FUEL DEFECT ROOT CAUSE INVESTIGATION AT WOLSONG-1

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ABSTRACT

Wolsong Unit 1 had experienced a number of fuel failures from September 1995 until August 1996. There was a rapid increase in the primary heat transport system (PHTS) activity during that period. I-131 and Xe-133 levels of up to 290 and 80,000 μCi/kg, respectively, were recorded. The investigation concluded that the root cause was high hydrogen content within the fuel elements resulting from insufficient baking of the CANLUB graphite coatings. After the manufacturing process and hydrogen analyses procedures were improved, the total amount of hydrogen within a fuel element now remains below 0.6 mg. Fuel manufactured with the improved process is performing well and the coolant activity levels have slowly returned to normal as the defects were discharged from the core.

1. INTRODUCTION

The Wolsong Unit 1 NGS, located in Korea, is a CANDU 6 reactor designed by Atomic Energy of Canada Limited (AECL). It is owned and operated by Korea Electric Power Corporation (KEPCO). Since it was declared in service in 1983, the unit has performed exceptionally well with a lifetime capacity factor of 85%. Since 1987, Wolsong Unit 1 has been fueled with fuel bundles manufactured by a domestic vendor, Korea Atomic Energy Research Institute (KAERI). Until the end of 1994, the fuel has performed well with an overall bundle defect rate of about 0.1%. Table 1 shows the defect rate of KAERI fuel classified by production year. The fission product levels in the primary heat transport system have remained low, generally below 100 μCi/kg for both I-131 and Xe-133.

After the annual maintenance outage in September 1995, the fission product activities in the PHTS began to increase slightly, and in December 1995 the activities continued to increase substantially indicating the presence of many defective fuel elements in the core. Figure 1 and 2 show the I-131 and Xe-133 activity concentration trend in the PHTS, respectively, from April 1995 to September 1996. This paper summarizes the investigation and actions taken by KEPCO, KAERI and AECL to reduce the activity level at the station and to determine the root cause of the fuel failures.

2. ACTIONS TAKEN TO REDUCE ACTIVITY LEVELS

In late 1995, KEPCO took the following actions in an attempt to lower the fission product activity levels at the station.

- The coolant purification flow rate was increased from 10 kg/sec to 12 kg/sec initially, and later to 24 kg/sec to lower the radioiodine levels.
- The frequency of calibration and scanning of the Delayed Neutron (DN) system (or the failed fuel location system) was increased from once per month to once per week to improve the search for defective fuel.
- To reduce the rate of fuel failures, refueling operations were switched from fuel bundles from the 1994 batch to ones from the 1995 batch only. At the time, the defect rate of the 1994 production bundles was observed to be higher than normal. As a follow-up, two 1994 bundles stored in the new fuel room were sent to KAERI for destructive examination to identify the root cause of failure.

In spite of these efforts, the fission product levels in the coolant continued to increase and the failure cause remained unknown. Defective fuel bundles were visually inspected in the spent fuel bay. Table 2 summarizes the inspection results of the 1994 and 1995 batch fuels. The visually confirmed fuel defects had visible holes or spots(light colored patches) along the fuel element cladding. Although not conclusive, these spots were considered to be regions of secondary deuteriding or primary hydriding damage. In addition to the visually confirmed fuel defects in Table 2, there were indications of more defects based on the DN data from the failed fuel location system and on the number of incidents involving high levels of airborne activity released during the transfer of discharged bundles to the bay.

The I-131 activity concentration peaked to 290 μCi/kg in February 1996. Again, it was decided to suspend refueling of the 1995 batch and to refuel with a Canadian built bundles only. Two 1995 bundles stored in the new fuel room were also sent to KAERI for destructive examination. Fuel bundles from a Canadian supplier were loaded into Wolsong Unit 1 core from April 1996. Due to the presence of fuel failures in the core, "iodine spikes" were observed during reactor trips.

3. ASSESSMENT OF FUEL FAILURES

In February 1996, a more detailed assessment of failed fuel situation was performed jointly by KEPCO staff and a specialist from AECL. After reviewing the station data that included visual inspection results, DN system data and power histories of the known failures, the following observations and recommendations were recorded:

- Since the fuel element is designed and tested to operate above 60 kW/m, the bundle power histories of the known failures were not considered to be excessive, indicating that the cause was not likely related to operations.
- The known failures at Wolsong Unit 1 generally operated about 700 kW which correspond to an outer element linear power of at least 45 kW/m indicating that the failure mechanism has a power dependent threshold. The onset of failure was not associated with a power ramp.
- Almost 80% of all channels having fuel failures or suspected to have fuel failures belonged to the region of the core called "high power annulus"(See Figure 3). This is the region where the channel powers are the highest.
- With the exception of a small number of channels, all fuel failures seemed to have occurred in one of the center four bundles in the channel. As a result, it was recommended that four bundle shifts be avoided and all refueling operation for suspect channels be performed with eight bundle shifts to ensure that the center four bundle were discharged.
- Although very few of the 1995 bundles had been discharged by early 1996, the fuel defect rate for this batch appeared to be higher than the 1994 batch that was previously quarantined. The observations that led to these findings are listed below:
  - ♦ Multiple fuel element failures were observed on one of the 1995 discharged bundles while all previously inspected bundles from the 1994 batch had only single element failures.
  - ♦ The iodine spikes observed during the refueling of the suspect channel containing 1995 bundles was significantly higher than those observed during the refuelings of the suspect channels containing 1994 bundles, and
  - ♦ Many of the suspect channels in the core contained 1995 batch fuel in the center four positions where the defects were occurring.
- Due to the high levels of Xe-133 activity in the coolant and the difficulty experienced in locating the fuel failures in the core with the DN system, it was concluded that most of the fuel failures in the core were pinhole type failures operating at high linear powers. The failures in the core were considered to be hydrided and without any significant cracking. To avoid additional cracking of the hydrided regions of the failures, it was recommended that the reactor power ramp down rate be limited to less than 1%/hr.

The characteristics of the Wolsong Unit 1 fuel failures were very similar to those observed for fuel failures experienced at the Point Lepreau NGS in 1992 (Ref. 1). At the time, the failure cause at Lepreau was attributed to excess hydrogen gas within the fuel element due to underbaking of the CANLUB graphite coatings.

4. ROOT CAUSE EXAMINATION

In order to identify the root cause of failure, a review of fuel manufacturing processes was performed jointly by KAERI and AECL. This review included a detailed review of manufacturing system and processes with emphasis on possible failure scenarios, and Reverse Engineering by destructive examination of fuel bundles from inventory. Current fuel inventories were assessed and manufacturing process was reviewed to:

- evaluate the quality of the fuel waiting for shipment by Reverse Engineering
- evaluate the quality of the delivered fuel by Reverse Engineering.
- identify any contributing factors in manufacturing that could cause failures in Wolsong Unit 1 by looking for deviations from normal in the processes and other manufacturing operational factors that are known to have contributed to the development of fuel failures in the past, in other CANDU reactors.

Manufacturing Review

The manufacturing review consisted of an inspection of the manufacturing facilities, a review of the confirmed failed bundles to identify higher risk batches or common characteristics, and a review of the documentation and records. The document review included a comparison of manufacturing drawings, product specifications and purchasing specifications to design requirements and how the requirements of the Inspection and Test Plan were met through inspection and manufacturing instructions. Manufacturing records were examined, including process qualifications, process record sheets, inspection records, chemical and physical test data, process control charts, and non-conforming material reports. The primary focus of the manufacturing review was to identify any change in the system or processes that could account for possible defect scenarios, such as contamination, sources of excessive hydrogen or possible incomplete end cap welds. The manufacturing review was able to reduce some possible causes to improbable failure scenarios.

- The confirmed failed bundles are not specific to a high humidity season.
- Incoming material inspection reports show that all purchased materials have met specifications.
- In-process material storage has been consistent and delay times are not a factor.
- Element internal dimensions have not changed. Axial gaps and diametral clearances have remained consistent since the production prior to the failures.
- End cap welding has been consistent with no evidence of deterioration in the process. The fuel failures were equally distributed on product from the two end cap welders.

Process and inspection records showed only two areas where changes in the product have occurred with relevance to the time period of fuel failures in Wolsong Unit 1. In early 1993, a change in the UO_2 powder source resulted in higher sintered pellet densities and higher bundle Uranium masses. Due to the powder changes from AUC to ADU, the bundle mass increased from about 18.8 kgU (10.56 tonne/m^3) to about 19.15 kgU (tonne/m^3).

Pellet dimensions, stack lengths and tubing inside diameters have not changed. However, considering a Canadian CANDU 6 has operated with fuel averaging 19.3 kgU per bundle for the past 4 years with no failures, these higher bundle masses are not a contributor to the failures.

The second, more significant change noted in the review was an increase in the CANLUB coating thickness coinciding with the fuel failures. The decision to increase the coating thickness was done as a reaction to knowledge that there was a consideration by AECL to increase the minimum coating thickness to 6 μm. Coating thickness was achieved through increased graphite slurry viscosities. The change was accomplished within the allowable process parameter range. The overall average thickness has increased from 6.4 μm in 1993, to 6.9 μm in 1994, and to 7.8 μm in 1995. More significantly, the maximum thickness values have increased since 1993 in the lower sections of the coated sheaths, while the coating thickness on the top sections has not changed. In the flood coating process, the draining of the graphite slurry with the tubes held vertically results in a thickness differential in the CANLUB layer between the top and bottom ends of the tube. The average maximum values in 1993 ranged from 8 to 9 μm, in 1994 from 9 to 11 μm, and in 1995 from 10 to 14 μm. This data has been taken from the QC records listing coating thicknesses per batch. About 32 sheaths are sampled for every 1000 sheaths baked and three measurements are taken on each; top, middle and lower section CANLUB coatings are measured.

In order to quantitatively evaluate the correlation between coating thickness and hydrogen content, hydrogen contents in several test samples having various coating layer thicknesses were analyzed. As a result of the analyses, it was shown that hydrogen content increased from 1.3 μg/g in a 3 μm thick layer to 10.0 μg/g in a 12 μm thick layer. The analyses results are shown in Table 3. The general increase in hydrogen gas content with coating thickness is an indication of underbaking. Hydrogen gas content for fully baked coatings should not have a strong dependence on coating thickness. Another significant finding from the review of manufacturing system was that non-uniform temperature distribution exists in the baking oven. The time-temperature cycle of the facility's baking oven is controlled by thermocouple readings from the back center of the oven. A characteristic of this baking oven is that the baking times and temperature may vary in different regions inside the oven. According to the manufacturing instructions, temperature in the baking oven should be greater than 320℃ for more than two hours. However, time-temperature profile measurements have shown that complete baking conditions are not being met close to the bottom of the oven, particularly in the region close to the door. Figure 4 shows the results from 9 separate measurements at various locations in the oven.

Moreover, it was revealed that the sheaths are preferentially loaded into the baking oven, that is, the bottoms of the sheaths are always oriented to the front of the oven, at least since mid 1994. This presents a worst case scenario where the thickest coating receives the lowest temperature and shortest times in the baking cycle for sheaths located in the bottom of oven. Relative measurements have shown that hydrogen content is about three times higher for sheaths baked in oven bottom locations compared to sheaths baked in other areas in the oven chamber (See Table 4). This method of loading was done by operator preference. Previously, the loading had been random.

Reverse Engineering

Specific bundles in inventory were selected based on date of manufacture, baking cycle data, and delay times between CANLUB baking and end cap welding. Fourteen bundles were selected, including eight manufactured in the worst baking condition in terms of temperature and time, two sent back from Wolsong site, and four chosen by random sampling from each group. These fuel bundles were evaluated for conformance to requirements as well as to identify any shift in process or product variables. The destructive examinations were performed for a total of 76 fuel elements selected from 14 bundles.

The examined items are weld strength at end-plate, dimensional, metallographic and chemical analysis for fuel element, sheath with brazed appendages, graphite coating, and fuel pellets. In particular, a major concern was the hydrogen gas content in the fuel elements. All of the inspected items were within the design criteria. However, although all measurements appeared to satisfy the design criteria of 1 mg per element, the total hydrogen in a fuel element showed quite a wide variation from 0.07 to 0.758 mg. Based on the manufacturing review results, this variation was believed to be caused by the underbaking of the CANLUB and the increase in coating thickness. It was also verified that, due to the difference in baking temperature and the CANLUB coating, the hydrogen content can vary along the element cladding. For fully baked coatings no variation in hydrogen gas content would be expected.

Estimation of Maximum Hydrogen Content in Fuel Element

Since the fuel elements having higher hydrogen content might not be included in the test samples for the destructive examination, it was decided to estimate the maximum hydrogen gas content in a fuel element. Test samples for the estimation were made as follows:

- As the CANLUB coating thickness increases, the hydrogen content in the coating also increases. Therefore, in order to achieve a thick graphite coating, a test sheath was made using a graphite solution of 87 cps which is close to the maximum viscosity limit of 90 cps.
- The test sheath having the thick graphite coating was loaded into the baking oven at about 280℃ in order to simulate the worst underbaking condition.

A total of 4 test sheaths were made and analyses of hydrogen content were then performed for three specimens from each test sheath. The residual hydrogen content maximized when a sheath having the thickest graphite coating is baked under the worst baking condition. Therefore, using the conservative values of the hydrogen content in fuel pellet and helium gas, the hypothetical maximum hydrogen content in a fuel element was calculated as follows:

$$H_{2,max} = G_{sh} \times (G_{ptmax}/G_{st}) \times M_{sh} + G_{pe,max} + G_{He,max}$$

where, $H_{2,max}$ = estimated maximum hydrogen content in a fuel element

G_{sh} = (average analyzed hydrogen content in specimens, ppm)

- 0.41 ppm (average hydrogen content in Zircaloy-4)

G_{ptmax} = max. graphite coating thickness in manufacturing record, 14.87 μm

G_{st} = measured graphite coating thickness of the test sheath

M_{sh} = weight of sheath, 51.3 g

$G_{pe,max}$ = maximum hydrogen content in fuel pellet, 105 μg

$G_{He,max}$ = maximum hydrogen content in helium gas, 20 μg

This equation is based on a linear relationship between hydrogen content and the CANLUB coating thickness. The maximum hydrogen content in a fuel element was calculated for the worst case in the test sheaths. In this case, G_{sh} = 9.06 ppm and G_{st} = 8.0μm, therefore, it gives

$H_{2,max}$ = 9.06 x (14.87/8.0) x 51.3 + 105 + 20 = 988.9 (μg),

which is very close to the specification limit of 1.0 mg.

Root Cause Conclusion

- The root cause of the fuel failures in Wolsong Unit 1 is most likely hydriding due to localized elevated hydrogen gas content in the lower sections of some sheaths.
- This localized elevated hydrogen content was caused by the combination of an increase in the CANLUB graphite coating thickness and localized underbaking in the lower section of some fuel sheaths.
- The analyzed hydrogen content in the selected fuel elements for analyses satisfied the design specification, however, the hydrogen levels in the CANLUB graphite coating were shown to vary by about a factor of 3 depending on location in the baking oven. This was believed to be caused by an increase in the CANLUB graphite coating thickness and localized underbaking in the lower section of fuel sheaths.
- Based on the hydrogen analyses of the test samples made in the simulated worst conditions and on conservative values for hydrogen gas content in the fuel pellets and helium filling gas, the maximum hydrogen gas content in a fuel element having a 14.87 μm CANLUB coating was calculated to be 0.989 mg. However, since the sample size was very limited, the hydrogen content in some fuel elements might have exceeded the design limit of 1.0 mg.

5. CORRECTIVE ACTIONS

Improvement of Manufacturing Process

Based on the results of the manufacturing review and the reverse engineering, the manufacturing process was improved as follows:

- Changing graphite solution temperature from 23℃ to 20℃.

  Variation of the CANLUB graphite coating thickness is very sensitive to the graphite solution temperature. As the solution temperature decreases, the isopropyl alcohol contained in the solution is vaporized more slowly, thus, the solution is drained enough before the graphite solution coagulates. This can contribute to a more uniform distribution of the CANLUB coating.

- Reducing temperature difference in baking chamber

  In order to reduce the temperature difference in baking chamber, the thickness of thermal barrier in the entrance of the baking chamber was increased. Also, the operation program of the baking oven was modified and local heating rates were adjusted.

- Routine hydrogen analysis

  In the original process qualification tests, the routine hydrogen analysis in the manufacturing process was determined to be unnecessary as long as baking time and baking temperatures were met. Manufacturing procedures were revised as follows:

  - ♦ Hydrogen analysis for CANLUB graphite coatings should be performed for one cladding out of one batch of baking oven. Hydrogen gas content in graphite coating is aimed to be less than 0.5 mg.
  - ♦ Hydrogen analysis for fuel elements should be performed for one element per month. The total hydrogen gas contents in a fuel element should be less than a conservative new limit of 0.6 mg to ensure that the product remains well within the design limit of 1.0 mg.

Requalification of Process

Hydrogen analyses were performed for the test fuel elements manufactured under the improved process. As a result of the analyses, it was shown that the hydrogen gas content in CANLUB graphite coating were remarkably reduced to 40~60 μg. Also, it was observed that there was no particular correlation between coating thickness and hydrogen gas content, and the hydrogen gas content in the cladding was uniformly distributed. The total hydrogen gas content in a fuel element was found to be decreased to 50~70 μg, therefore, it was concluded that the hydriding failures will be prevented by the improved manufacturing process. Fuel bundles manufactured under the improved process are being loaded into Wolsong Unit 1 core since June 1996. Due to the continuous discharge of the defective fuel bundles from the core and the loading of fuel bundles manufactured under the improved procedure, the fission product activities in the PHTS steadily decreased to the same level as it was before the failure occurred.

The fuel performance feedback from Wolsong Unit 1 confirms that the root cause of failure has been eliminated.

6. REFERENCES

1. A. M. Manzer, R. Sejnoha, R.G. Steed, T. Whynot, N. A. Graham, A. P. Barr, and T. J. Carter, "Fuel Defect Investigation at Point Lepreau", Third International Conference on CANDU Fuel, Chalk River, 1992 October.

TABLE 1. FAILURE RATES OF KAERI BUNDLES

Production Year	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	#1996	Total
No. of Loaded Bundles	363	2674	5137	5222	1428	4949	5177	529	5070	2571	3302	36422
No. of Failed Bundles	0	0	8	6	5	2	4	2	12	93	0	132
Failure Rate (%)	0	0	0.16	0.11	0.35	0.04	0.08	0.04	0.2	3.6	0	0.36

Fuels manufactured under the improved process

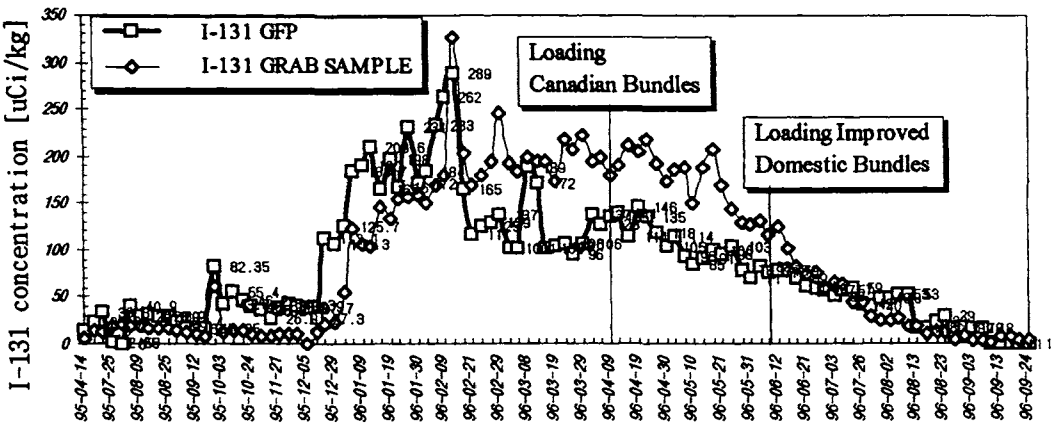

FIGURE 1. I-131 ACTIVITY CONCENTRATION TREND IN THE PHTS

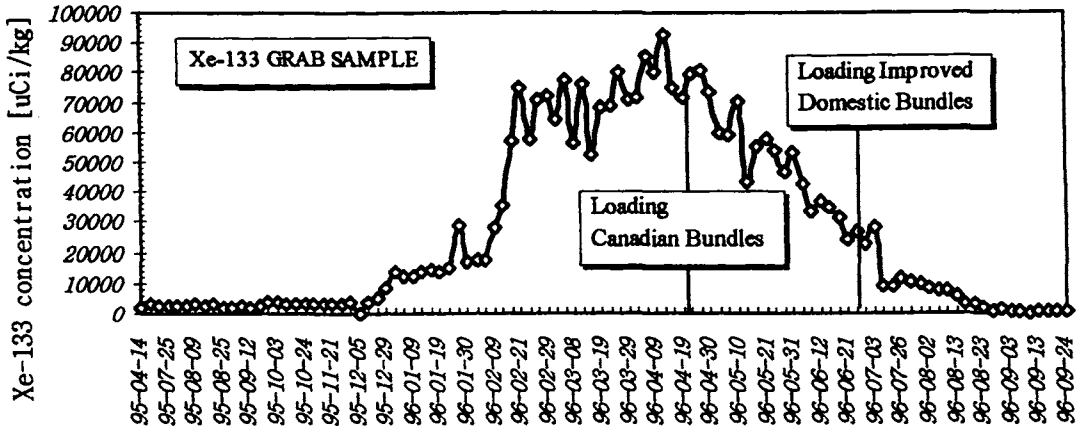

FIGURE 2. Xe-133 ACTIVITY CONCENTRATION TREND IN THE PHTS

TABLE 2. VISUAL INSPECTION RESULTS

Production Year	Number of Inspected Bundles	Number of Confirmed Failed Bundles	Visual Signs		
			Holes	Discolored	Spots
1994	71	12	6	3	3
1995	188	93	61	22	10
Total	259	105	67	25	13

TABLE 3. HYDROGEN ANALYSES FOR DIFFERENT CANLUB THICKNESSES

Thickness (μm)	3.2	4.8	5.3	5.6	6.9	8.7	10.3	11.1	12.1
Hydrogen Content (ppm)	1.271	1.249	2.406	1.372	1.866	6.540	10.480	7.609	10.090

TABLE 4. RELATIVE HYDROGEN CONTENT IN THE GRAPHITE COATING LAYER AT VARIOUS POSITIONS IN BAKING CHAMBER

Oven Position	Oven Front (ppm)		Oven Back (ppm)		Average (ppm)	Total Hydrogen Content in the Graphite Sheath (52g × Avg., μg)
	Sect. 1	Sect. 2	Sect 1.	Sect 2.		
Bottom 1	7.936	5.331	1.901	1.880	4.262	221.6
Bottom 2	4.842	5.427	2.228	2.181	3.670	190.8
Bottom 3	9.235	6.996	2.191	1.992	5.104	265.4
Bottom 4	5.268	6.619	1.999	2.034	3.980	207.0
Center	2.634	2.569	1.503	1.494	2.050	106.6
Upper	2.023	1.789	1.351	1.272	1.609	83.7
Left Side	2.422	2.077	1.771	1.767	2.010	104.5
Right Side	1.703	1.639	1.107	1.067	1.379	71.7

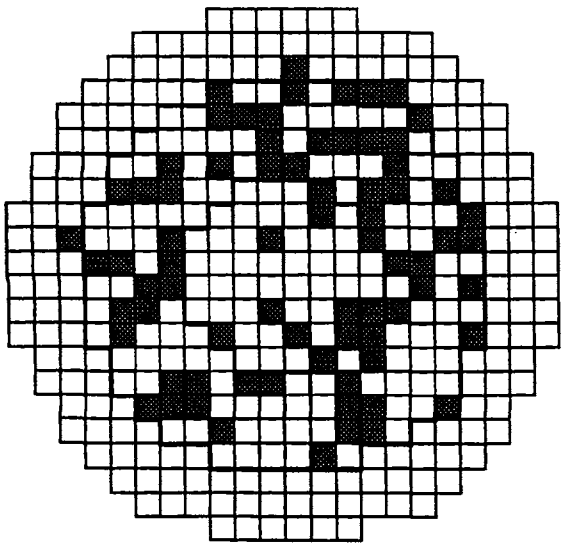

FIGURE 3. CHANNEL LOCATIONS OF DEFECTIVE FUEL DISCHARGED FROM WOLSONG UNIT 1 (1995/96)

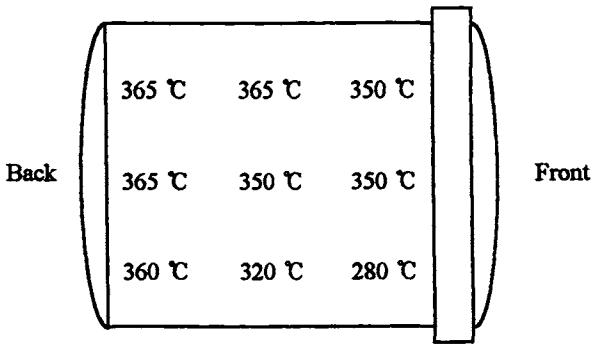

FIGURE 4. TEMPERATURE DISTRIBUTION IN BAKING OVEN