JAERI-M
90-231

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-DEVELOPMENT OF THE CRUD SEPARATOR SYSTEM (II)-

January 1991

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編集兼発行　日本原子力研究所
印　　刷　日立高速印刷株式会社

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(Received December 7, 1990)

The out-of-pile test results of the advanced crud separator system was previously investigated. It was suggested that the system characteristics (separatin factor) depended on magnetic susceptibility of crud, crud particle diameter and flow rate, and that utilization of the crud size enlarger, a high gradient magnetic system, was effective especially in the lower separation factor region.

After the out-of-pile test, the system was shipped to the HBWR (Norway), and the final in-pile test was carried out under the operating conditions similer to BWR.

As the test results, the separation factor decreased with increasing inlet crud concentration in the lower inlet concentration region, and crud production (or release) rate and crud separation rate seem to reach the state of equilibrium at the inlet iron concentration approximately 6 ppb for this system size. It was also suggested that separation factor became higher when coolant temperature increased.

Keywords : Corrosion Product, Crud Separator, High Temperature, High Pressure, In-pile

JAERI－M 90－231

クラッド分離装置のＨＢＷＲにおける炉内試験
－クラッド分離装置の開発(II)－

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（１９９０年12月７日受理）

著者らは前報において，常温常圧環境下で行なわれたクラッド分離装置の性能試験結果について述べた。その結果として，本装置の特性（分離効率）は少なくともクラッドの磁化率，クラッド径及び流量に依存することが示唆された。また，造粒器の使用は低分離効率時において有効であることも示唆された。

性能試験後，本装置はＨＢＷＲ（ノルウェー）へ船輸送され，最終的な確試試験がＨＢＷＲのＢＷＲ用水ループを用いて行われた。

確証試験の結果として，分離効率はクラッド入口濃度が低い場合，その濃度に比例することが明らかとなった。さらに，入口鉄濃度６ppb でクラッドの生成（放出）速度と分離装置の分離速度が見かけ上平衡状態となることが示唆され，本装置の分離限界が明らかとなった。また，分離効率は原子炉冷却水温度上昇時に高くなることが示唆された。

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1. Introduction

The out-of-pile test results of the advanced crud separator system were investigated in a previous paper[1]. Satisfactory performance was obtained in that test, which was performed under the condition of atmospheric pressure and room temperature.

Advantages of utilizing the crud separator system, when compared to the other filtration systems, are to be able to remove magnetized crud directly under the conditions of high pressure and high temperature and to save the secondary wastes produced by the system itself. Thus, it is necessary to verify the system performance under the such severe conditions for the next step to the out-of-pile test.

The in-pile test of the crud separator system was proposed by the JMTR Project with utilizing an irradiation loop in the HBWR[2]. The test started in April 1989 and terminated in March 1990. This report investigates the in-pile test results of the crud separator system.

2. System characteristics

The crud separator system removes crud by moving alternating magnetic field produced by the magnet assembly surrounded around the separator vessel inside and outside. A schematics of the separator vessel is shown in Fig. 1. The system consists of crud size enlarger, crud separator, demagnetizer and control consoles. The details of the system were presented in previous papers[1-3].

It was found in the previous out-of-pile test that separation factor depended on crud particle diameter, magnetic susceptibility of crud and flow rate, and the following equation was derived from the equation of motion for a crud particle[1].

$$SF = C\chi a^2/Q \qquad (1)$$

where,
- SF : separation factor
- C : constant which depends on size of vessel, strength of magnetic field and viscosity of operating fluid
- χ : magnetic susceptibility of the crud particle
- a : crud particle radius

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Q : flow rate

3. Installation of the system

The advanced crud separator system was installed in an irradiation loop of the HBWR. The loop had been operated at pressure of 70 bar and temperature slightly below boiling temperature of 285°C.

A flow diagram of the test equipment is shown in Fig.2. There are two crud holders, which are placed inlet and outlet positions of the separator, in the sampling lines from the separator. Millipore filters (0.45 μm) were installed in the crud holders. An isokinetic branching technique was applied at the junction point between the main line and the inlet of the system from the main line, to evaluate crud amount in the loop correctly. After flowing into the separator line, sampling water was devided into two ; one goes to the inlet of the crud separator vessel and the other goes to the crud holder directly.

4. Test procedure

Most of the samplings were performed during the reactor transition condition, such as reactor power up or down, because it is known that comparatively much crud will be released during such reactor conditions than during the steady state condition.

Crud collected at the inlet and the outlet positions of the filters were compared by means of an atomic absorption spectrometer and Ge detector. In this report, most of separation factors were derived from Fe and Co-60 because those are thought to be most important species for crud removal and man-rem control[4).

For some of crud samples collected, X-ray diffraction technique was applied to investigate a type of crud, and scanning electron microscopy observation was also carried out to check the typical crud morphology.

As the separator operating conditions, rotation of magnet assembly and flow rate were varied at the start period of the test. After finding suitable set point for rotation of magnet assembly, it was fixed to 120 rpm, and, the crud size enlarger and demagnetizer were usually operated during sampling.

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5. Results and discussion

The mean chemical concentrations for crud in the irradiation loop, which measured by the atomic absorption spectrometer, are shown in Table 1. Major elements in crud are iron, nickel and chromium. The scanning electron micrographs for crud at the inlet and the outlet positions of the separator are shown in Fig. 3(a) and (b) respectively. Typical crud for the inlet position includes both large and fine ones, however, that for the outlet position is fine. This means that larger diameter crud would be easily removed by the separator, which is in good agreement with the equation (1).

Table 2 shows the X-ray diffraction measurement results for crud taken in January 1990. Major type of crud is magnetite during lower oxgen concentration in the loop water. The oxgen injection to the loop water has been started since March 1990 for an original experimental purpose of the loop. It was difficult to analyse for samples taken during higher oxgen concentration due to the small amount of crud. However, those are thought to be hematite because of higher oxgen concentration in the water. Then, it is considered that the separator can remove magnetite easier than hematite, because of those magnetic properties difference.

The relation between nickel and iron collected by the separator during the start period of the test is shown in Fig.4. There is a certain linear relation between those elements.

It has been found in the previous out-of-pile test that there was no correlation between separation factor and inlet concentration in the crud concentration range of the order of ppm[1]. However, as shown in Fig.5, separation factors obtained in this test, which is in the concentration range of the order of ppb, are thought to be dependent on the inlet iron concentration. Especially, separation factors up to 10 ppb of iron concentration seem to increase with increasing the inlet iron concentration.

The relation between separation factor and Co-60 activity at the inlet position is shown in Fig.6. In the calculation for separation factors hereinafter, the ratios of Co-60 are used, while separation factors in Fig.5 are derived from iron ratios. As seen in Fig.6, separation factor increases with increasing inlet Co-60 activity in the lower activity region, at least, up to 0.2 μCi.

Figure 7 shows the relation between Co-60 activity and Co amount at the inlet and the outlet positions of the separator. It is found that specific Co-60 activity for the inlet is greater than that for the outlet

(0.18 μCi/ μg for the inlet and 0.1 μCi/ μg for the outlet). It is thought that larger diameter crud particle activates more than smaller one, because crud separator removes larger crud easily so that most of crud remained in the outlet position are fine. This relation is also clear as seen in Fig.8, and separation factors derived from Co-60 are higher than that derived from Co element. This tendency was also suggested in the test carried out in the JMTR Project for the prototype crud separator[5].

As clarified in the equation (1), the separation factor depends on at least magnetic susceptibility of crud, crud particle radius and flow rate. However, it is difficult to estimate the magnetic susceptibility for crud of this test, then, the relation between separation factor and flow rate are shown in Fig.9 as the system performance for the high temperature and high pressure conditions. As seen in Fig.9, it was clearly found that separation factor derived from iron decreases with increasing flow rate for the inlet iron concentration gtrater than 10 ppb. Figure 10 shows the relation between separation factor derived from Co-60 inlet activity greater than 0.2 μCi and flow rate. It is also the same relation as Fig.9, showing that separation factor derived from the activity decreases with increasing flow rate. Those relation are in good agreement with equation (1), which was derived from the equation of motion for a crud particle in water.

It is known that crud (corrosion product) behavior is devided into five process ; production, removel, transportation, activation and deposition[6]. It is considered that crud transportation phenomena under high pressure and high temperature conditions (in-pile conditions) are very complicated because reactor condition changes continuously. However, those phenomena are thought to relate to, at least, the reactor operating history. Figure 11 shows separation factor (calculated from iron) and inlet iron concentration variations together with reactor operating history for the start period of the test. As seen in Fig.11, inlet iron concentration was comparatively high at the start period of the test, and was lower during the use of the separator. It is very remarkable that separation factor becomes higher when the coolant temperature increases. This phenomanon suggests that strongly magnetized crud, such as magnetite, would be easily released to the coolant during such period. At inlet iron concentration approximately 6 ppb, it seems to saturate. Therefore, it is considered that crud production (or release) rate and crud removel rate by the separator reaches a state of equilibrium. Then, the inlet crud concentration limit, removed by this crud separator is considered to be approximately 6 ppb.

6. Conclusions

The in-pile test of the crud separator system was performed in an irradiation loop of the HBWR to verify the system performance under the condition of high pressure and high temperature, simulating BWR conditions. Following conclusions were obtained ;

1) Separation factor increases with increasing inlet crud concentration, and seems to be no correlation above inlet iron concentration of 10 ppb.
2) At inlet iron concentration approximately 6 ppb, crud production (or release) rate and crud separation rate reaches a state of equilibrium.
3) Separation factor becomes higher when coolant temperature increases.
4) Separation factor decreases with increasing flow rate. This relation was in good agreement with the separation equation derived from the equation of motion for a crud particle.
5) The Crud separator removes magnetite crud easier than hematite one because of difference in magnetic properties, and gives better spparation factor for larger diameter crud.

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Table 1 Chemical compositions of crud collected at inlet position measured by an atomic absorption spectrometer (wt.%)

Fe	Ni	Cr	Cu	Co	Zn
84.76 ±1.98	10.46 ±1.23	3.97 ±1.67	0.21 ±0.08	0.27 ±0.09	0.35 ±0.23

Table 2 Type of crud collected at inlet and outlet of the separator.

O_2 conc.	< 5 ppb	
Type of crud	M_2O_3	M_3O_4
Inlet (%)	17	83
Outlet (%)	30	70

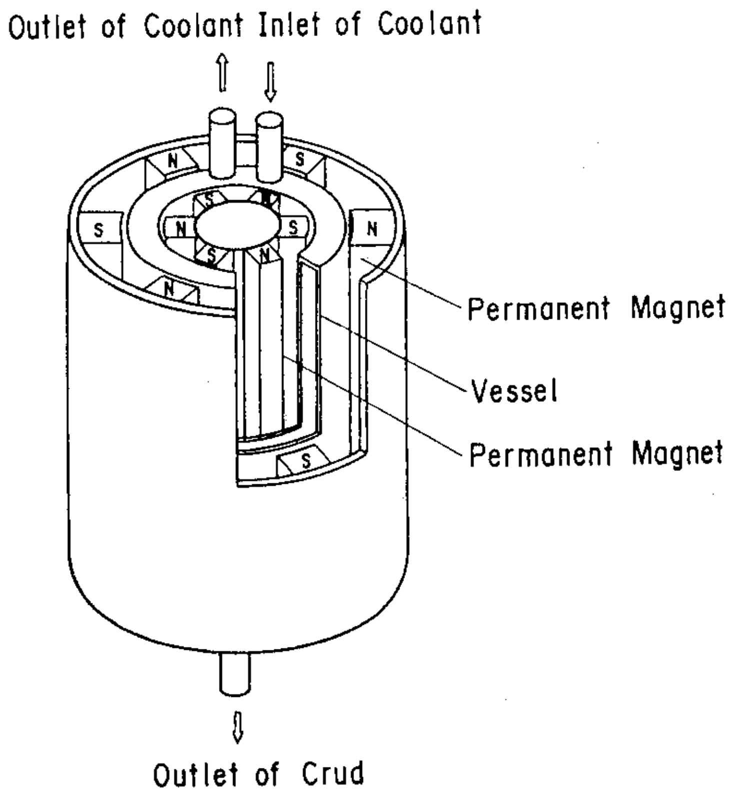


Fig. 1 Crud separator vessel. Rotation of permenent magnet assemblies which surround the separator vessel inside and outside produce moving alternating magnetic field, and separate crud from coolant.

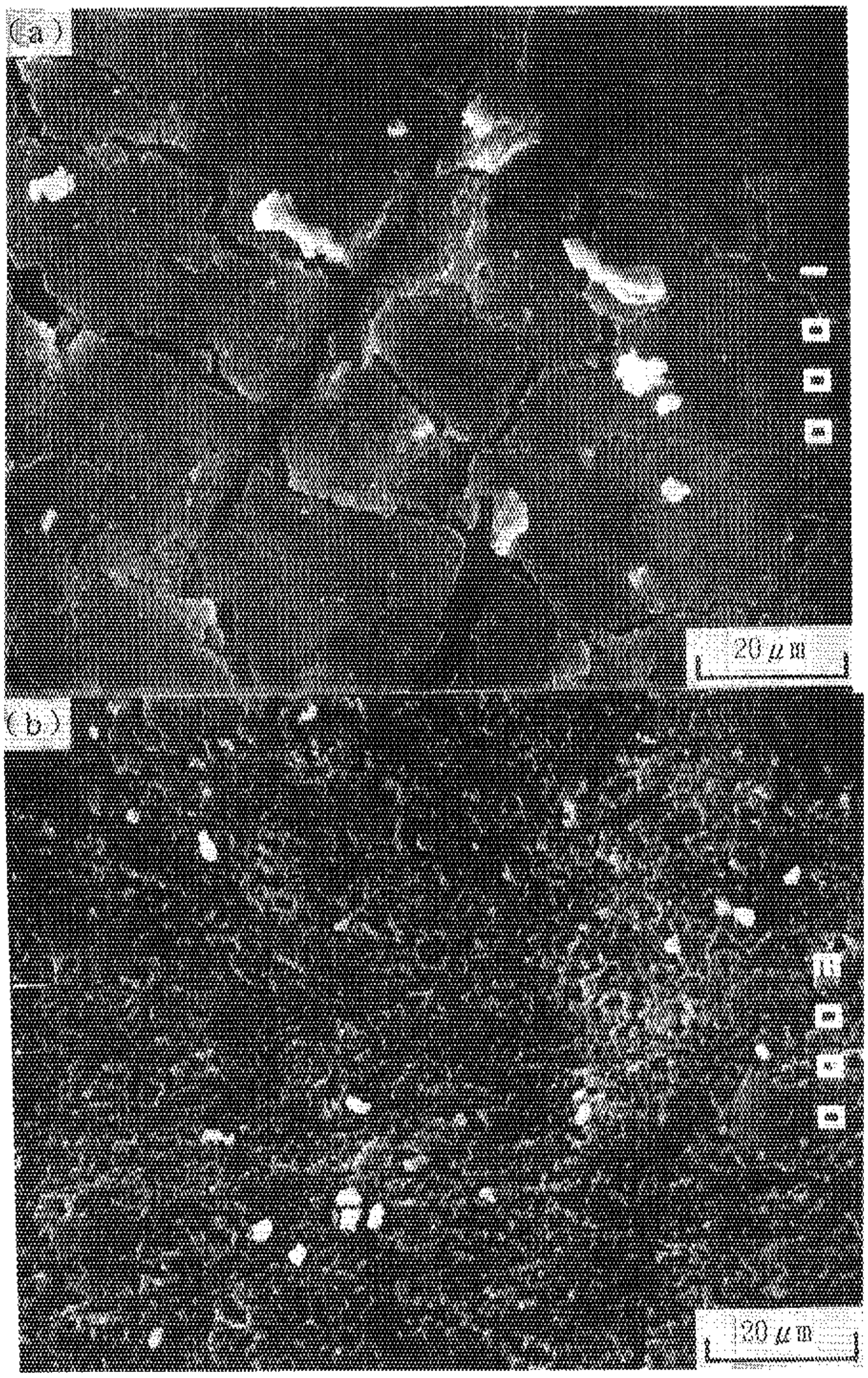
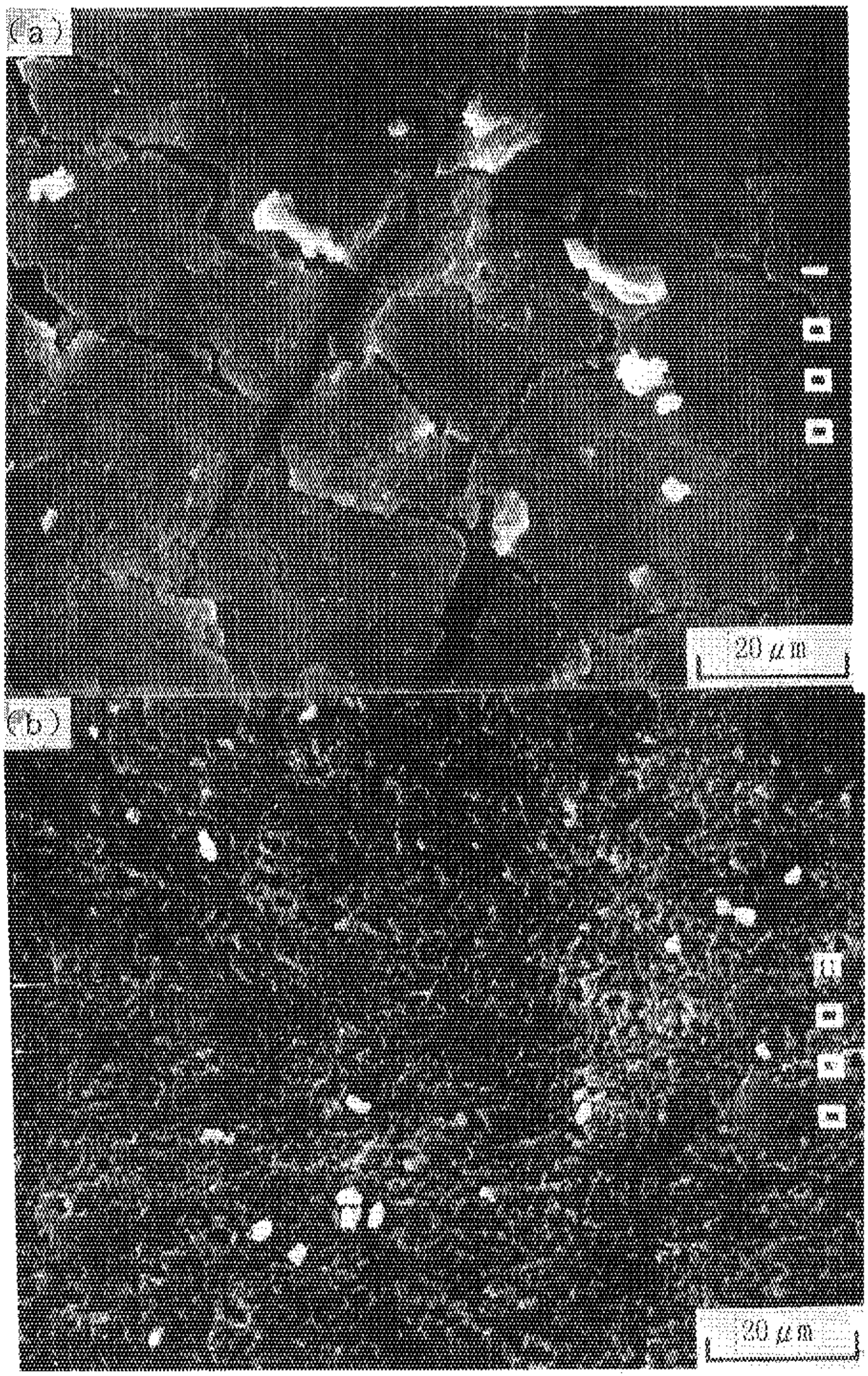


Fig. 3 Typical scanning electron micrographs of crud collected. (a) shows crud collected at inlet position and (b) shows crud collected at outlet position of the separator. Collected crud at inlet position is both large and fine, however, that collected at outlet position is fine.



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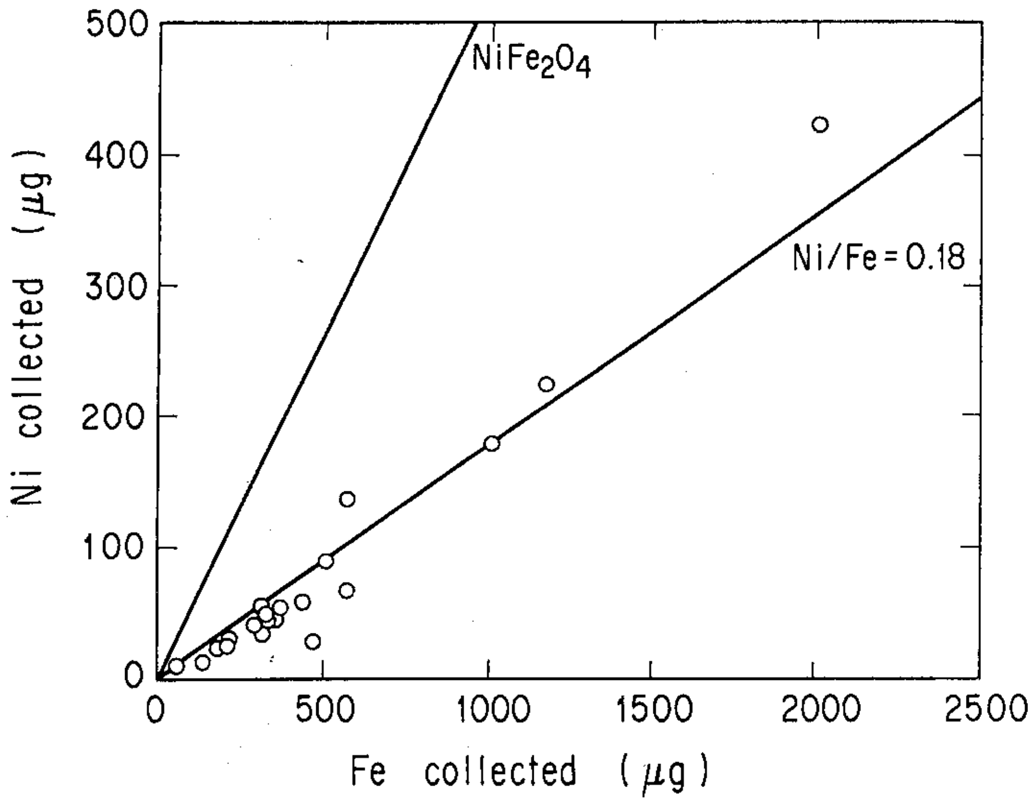

Fig. 4 Relation between nickel and iron collected by the separator. Linear correlation exists between nickel and iron collected by the separator.

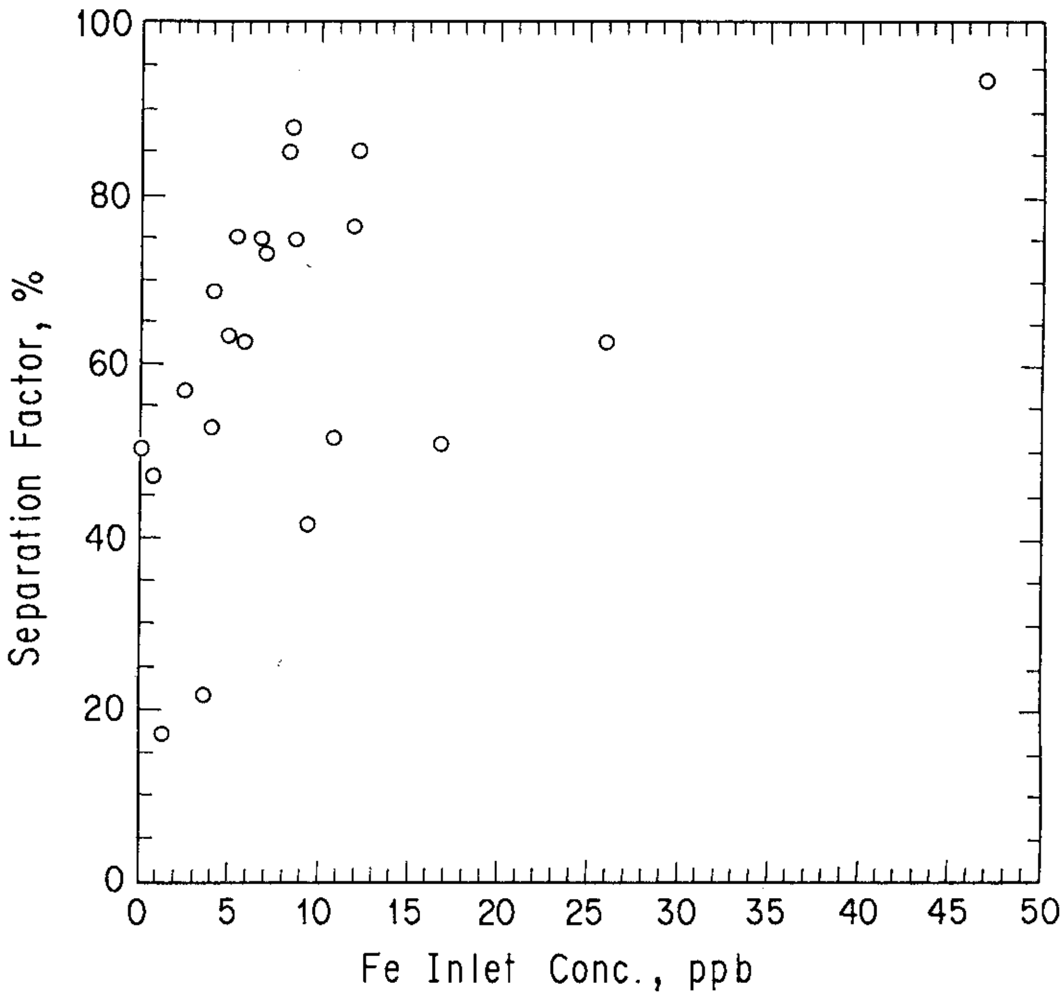

Fig. 5 Relation between separation factor and inlet iron concentration. Separation factors up to 10 ppb of iron concentration seem to increase with increasing the concentration.

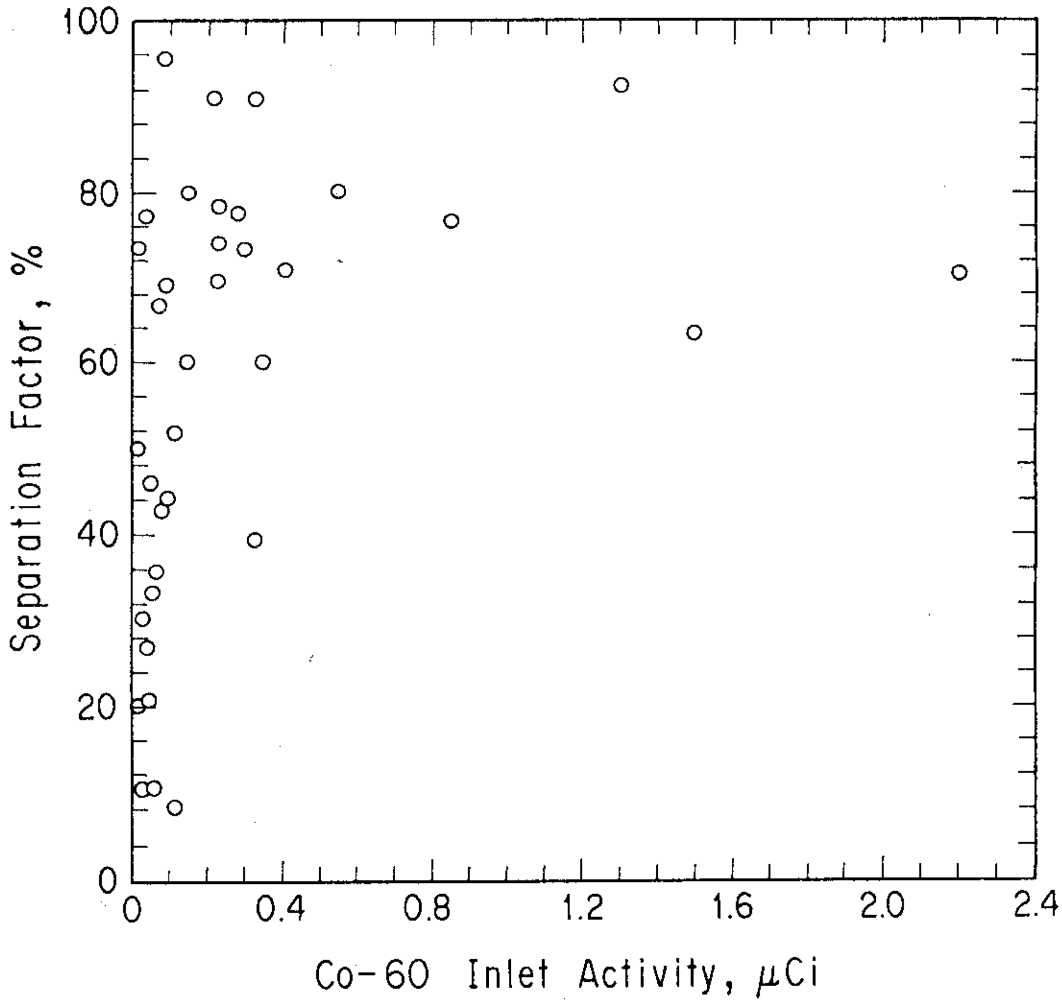

Fig. 6 Relation between separation factor and Co-60 activity at the inlet position. Separation factor increases with increasing inlet Co-60 activity in the lower activity region.

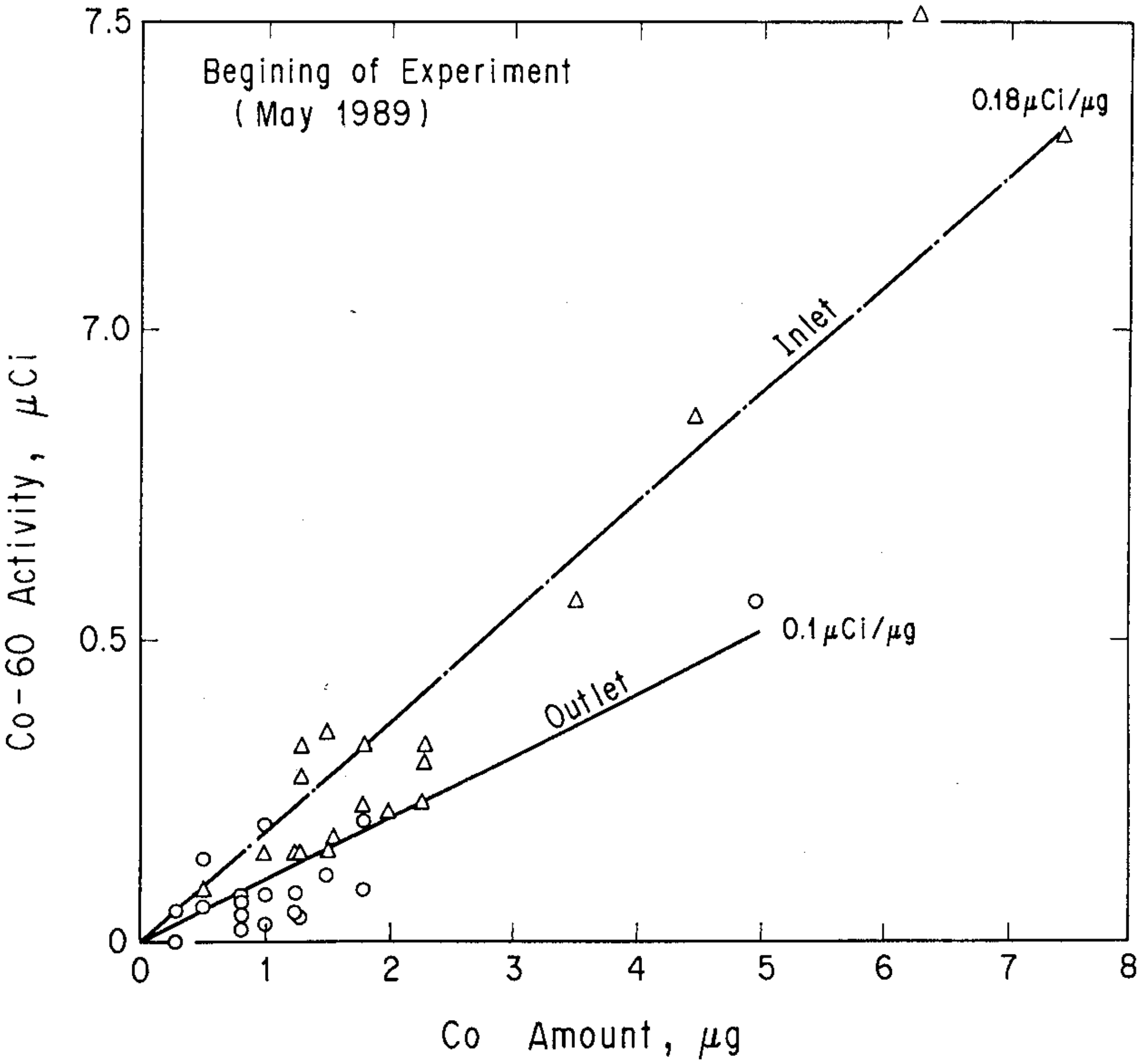

Fig. 7 Relation between Co-60 activity and Co amount. Co-60 activity for the inlet seems to be greater than that for outlet.

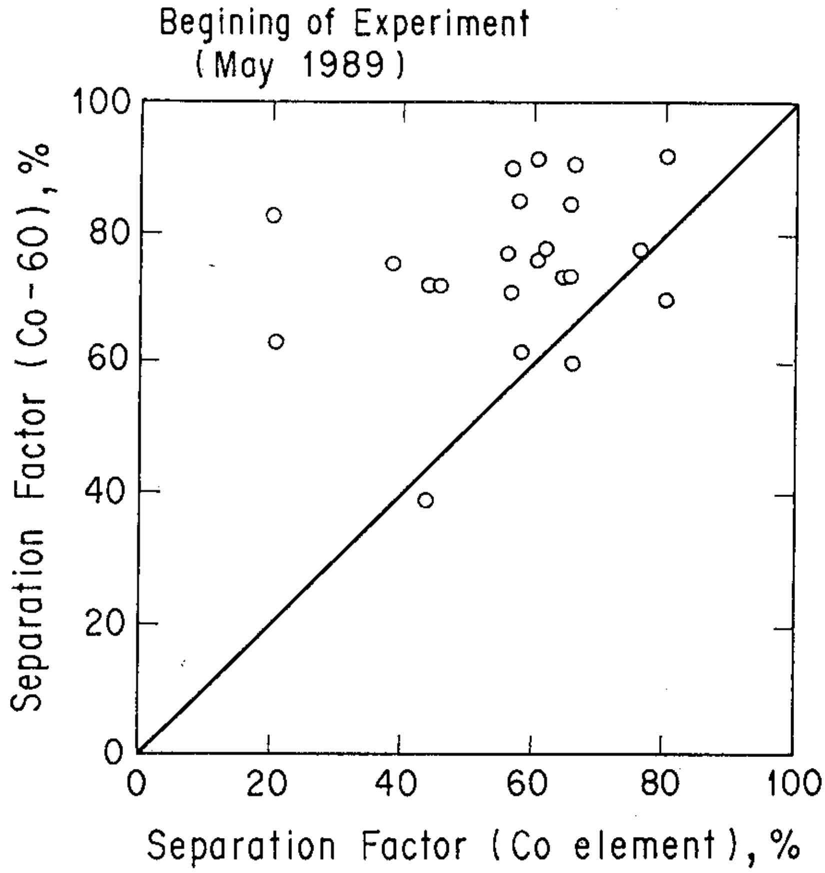

Fig. 8 Difference in separation factors derived from CO-60 activity and Co element. Separation factors derived from Co-60 are higher than those derived from Co element.

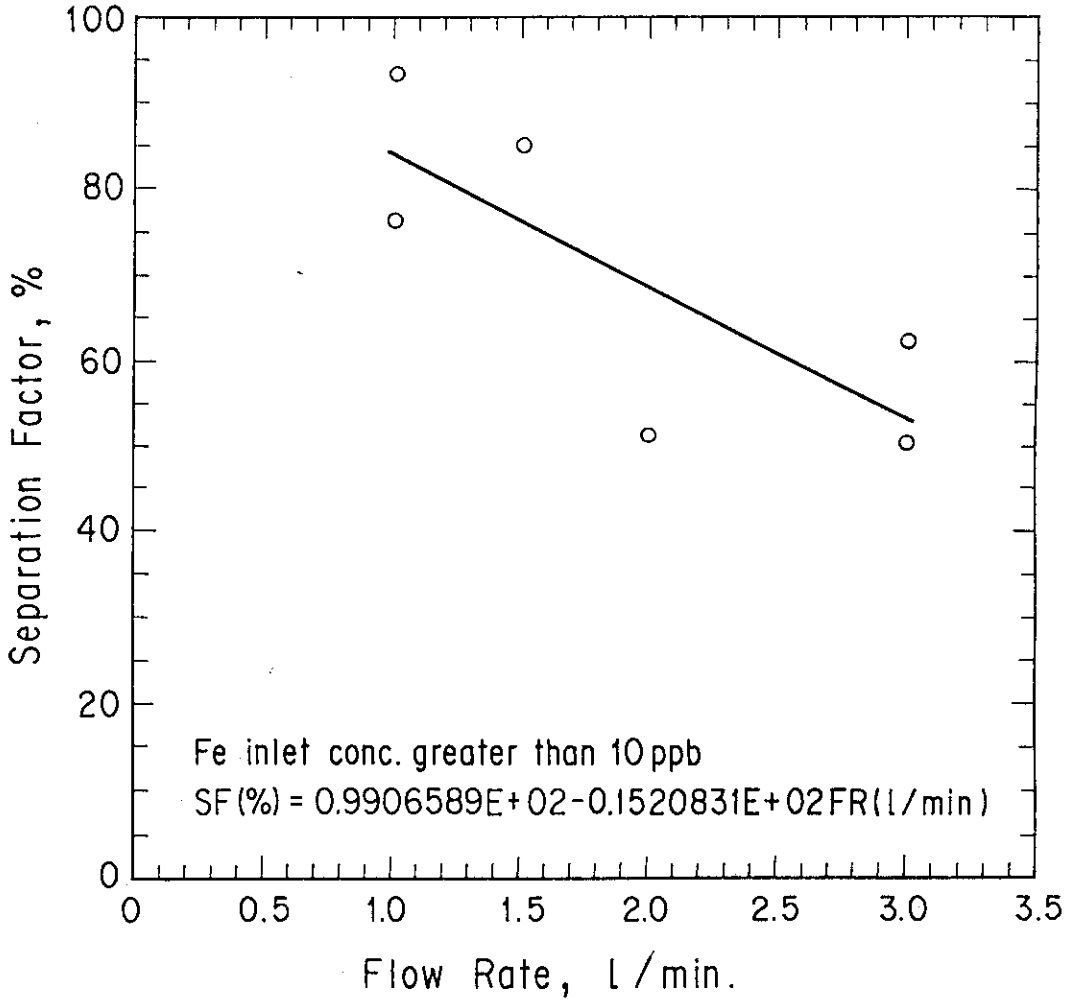

Fig. 9 Crud separator system performance. Separation factors were from iron ratio between inlet and outlet of the separator for iron inlet concentration greater than 10 ppb. Separation factor decreases with increasing flow rate for given iron concentration range.

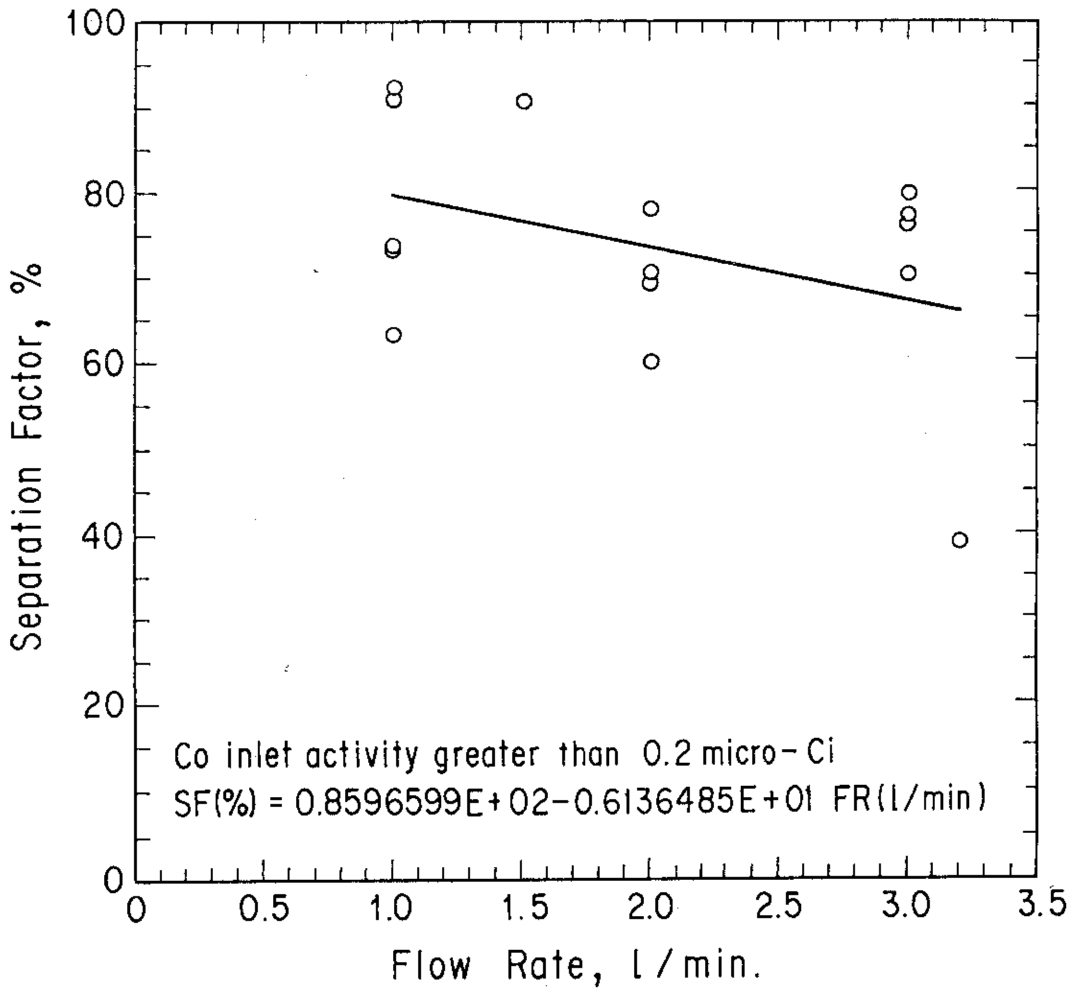

Fig. 10 Crud separator system performance. Separation factors were from Co-60 activity ratio between inlet and outlet of the separator for Co-60 inlet activity greater than 0.2μCi. Separation factor decreases with increasing flow rate for given activity range.

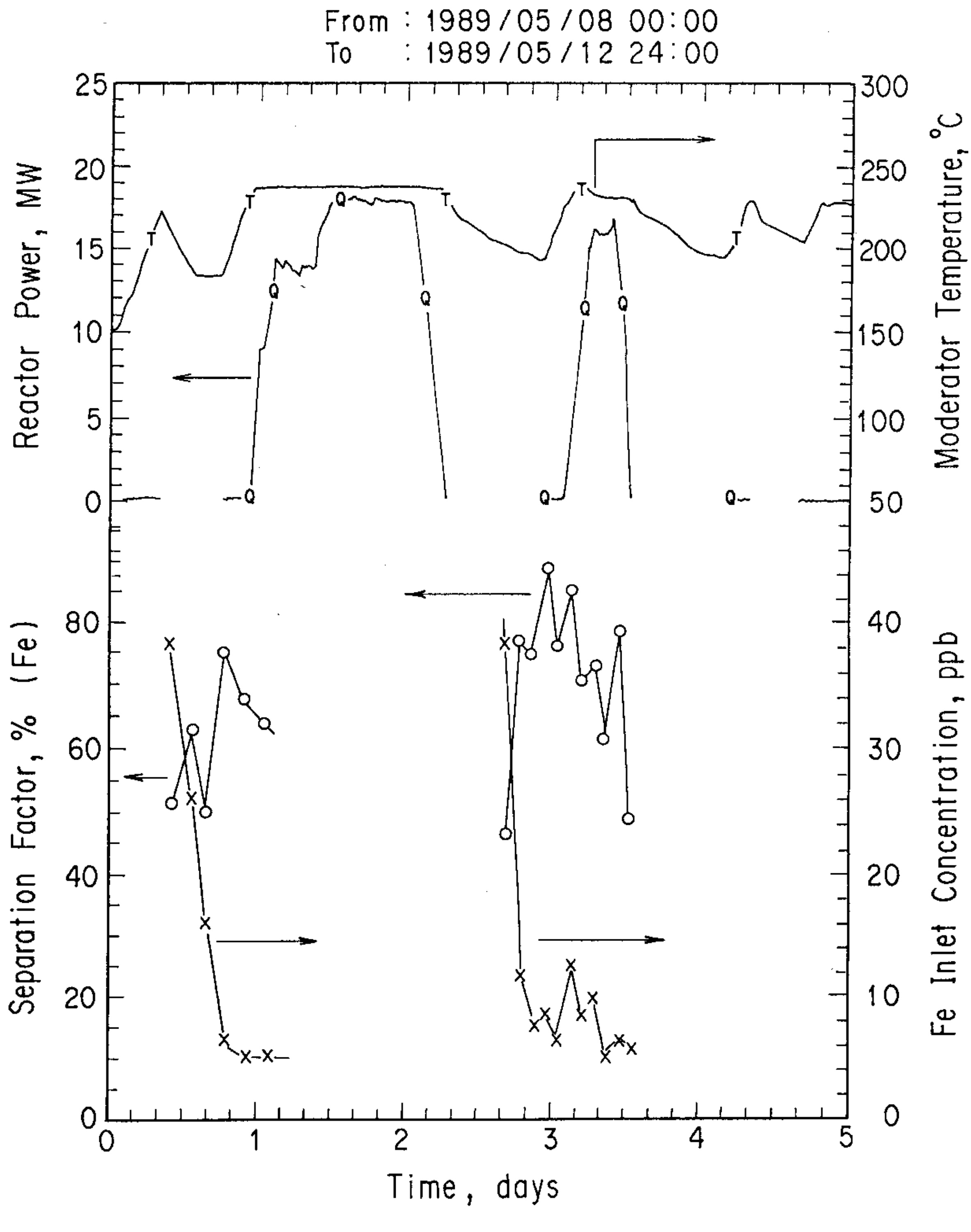

Fig. 11 Reactor operating history showing variations of separation factor and inlet iron concentration. Separation factor becomes higher when coolant (moderator) temperature increases.