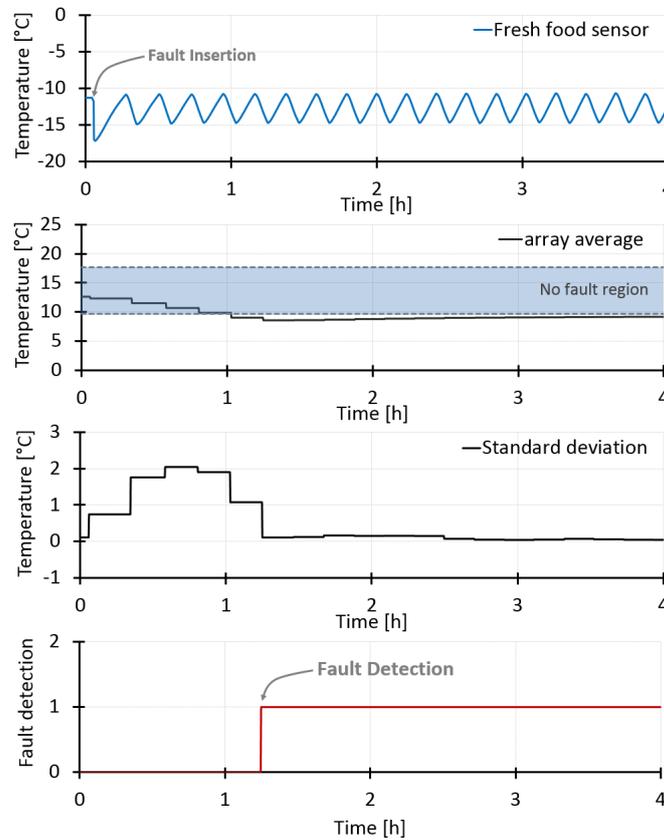


Figure 8. Fault detection test: Ambient temperature 25°C with offset fault of -5°C

When an offset fault is introduced in the system, it can be observed a gradual reduction on the array average gap due to the reduction in the defrost sensor temperature caused by changes in the operating point of the refrigerator. This type of fault causes significant variations in the compressor run time leading the evaporating temperature to operate in atypical values affecting the temperature difference between the sensors.

Figure 9 shows a performed test where the compressor do not turn off due to the high offset amplitude. In this case, are evaluated the filtered temperature variation and how much time the compressor is kept on. In situations where these conditions are met and no door opening events has occurred a failure is identified.

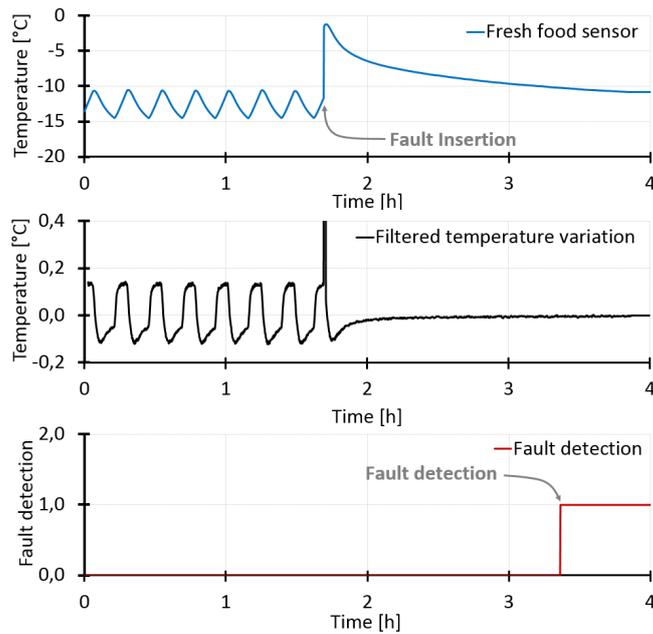


Figure 9. Fault detection test: Ambient temperature 25°C with offset fault of 5°C

In experimental tests where offset faults were not detected, Fig. 10, it can be observed that the measured defrost sensor is out of the predicted temperature from a threshold defined for a good condition of the defrost sensor. In this situation, the \overline{gap} is not loaded into array and the fault is not detected. Note that the array average is kept constant and within the no fault region. Even though the refrigerator operates under failure conditions, the algorithm is not able to detect this fault due to the uncertainty of the good functioning range of the defrost sensor.

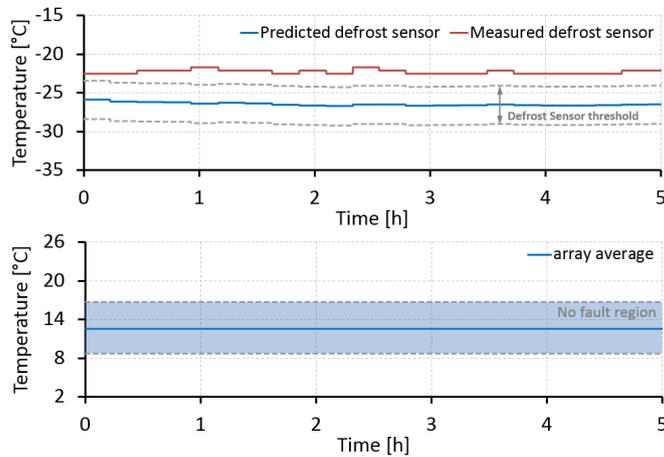


Figure 10. Fault detection test: Ambient temperature 16°C with offset fault of -5°C

Table 3 details the experimental tests in each ambient temperature condition in terms of performance criteria previously defined in this research.

Table 3. Algorithm results.

Performance Criteria	16 °C	25 °C	32 °C
False positives	1	0	2
False negatives	3	0	1
Correct detections	4	8	5

Figure 11 shows the detection fault results summarized in terms of performance criteria. The detection speed was separated in negative and positive offsets and calculated the average detection time of each group of fault.

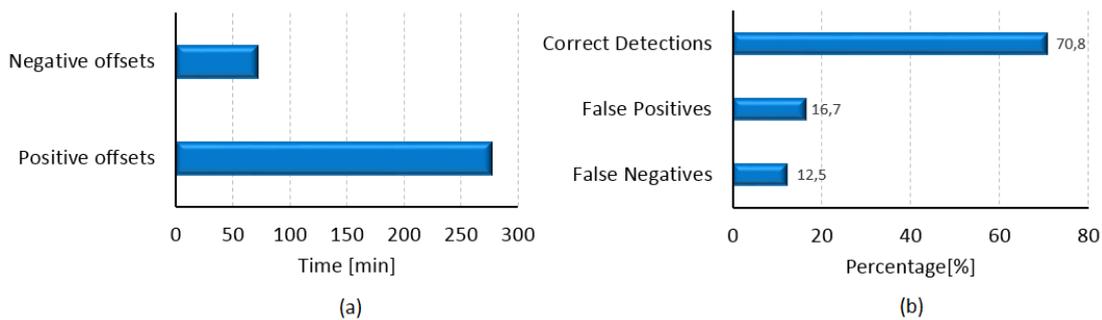


Figure 11. Experimental test results

6. CONCLUSIONS

In this paper, a new fault detection algorithm was proposed for household refrigerators. Correct detections were obtained in 70.8% of experimental tests with detection time less than 3 hours in most cases. On the other hand, in some tests (12.5%) the presence of offset faults were not identified and false positives were inferred by the fault detection algorithm in 16.7% of the experimental tests. The proposed method for evaluating the defrost sensor generated these incorrect detections due to changes in the ambient temperature that affect the curve relating run time and defrost sensor temperature. The experimental tests performed in 25°C (condition under which the defrost curve was obtained) generated 100% of correct detections. Although the tests performed in more extreme ambient temperatures (16°C and 32°C) presented some incorrect detections, they are due to the difficulty for evaluating good functioning conditions of the defrost sensor. In spite of these classification failures, the number of false positives was small if compared to correct detections reached by the proposed algorithm that is of easy implementation, low computational cost and uses a limited number of sensors in its detection process.

7. ACKNOWLEDGEMENTS

This study was carried out at the POLO Labs (National Institute of Science and Technology in Refrigeration and Thermophysics). The authors are grateful to Whirlpool S.A. and EMBRAPPII for the financial and technical support.

8. REFERENCES

- Gertler, J.J., 1998. *Fault detection and diagnosis in engineering systems*. Pergamon.
- Hu, Y., Chen, H., Xie, J., Yang, X. and Zhou, C., 2012. "Chiller sensor fault detection using a self-adaptive principal component analysis method". *Energy and buildings*, Vol. 54, pp. 252–258.
- Isermann, R., 2006. *Fault-diagnosis systems: an introduction from fault detection to fault tolerance*. Springer Science & Business Media.
- Montgomery, D.C. and Runger, G.C., 2010. *Applied statistics and probability for engineers*. John Wiley & Sons.
- Seo, J.A., Lim, T.H., Shin, Y., Lee, S.H. and Kim, S., 2016. "Case study of fault detection and diagnosis of a household air conditioner with a dynamic refrigeration cycle simulator". *Applied Thermal Engineering*, Vol. 94, pp. 198–208.
- Zhao, Y., Wang, S. and Xiao, F., 2013. "Pattern recognition-based chillers fault detection method using support vector data description (svdd)". *Applied Energy*, Vol. 112, pp. 1041–1048.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.