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Development of Acoustic Emission Monitoring System for Fault Detection of Thermal Reduction Reactor

Gee Young Park, Ji Sup Yoon, Byung Suk Park, Dong Hee Hong, and Young Hwan Kim
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yuseung-gu, Daejeon 305-353, Korea
gypark@kaeri.re.kr

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Abstract

The research on the development of the fault monitoring system for the thermal reduction reactor has been performed preliminarily in order to support the successful operation of the thermal reduction reactor. The final task of the development of the fault monitoring system is to assure the integrity of the thermal reduction reactor by the acoustic emission (AE) method. The objectives of this paper are to identify and characterize the fault-induced signals for the discrimination of the various AE signals acquired during the reactor operation. The AE data acquisition and analysis system was constructed and applied to the fault monitoring of the small-scale reduction reactor. Through the series of experiments, the various signals such as background noise, operating signals, and fault-induced signals were measured and their characteristics were identified, which will be used in the signal discrimination for further application to full-scale thermal reduction reactor.

Key Words : acoustic emission, data acquisition system, monitoring integrity, thermal reduction reactor

1. Introduction

The research for the fault monitoring system of the thermal reduction reactor that is a main process in the advanced spent fuel conditioning process has been performed since 2001. In the reduction reactor, the metal reduction takes place by very reactive de-oxidizer (Li) under high temperature above 600℃. The internal vessel of the reduction reactor, therefore, is to be designed to cope with the thermal stresses from high-temperature distribution and any chemical attack on the reactor internal surface.

The objective of this study is the development of the monitoring technique for detecting the internal defects such as cracks, corrosions, etc., which will grow to be a high-risk failure, at the surface of or within the boundary of the internal vessel in the reduction reactor. From this monitoring result, the operator can recognize the status of the internal vessel integrity and might set up the schedule for maintenance or decide whether the process should be halted down or not. In the project of the development of the fault monitoring system, two types of techniques are evolved: One is the development of the monitoring technique by acoustic emission for the thermal reduction reactor integrity and the other is the development of monitoring technique by use of vibration signals for identifying on-line the abnormal state of the agitator driving system which is composed of the magnetic drive and the agitator whose rotating axis are connected to the motor via the flexible cable [1]. In this paper, only the monitoring technique for the integrity of the thermal reduction reactor is described and the monitoring technique for the agitator driving system will be presented later.

As mentioned previously, for monitoring the internal integrity of the thermal reclution reactor, the acoustic emission (AE) method, which is widely used in the non-destructive testing, is employed. AE method is only one of the non-destructive testing methods for fulfilling the detection of some defects distributed globally within the structure during operation. In reality, this method has been applied intensively to the nuclear power plants [2][3][4], pressurized systems [5], and to the cemented waste canisters [6], but little has been done in the field of spent fuel conditioning process in which a high-temperature furnace is involved.

In the study of 2001, the major purposes were the identification of the possibility of detecting some defects within the internal vessel of the reduction reactor because the configuration of the thermal reduction reactor provides the extremely difficult environment in the sensor installation and also the identification of the characteristic features of defects, if it is possible to measure, for further delicate signal analysis. In order to achieve the purposes, a compact and high-speed data acquisition system was configured and a wideband AE sensor was used for the identification of the characteristics of the various signals.

2. Basic Description of Acoustic Emission

Acoustic emissions are stress waves produced by sudden movement in stressed materials [7]. Fig.1 shows the process of stress wave generation and the detection procedure. Sudden movement at the source produces a stress wave, which radiates out into the structure and excites a sensitive piezoelectric transducer. The detection equipment of the acoustic emission signals are composed of a transducer, which was coupled to the material using a so-called couplant like a gel, a pre-amplifier, a band-pass filter which is sometimes replaced by low-pass or high-pass filter depending on the application, and a data acquisition system which is far apart from the sensing position. The excitation of the piezoelectric transducer is converted into the electric voltage change and the resulting voltage signal is amplified in the pre-amplifier for transmitting this signal to the data acquisition system through the long BNC cable unless it is too attenuated to acquire. The pre-amplifier also filters out the amplified signal. The data acquisition system receives the signal and amplifies again, if necessary, and filters out accurately. Then, this signal is digitized and the signal analysis technique is performed on the digitized data.

A major benefit of the acoustic emission inspection is that it allows the whole volume of the structure to be inspected non-destructively during a single operation. It is not necessary to scan the structure looking for local defects and it is only necessary to connect a suitable number of fixed sensors without removal of the whole insulation or decontamination for entry into vessel interiors.

Thus, this technique is the most suitable for application to the monitoring the internal integrity of the reduction reactor covered fully by the high temperature furnace.

3. Descriptions of Experimental Setup

3.1. Brief Description of Thermal Reduction Reactor

Thermal reduction reactor is for the metal reduction process where the chemical reaction is performed under the very high temperature of $650^{\circ}C$. Fig.2 shows the three-dimensional graphic display of the full-scale thermal reduction reactor whose dimension is 2.4(H) × 1.2 (ID) m surrounded by the heater. Fig.3 shows the internal components of the thermal reduction reactor. These components are the internal vessel, the outer protective vessel, the molten salt recovery bucket, two agitators (not shown in Fig.3), a pneumatic-operating valve, and the upper cover. The agitator driving system and the valve operating system are equipped on the upper cover as shown in Fig.2 and Fig.3.

The operating pressure within the thermal reduction reactor is not high and is set to a pressure slightly larger than the atmosphere pressure although the operating temperature is high. Hence, most of defects are generated from the chemical attack on the internal surface rather than the unbalanced thermal stress distribution. The thermal reduction reactor is fully covered by the furnace except for the upper part of the reactor as can be seen in Fig.3 and all of the internal defects/faults are generated below the middle of the internal reactor vessel. This makes the poorest sensing environment in that the space of the sensor installation is confined to the upper part of the thermal reduction reactor.

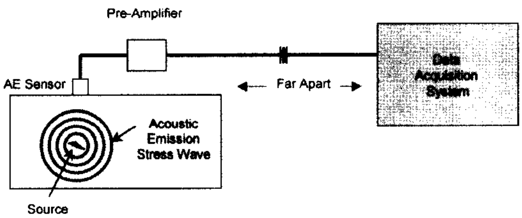


Fig. 1. Basic Principle of Acoustic Emission Method

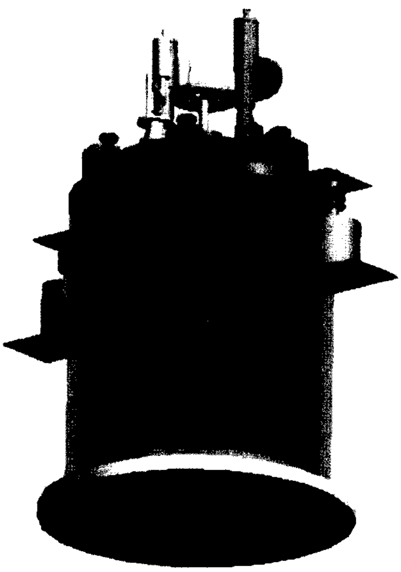


Fig. 2. Thermal Reduction Reactor (3-D Graphic Modeling)

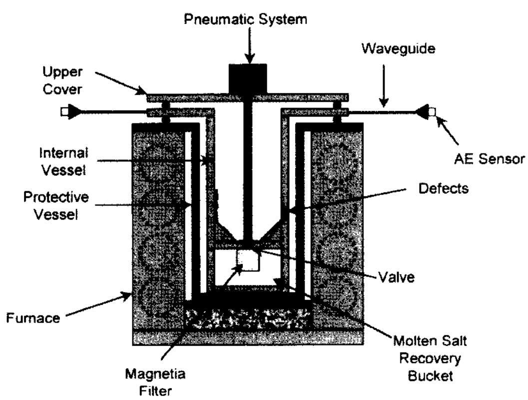


Fig. 3. Configuration of Thermal Reduction Reactor

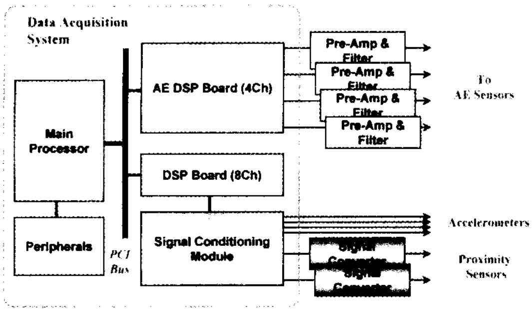


Fig. 4. Configuration of Data Acquisition System

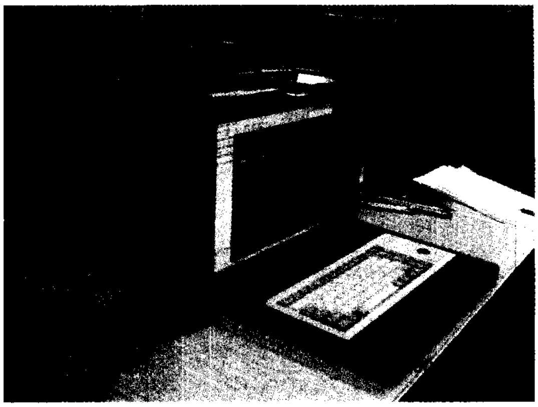


Fig. 5. Configuration of Data Acquisition System

3.2. Configuration of Data Acquisition System

In order to acquire the weak signals induced by defects within the internal vessel, an appropriate data acquisition system is configured. Fig.4 shows the configuration of the data acquisition system. The data acquisition system composes of the three parts: the main processor and peripherals, two digital signal processor (DSP) boards, and the signal-conditioning module. In this configuration, one DSP board and the signal-conditioning module are provided for use in the monitoring of the agitator driving system and so those components are not described here. Another DSP board, i.e., AE DSP board, is configured for AE signal processing by use of the product, PCI/DSP, from the Physical Acoustics Co. AE DSP board has 4 input channels and the maximum 10MHz/Channel. The sampling can be varied to 5, 2.5, 1.2 MHz. It has various low-pass, high-pass, band-pass filters. In the experiment, the wide-band AE sensors are selected for identifying the overall characteristics of fault and other signals. The electronic components and the precise power-supply are installed on the compact and portable case, whose dimension is 410(L) $\times$ 230(W) $\times$ 290(H) mm with being designed to shield against the electronic noise. And, thereby, the data acquisition system provides an efficient way to measure the high frequency ($\geq$100kHz) AE signals. The construction of the data acquisition system is shown in Fig.5. The pre-amplifier shown in the upper right in Fig.4 has the amplification gains of 20, 40, and 60dB and the band-pass filter with the range of 100kHz ~ 1MHz.

3.3. Experimental Setup

For the experiments, the Advanced Spent Fuel Conditioning team in KAERI developed the small-scale reduction reactor for preliminary testing the metal reduction process and the fault monitoring experiment was carried out for this small-scale reduction reactor. Fig.6 shows the small-scale reduction reactor where the dimension of the internal vessel is 300(H) $\times$ 150(ID) mm. The small-scale reduction reactor has also the poorest sensing environment because of full coverage over the reduction reactor by the furnace except for the upper part, so that AE sensors should be installed at the small flange surface of internal vessel as shown by Fig.7, similar to those in the schematic of the full-scale reduction reactor in Fig.3.

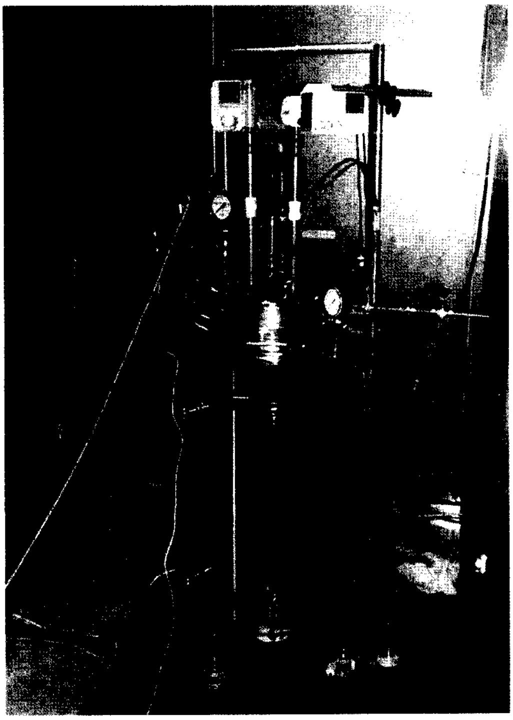


Fig. 6. Small-Scale Reduction Reactor

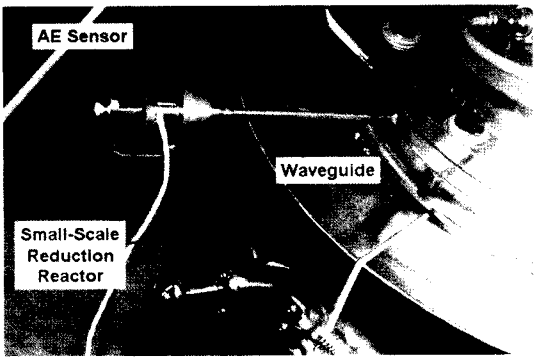


Fig. 7. AE Sensor and Waveguide

Moreover, AE sensors are to be mounted on the so-called waveguide to protect from the effect of high temperature with the expense of the AE signal attenuation. The waveguide was adhered to the flange surface by the spot welding. Most of the reactions and events occurred below the horizontal middle of the internal reactor. In order to acquire the signal from lower portions of the internal reactor, the amplification gain in the pre-amplifier is set to the maximum level of 60dB. In this experiment, single AE sensor was installed because more installing AE sensors and waveguides induce the serious problems in the operator's operation in performing the metal reduction process. The couplant was used to couple between the AE sensor and the sensor holder on the waveguide. The couplant used was mainly for high temperature environment up to 500℃ but, in fact, the temperature on the surface of the sensor holder was below 150℃.

4. Experiments

For the reduction process, before heating up, the air environment is changed into the inert gas environment and the metal and the salt powder are placed into the internal reactor. The furnace starts to heat up and the temperature is controlled to rise to about 650℃ under the continuous flow of the inert gas into and out of the interior of the reduction reactor. At 650℃, the salt powder begins to melt down. Then, it begins that the de-oxidizer is inserted into the internal reactor and at the same time, the agitator driving system starts to rotate the agitator. After the overall process is completed, the valve at the bottom of the internal reactor vessel is opened and the power for the furnace is shut off to cool down the reactor.

4.1. Analysis of Background Noise and Operating Signals

Before the experiment, the AE signals for tuning the sensor are acquired for various points around the internal vessel and the molten salt recovery bucket. Fig.8 shows one of tuning (or calibration) signals by use of the pencil lead break at the middle point of the internal vessel directly below the waveguide. The AE signal has a sharp rising

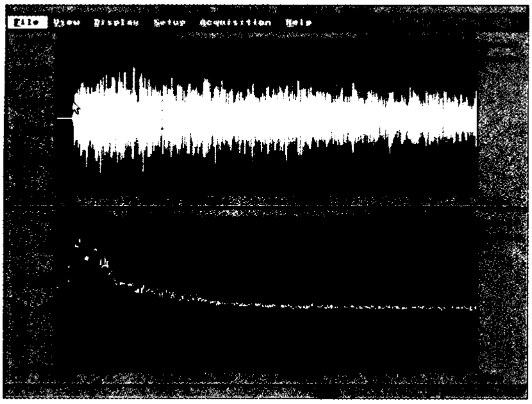
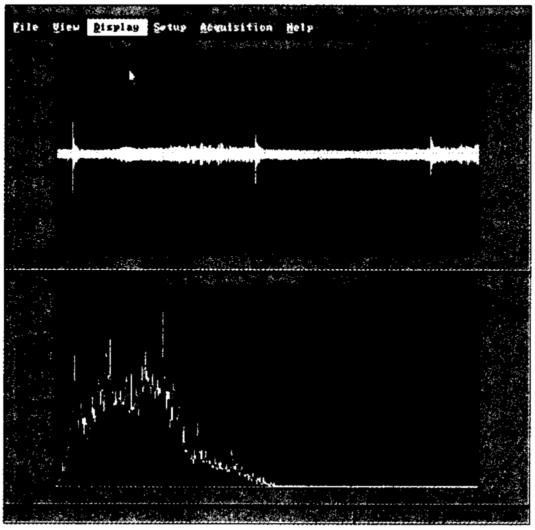


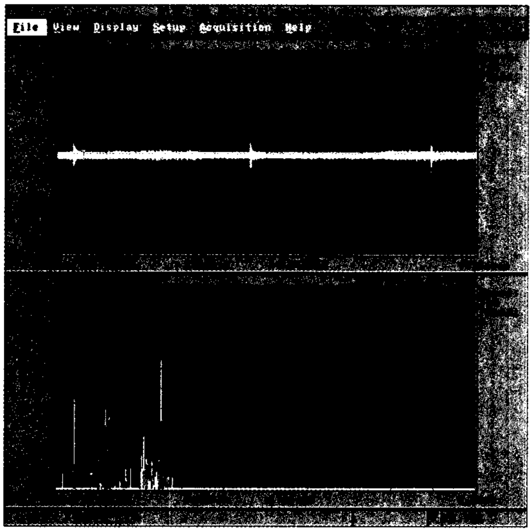
Fig. 8. AE Tuning Signal at Middle Part of Internal Vessel

time and the relatively large magnitude and shows dominant frequency range of 100~200 kHz. The magnitude of the AE signal decreases rapidly as the pencil lead break point approaches the bottom of the internal vessel (more far from the sensing point) but the dominant frequency contents remain unchanged.

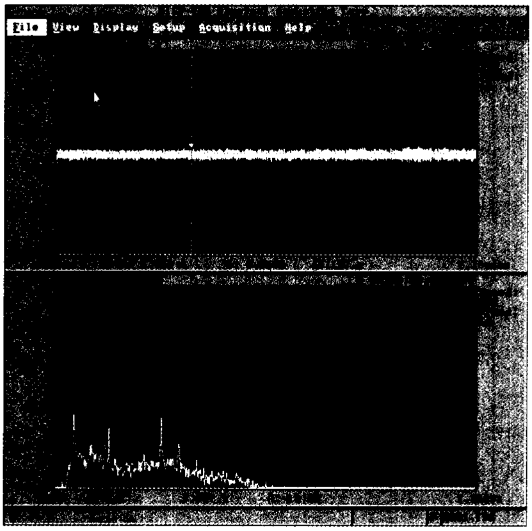
In performing a series of experiments, various signals such as operational signals (inert gas flowing, agitator operation, furnace interference, etc.) and background noise levels for temperature variations were measured and analyzed. For the background noises and furnace interference, Fig.9(a), (b), and (c) show the background noise signals and the furnace interference peaks for various temperatures. As can be seen in these figures, the noise levels are different for three



(a) At Start Up



(b) At 200~300℃



(c) At 400~600℃

Fig. 9. Background Noises for Temperature Changes

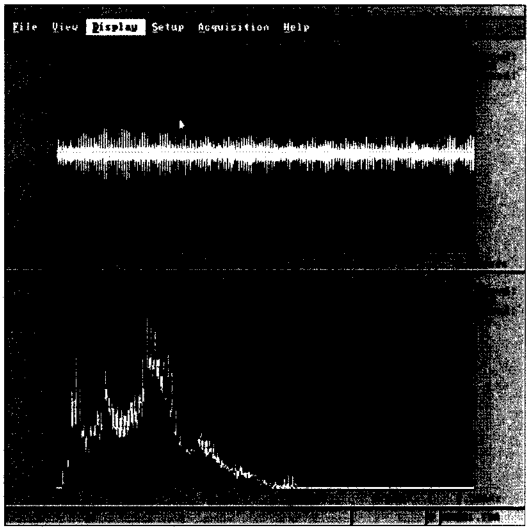


Fig.10 AE Signal by Inert Gas Discharge

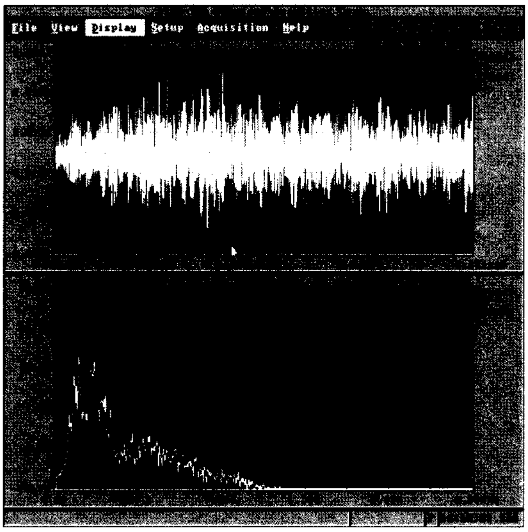


Fig.11 AE Signal by Agitator Driving (at 200 rpm)

temperature ranges: the peaks by furnace interference and the noise level are reduced as the temperature is raised. From this result, the threshold level in the AE DSP board should be set by the floating type rather than set to a fixed point in order to cover the all range of the temperature change. But, in this study, the threshold level is set to a fixed point in order to identify the characteristics of noise signals and this value is modified for the significant variation of the background noise and the operating signals. In Figs.9, the peaks in AE signals are the interference from the heating-up of the furnace coil. This intervention peak is severe at low temperature and as temperature is raised from 200 to 400℃, however, this peak is reduced remarkably, and finally, at the temperature near 600℃, these periodic or cyclic peaks are disappeared as can be seen in Fig.9(c). The frequency contents of the background noise are distributed over 100~1200 kHz.

Fig.10 shows the AE signal for the discharge of inert gas (Ar) at the onset of the experiment. The AE signal caused by inert gas discharge has the shape of continuously rising and down form, not the burst-type and has the dominant frequency range of 500~600 kHz. The AE signal induced by the inert gas flow is reduced enough to be below the threshold level at high temperature above 200℃. Fig.11 shows the AE signal resulted from the rotation mechanism of the agitator drive. This signal sometimes interfered the fault signal acquisition by triggering the threshold level set by 50 dB. The high-frequency AE signal by the agitator drive mechanism is, in this experiment, due to the misalignment of the motor and the rotating axis of the agitator drive. The problem could be circumvented by slightly raising the threshold level and it is expected that in the application of the full-scale reduction reactor, the agitator drive will not make significant AE signals because of a better alignment than in the small-scale reduction reactor.

4.2. Analysis of Defect/Fault Signals

With the small-scale reduction reactor, AE signal acquisition was performed four times. At every

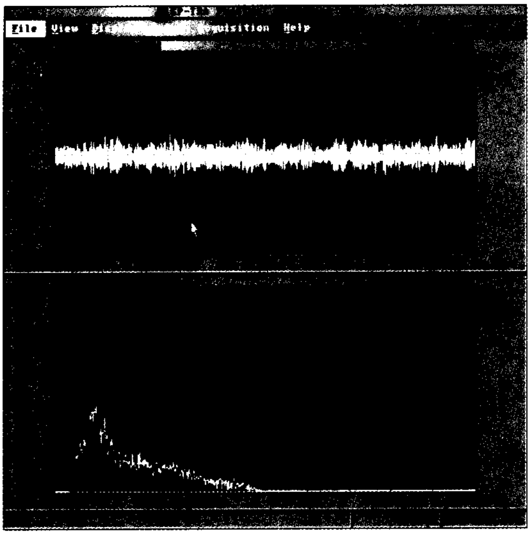


Fig. 12. AE Signal by Molten Salt Leak

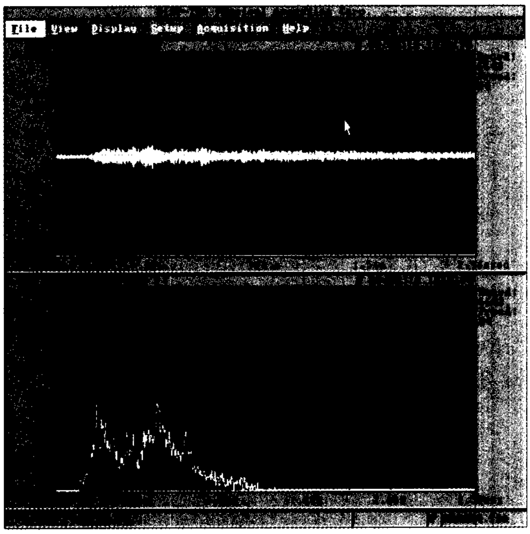


Fig. 13. AE Signal by Local Crack in Corrosion Product Layer

operation, none of noticeable AE signals was detected when heating-up from 20℃ to 650℃ was performed normally and the chemical reactions at 650℃ performed stably except for the operation-related AE signals such as sampling the molten salts by operators: operator' s sampling or working time is usually short (<5 min) and so the data acquisition is paused during that time. When a certain event in the internal reactor takes place, however, the flourishing AE signals were detected for a long time.

The first and second experiments were performed mainly for the sealing test of the valve and hence the reduction process was not performed at these experiments. The sealing test of the first experiment was successful but the leak of the molten salt has been occurred in the second experiment. Fig.12 shows the AE signal from the molten salt leak through a valve. The AE signals of this type were measured for second experiment during short period around the melting temperature of salt powder. The appearance of this signal on the time axis is similar to that of the background noise but the signal level of this signal is slightly higher than that of the background noise and the noticeable difference between these signals can be recognized when comparing both frequency behaviors. The frequency content of the molten salt leak is similar to that of the AE tuning signal in Fig.8. The AE signal induced by the molten salt leak is usually so weak that it is hard to detect this signal for the case of high level of background noise.

In the 3^{rd} and 4^{th} experiments, the main purpose was the identification of the performance of the reduction process. Through 3^{rd} and 4^{th} experiments, no leak at valve was reported to occur, which was validated by use of the sampling the molten salt within the internal vessel during operations. Fig.13 and Fig.14 show the AE signal when the corrosions were produced extensively on the surface of the internal reactor at the 4th experiment. The AE signals in Fig.13 and 14 are occurred simultaneously and the AE signals in Fig.13 had more frequent appearance than those in Fig.14. Both signals are generated enormously immediately after the de-oxidizer is inserted and those intensive generation tendency was elapsed

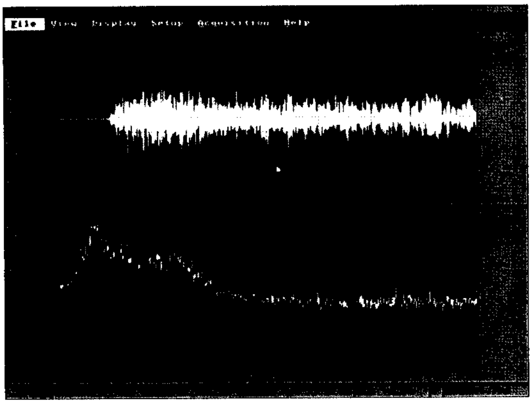


Fig. 14. AE Signal by Surface Pit by Spall of Corrosion Product Layer

for a long time (about 3~4 hours). The surface defects by extensive corrosions were identified after cooling down and opening the cover of the reduction reactor. It is supposed that the AE signals as in Fig.13 are resulted from the cracks in the corrosion product layer on the surface of the internal reactor and the AE signals as in Fig.14 are due to the spalling down of the corrosion product layer that makes many large and deep pits on the surface of the internal vessel [8][9].

5. Conclusions and Future Research

In this paper, the one of two researches on the development of fault monitoring system for the thermal reduction reactor is described. The main purposes of the research are the identification of the possibility of detecting the defects or faults within the reduction reactor by use of the acoustic emission method and the characterization of the defect signals if it is possible to measure. From the experiments on the small-scale reduction reactor, the internal defects could be measured and characteristic features of defect signals were identified. Moreover, the background and operating signals were measured and analyzed. From the information of the background and interferential operating signals, the threshold level in the data acquisition system was set to a value slightly larger than the maximum level of those signals and thereby, only the signals induced by defects could be measured on the metal reduction process. From the process of the AE signal acquisition, the triggering event in AE data acquisition was silent when the heat-up to 650℃ and the chemical reduction process were performed normally. But any defect in the internal vessel during the process induced the enormous AE signals for a long time.

At this time, the hardware settings are being altered from the wideband type to the band-pass type whose bandwidth is constrained to encompass the dominant frequency range of the defect signal, i.e., corrosion. More than 3 AE sensors are going to be installed along the circular small flange surface in the reduction reactor for more reliable detection via real time defect location calculation. The other research is the development of the monitoring technique for the agitator driving system [1] and the advanced signal processing method such as the wavelet decomposition is being implemented into the data acquisition system. The results of the research will be presented later.

In conclusion, this activity will help improve the safe operation in the advanced spent fuel conditioning process or any other processes that involve the high-temperature chemical reactor and the furnace.

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