JAERI-M--90-230

JP9104054

JAERI-M
90-230

# OUT-OF-PILE TEST OF THE CRUD SEPARATOR SYSTEM

## -DEVELOPMENT OF THE CRUD SEPARATOR SYSTEM (I) -

January 1991

Akito TAKASAKI, Katsumichi IIMURA and Isao TANAKA

日 本 原 子 力 研 究 所
Japan Atomic Energy Research Institute

JAERI-M レポートは、日本原子力研究所が不定期に公刊している研究報告書です。

入手の問合わせは、日本原子力研究所技術情報部情報資料課（〒319−11茨城県那珂郡東海村）あて、お申しこしください。なお、このほかに財団法人原子力弘済会資料センター（〒319-11茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

JAERI-M reports are issued irregularly.

Inquiries about availability of the reports should be addressed to Information Division, Department of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

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

# Out-of-pile Test of the Crud Separator System
## - Development of the Crud Separator System (I) -

Akito TAKASAKI, Katsumichi IIMURA and Isao TANAKA

Department of JMTR Project
Oarai Research Establishment
Japan Atomic Energy Research Institute
Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

(Received December 7, 1990)

The JMTR Project has been developing the crud separator system since 1981, and the advanced system has been fabricated for the in-pile test to be performed in the HBWR (Norway).

The crud separator system removes magnetized crud circulating in a primary circuit by the permanent magnet assembly surrounded inside and outside of the separator vessel.

Before the in-pile test, out-of-pile test was carried out in the JMTR Project under the condition of atmospheric pressure and room temperature, and the simplified theoretical analysis for crud separation mechanism was also carried out.

The out-of-pile test results suggested that separation factor increased with increasing magnetic susceptibility of crud and crud particle diameter, and decreased with increasing flow rate. These results were in good agreement with the theoretical analysis.

The test results also showed that the crud size enlarger was effective in lower separation factor region, which related to lower magnetic susceptibility of crud, smaller crud diameter and higher flow rate.

Keywords : Corrosion Product, Crud Separator, Out-of-pile

# クラッド分離装置の炉外試験
## —クラッド分離装置の開発Ⅰ—

日本原子力研究所大洗研究所材料試験炉部
高崎　明人・飯村　勝道・田中　勲

（1990年12月7日受理）

ＪＭＴＲは，1981年よりクラッド分離装置の開発を行っており，ＨＢＷＲ（ノルウェー）で用いる予定の確証試験（炉内試験）用装置の製作が完了した。

本装置は，一次系冷却水中に循環するクラッドを分離容器回りに配置した磁気回路により除去しようとするものである。

ＪＭＴＲでは，確証試験に先立ち常温・常圧環境下において本装置の性能試験（炉外試験）を行った。また，クラッド分離メカニズムの簡単な理論解析も行った。

それらの結果，クラッド分離効率は，クラッド磁化率及びクラッド粒径の増加に伴い上昇し，一方，流量の増加に伴い低下することが示唆された。また，クラッド粒径を増大させる目的で本装置入口に取り付けられた造粒器の使用は低分離効率時（低磁化率，低クラッド粒径もしくは高流量時）に有効であることが示唆された。

---

大洗研究所：〒311-13 茨城県東茨城郡大洗町成田町字新堀3607

## Contents

## 目　　次

## 1. Introduction

Major interests for water quality control in nuclear power plants are reduction and separation techniques of metallic corrosion product in a primary circuit. Appropriate materials are chosen for the equipment and pipes to avoid such corrosion.

Most ionized corrosion product can be removed comparatively easily by ion exchange resin. Non-soluble corrosion product (crud), however, are difficult to be removed by such a method. Those crud, are circulating through a primary circuit and activated in a reactor core, causes to increase personal radiation exposure in a reactor site.

The JMTR Project has started to develop the crud separator system, whose development background are well described in a previous paper$^{1)}$, under personal radiation exposure reduction technology program supported by Science and Technology Agency. The crud separator utilizes a moving alternating magnetic field produced by rotating permanent magnets, for separating crud.

The development program started in 1981. The first short term operation test to investigate the system characteristics under the atmospheric condition was performed in the JMTR Project by the first prototype system$^{2)}$. The advanced system, which was improved to get better separation factor (separation efficiency), was fabricated for the final verification test in the HBWR, Norway $^{1)}$.

This report summarizes the out-of-pile test results of the advanced system performed in the JMTR Project before shipment to the HBWR.

## 2. Main characteristcs of the system

The crud separator system consists of crud size enlarger, crud separator and demagnetizer mainly as shown in Fig.1 and is operated by control consoles. The roles for each main equipment were described briefly as follows;

(1) Crud size enlarger

Crud size enlarger installed at inlet of the separator main frame makes crud diameter larger and gives better separation factor because crud particle size is considered to have strong effect on separation ability of the separator system. The enlarger is a high gradient magnetic system, and energizing a coil of the enlarger makes crud larger.

### (2) Crud separator

Crud separator has a cylindrical vessel made of austenitic stainless steel (Type-316). The vessel is surrounded by permanent magnet assembly. Rotation of the assembly is controlled by a drive motor to generate optimum moving alternating magnetic field.

### (3) Demagnetizer

Most of crud are removed by the separator. However, there is a possibility that some of crud may not be removed by the separator and may be flown out from the separator outlet. The demagnetizer installed at outlet position of the separator demagnetizes magnetized crud by a high frequency oscillator.

### (4) Console panels

Console panels includes a power source and a control consoles for operating the system. The separator system is operated remotely by those consoles which are placed outside of a reactor hall.

## 3. Crud separation theory

A magnetized particle in water will move with moving alternating magnetic field performed by S-N counter facing magnets as shown in Fig.2. The magnetic force pararell to the magnets movement received by the particle can be described by;

$$Fm = V\chi H\, dH/dx \tag{1}$$

where,
$V$ : volume of particle
$\chi$ : magnetic susceptibility of the particle
$H$ : strength of magnetic field
$x$ : distance pararell to the magnets movement

The resistanct force produced by water viscosity against the particle movement can be expressed by ;

$$Fd = 1/2(\rho v^2 Ap\ Cd) \tag{2}$$

where,
$\rho$ : density of water
$v$ : relative water velocity
$Ap$ : cross sectional area of projection for particle

Cd : resistant coefficient (= 24/Re)

Then, the following equation of motion is derived for the particle ;

$$m(dv/dt) = Fm - Fd + Fg \qquad (3)$$

where,
m : mass of particle
t : time
Fg : gravitational force

When the following conditions are assumed ;

i) movement velocity of crud is constant.

ii) the effect of gravitational force is ignored.

Then, equation (3) is ;

$$1/2(\rho v^2 Ap\ Cd) = V\chi H\ dH/dx \qquad (4)$$

If the crud radius is assumed to be a, equation (4) can be changed into equation (5).

$$v = (2/9\mu)\ a^2 \chi H\ dH/dx \qquad (5)$$

where,
μ : viscosity of fluid

Transfer time for crud from center of vessel to the wall can be expressed in equation (6).

$$\begin{aligned} t_1 &= h/(2v) \\ &= 9h\mu/[4a^2 \chi H(dH/dx)] \end{aligned} \qquad (6)$$

where, h : vessel width

And, transfer time for crud from inlet to outlet of the separator can be shown in equation (7). (Crud movement is assumed to follow water flow.)

$$t_2 = hyx/Q \qquad (7)$$

where,
x : vessel length (pararell to water flow)
y : vessel height
Q : flow rate

Separation factor is thought to be a ratio for the crud reaching to the vessel wall, before reaching to the outlet, when the crud separation is assumed to finish at the vessel wall. Then,

$$\begin{aligned} SF = t_2/t_1 &= 4a^2\chi xy\ dH/dh/(9\mu Q) \\ &= 4a^2\chi xy\ H^2/(9\mu Q) \end{aligned} \qquad (8)$$

Equation (8) can be converted simply into the following equation (9).

$$SF = C\chi a^2/Q \qquad (9)$$

where, $C$ : $4xyH^2/(9\mu)$

It is clear that separation factor depends on, at least, crud particle size, strength and gradient of magnetic field, flow rate, and density of water.

Equation (9) implys that particle separation in gas may show better separation factor than that in liquid, and it also implys that larger separator vessel size may improve the separation factor.

## 4. Test Procedure

A flow diagram of equipment for the out-of-pile test is shown in Fig.3. Artificial particles (not activated), shown in Table 1, were specially made for this test and used as crud particle. Some particle concentration levels were prepared by adding particles into purified water. The water in the tank container was mixed by a mixer during the test for disparsing the particles in the water well. Magnetic properties and average diameter of artificial crud particles used (manufacturing data) are also summarized in Table 1.

During the separator operation, sample waters were taken from both the sampling vessel (outlet) and the tank (inlet). The sampled water was filtrated by membrane filters (0.45 μm), and concentrations of chemical elements were analysed by ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectrometer) after dissolving the particles on the filters.

Separation factors were calculated from the followng equation (10).

$$SF = (CRUDIN - CRUDOUT)/CRUDIN \qquad (10)$$

where, SF : separation factor

CRUDIN : (specific) particle concentration at inlet

CRUDOUT : (specific) particle concentration at outlet

To assess the system performance, crud particle diameter, particle magnetic properties, particle inlet concentration, flow rate, rotation of magnet assemly and condition of the crud size enlarger (on/off) were varied as performance parameters.

## 5. Results and discussion

Full data set of the out-of-pile test is shown in Table 2. The test was performed under the atmospheric pressure and room temperature condition.

A relation between separation factor and magnetic susceptibility of crud particle is shown in Fig.4. It seems to be scattered widely, however, it is suggested that higher magnetic susceptibility of crud gives better separation factor. As shown in Fig.5, separation factor tends to increase with increasing crud diameter. Therefore, it is suggested that magnetite crud such as $Fe_3O_4$ can be removed by the separator comparatively easier than hematite one such as $Fe_2O_3$. It is also suggested that use of the crud size enlarger gives better separation factor.

Figure 6 and 7 show relations between separation factor and flow rate when the crud size enlarger was in use and out of use respectively. Separation factor tends to decrease with increasing flow rate in both cases. When the enlarger was in use, separation factor shifted up to higher factor side approximately 5-10%.

Relation between separation factors and inlet crud concentration when the enlarger was in use and out of use are shown in Fig.8 and Fig.9 respectively. In both cases, there seems to be no correlation between them in given concentration regions.

In above correlation from Fig.4 to Fig.9, parameter effects for separation factor were individually evaluated. However, many factors are thought to affect each other to separation factor. The relations between separation factor and values calculated from equation (9) when the enlarger was in use and out of use are shown in Fig.10 and Fig.11 respectively as the system total characteristics. It is suggested that separation factors tend to increase with increasing the parameter given by equation (9) in both cases. The best fitting lines are derived by the least square method as shown below.

When the crud size enlarger is in use,

$$SF = -1.313 + 17.004\ln(\chi a^2/Q), \quad (1.1 \leq \chi a^2/Q \leq 386.9) \qquad (11)$$

When the crud size enlarger is out of use,

$$SF = -34.400 + 23.796\ln(\chi a^2/Q), \quad (4.3 \leq \chi a^2/Q \leq 283.7) \qquad (12)$$

Where, SF : separation factor (%)
$\chi$ : magnetic susceptibility of crud ($\mu$H/m)
$a$ : crud diameter($\mu$m)
Q : flow rate (l/min.)

Figure 12 shows the effect of the enlarger utilization on separation factor. Higher gain of separation factor is expected in utilizing the enlarger when the parameter ($\chi a^2/Q$) has low value. The gain of separation factor decreases with increasing ($\chi a^2/Q$) value and is almost zero above 120 of ($\chi a^2/Q$).

## 6. Conclusions

Before the in-pile test to be performed in the HBWR (Norway), out-of-pile test of the advanced type crud separator was carried out under the conditions of atmospheric pressure and room temperature. The main results obtained are as follows ;

1) Separation factor increases with increasing magnetic susceptibility of crud. This suggests that magnetite crud can be removed by the separator easier than hematite.
2) Separation factor also increases with increasing crud particle diameter and decreases with increasing flow rate.
3) There seems to be no correlation between separation factor and inlet crud concentration in the concentration region from 0.3 to 7.8 ppm.
4) The crud size enlarger is effective in lower separation factor region, which relates to lower magnetic susceptibility of crud, smaller crud diameter and higher flow rate.

## Acknowledgements

The authors wish to thank to Mr. I.Yokouchi and Mr. I.Hisa, Engineering Testing Div., Department of JMTR Project for chemical analyses of crud samples.

We also wish to thank for many suggestions and encouragement to Dr. Y.Futamura, Director, Department of JMTR Project, Mr. H.Itami, Director, Department of Fuel examination, Mr. A.Nakano, Director, Department of Technical Information and Mr. H.Tanaka, Ishikawajima-Harima Heavy Industries Co., Ltd.

## References

(1) H. Itami et. al., "Proposal for In-pile Test of JAERI-developed Crud Separator System in the HBWR", JAERI-M 88-269(1989)

(2) H. Itami, "Crud Removal Technology", Genshiryoku Kougyo, 31-9(1985) pp.47 (in Japanese)

Table 1 Characteristics of crud particles used.

|  | Type of crud | mean crud diameter ($\mu m$) | magnetic susceptibitity (H/m) x $10^{-6}$ | saturation magnetic flux density (emu/g) | residual magnetic flux density (emu/g) | coercive force (Oe) |
|---|---|---|---|---|---|---|
| $\alpha-Fe_2O_3$ | $\alpha$ - 200 | 4.21 | 0.458 |  |  |  |
|  | $\alpha$ - RB-BL |  |  |  |  |  |
|  | $\alpha$ - BL-SP | 5.49 | 0.379 | 5.75 | 1.07 | 211.6 |
|  | $\alpha$ - MR |  |  |  |  |  |
| $\gamma-Fe_2O_3$ | $\gamma$ - 200 | 3.44 | 9.07 | 71.5 | 15.5 | 123.9 |
|  | $\gamma$ - 500 | 2.98 | 11.5 | 73.2 | 11.1 | 81.7 |
|  | $\gamma$ - RB-BL |  |  |  |  |  |
|  | $\gamma$ - BL-SP | 4.00 | 6.94 | 72.0 | 11.0 | 135.8 |
|  | $\gamma$ - MR |  | 8.84 | 73.9 | 33.3 | 318.4 |
| $Fe_3O_4$ | BL - 200 | 2.56 | 6.79 | 83.5 | 10.8 | 127.9 |
|  | BL - 500 | 2.72 | 8.76 | 84.8 | 9.7 | 70.5 |
|  | RB - BL | 3.60 | 6.31 | 87.6 | 18.0 | 199.4 |
|  | BL - SP | 4.74 | 9.47 | 84.7 | 6.82 | 62.4 |
|  | MR - BL | 3.12 | 7.34 | 82.2 | 36.2 | 402.2 |
| $CoFe_2O_4$ |  | 6.95 | 2.6 | 73.6 | 28.9 | 737.6 |
| $NiFe_2O_4$ |  | 4.88 | 6.0 | 47.7 | 55.5 | 72.7 |
| artificial-$\alpha$ |  | 2.87 | 4.34 | 28.2 | 4.3 | 79.9 |
| artificial-$\gamma$ |  | 3.98 | 3.63 | 33.1 | 4.27 | 85.7 |

Table 2 Full data of out-of-pile test for the crud separator.

| SF | CONC | Q | DIA | MAG | E |
|---|---|---|---|---|---|
| 84 | 7.00 | 1 | 2.98 | 11.5 | 0 |
| 62 | 6.30 | 2 | 2.98 | 11.5 | 0 |
| 85 | 3.85 | 1 | 2.98 | 11.5 | 1 |
| 69 | 4.14 | 2 | 2.98 | 11.5 | 1 |
| 59 | 5.48 | 3 | 2.98 | 11.5 | 1 |
| 52 | 0.26 | 1 | 2.98 | 11.5 | 1 |
| 60 | 0.43 | 2 | 2.98 | 11.5 | 1 |
| 57 | 0.60 | 3 | 2.98 | 11.5 | 1 |
| 90 | 6.34 | 1 | 3.60 | 6.31 | 0 |
| 57 | 3.57 | 2 | 3.60 | 6.31 | 0 |
| 31 | 3.94 | 3 | 3.60 | 6.31 | 0 |
| 65 | 2.34 | 2 | 3.60 | 6.31 | 1 |
| 62 | 4.14 | 3 | 3.60 | 6.31 | 1 |
| 69 | 7.77 | 1 | 3.12 | 7.34 | 0 |
| 38 | 4.74 | 2 | 3.12 | 7.34 | 1 |
| 32 | 6.10 | 3 | 3.12 | 7.34 | 1 |
| 74 | 0.95 | 1 | 6.95 | 2.60 | 0 |
| 82 | 1.31 | 2 | 6.95 | 2.60 | 0 |
| 71 | 1.79 | 3 | 6.95 | 2.60 | 0 |
| 94 | 4.01 | 1 | 4.88 | 6.00 | 0 |
| 61 | 0.98 | 2 | 4.88 | 6.00 | 0 |
| 50 | 1.90 | 3 | 4.88 | 6.00 | 0 |
| 36 | 3.02 | 1 | 3.44 | 9.07 | 0 |
| 27 | 4.19 | 2 | 3.44 | 9.07 | 0 |
| 36 | 5.91 | 3 | 3.44 | 9.07 | 0 |
| 55 | 0.35 | 1 | 3.98 | 3.63 | 0 |
| 41 | 1.38 | 2 | 3.98 | 3.63 | 0 |
| 31 | 1.85 | 3 | 3.98 | 3.63 | 0 |
| 79 | 1.01 | 1 | 4.00 | 6.94 | 0 |
| 88 | 1.86 | 2 | 4.00 | 6.94 | 0 |
| 82 | 2.58 | 3 | 4.00 | 6.94 | 0 |
| 93 | 2.01 | 2 | 4.00 | 6.94 | 1 |
| 87 | 3.24 | 3 | 4.00 | 6.94 | 1 |

Note : SF : Separation factor, %
CONC : Concentration, ppm
Q : Flow rate, L/min.
DIA : Crud diameter, $\mu$m
MAG : Magnetic susceptibility, $\mu$H/m
E : Condition of crud size enlarger
0 - Out-of-use
I - in-use

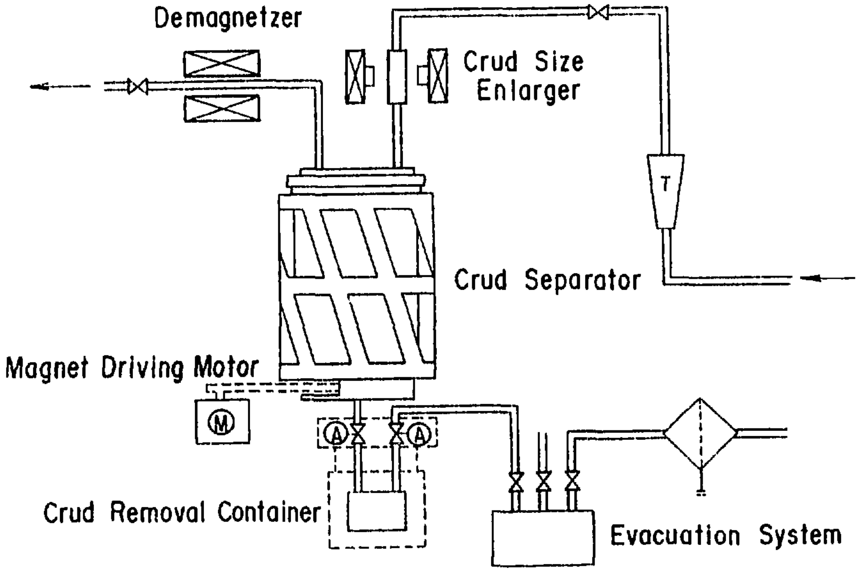

Fig. 1 Crud separator main system. The crud size enlarger is a high gradient magnetic system, and energizing a coil of the enlarger makes crud larger. The crud separator is a main system, and separate crud from coolant (See also Fig.2). The demagnetizer demagnetizes magnetized crud flown out from the separator by a high frequency oscillator.

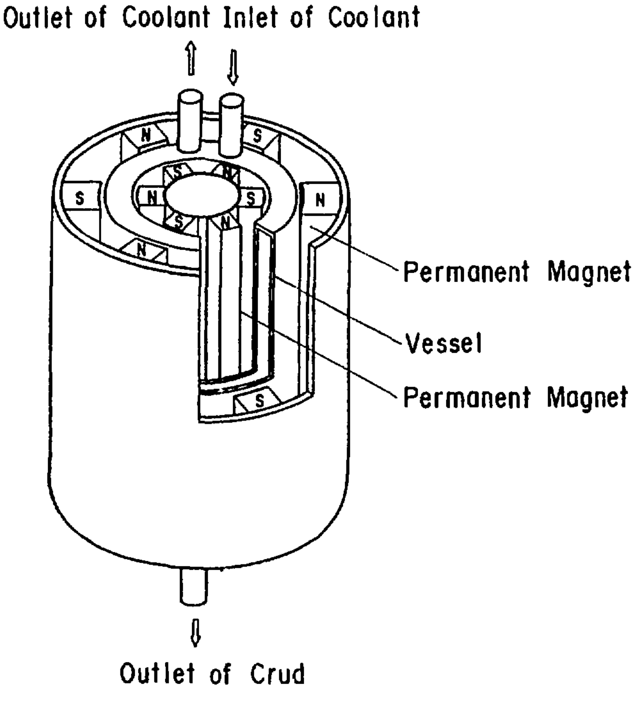

Fig. 2 Crud separator vessel. Rotation of permanent magnet assemblies which surround the separator vessel inside and outside produce moving alternating magnetic field, and separate crud from coolant.

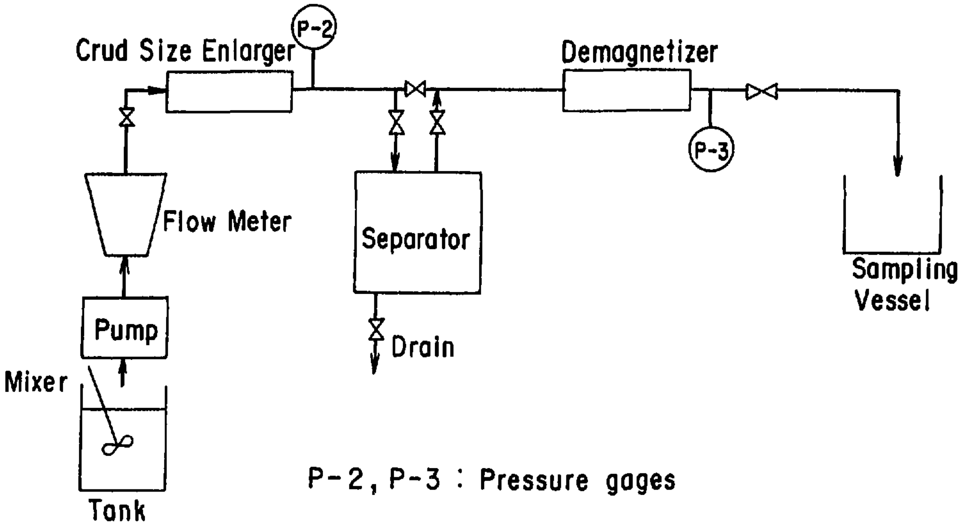

Fig. 3 Flow diagram of equipment for out-of-pile test. The test was performed under the condition of atmospheric pressure and room temperature.

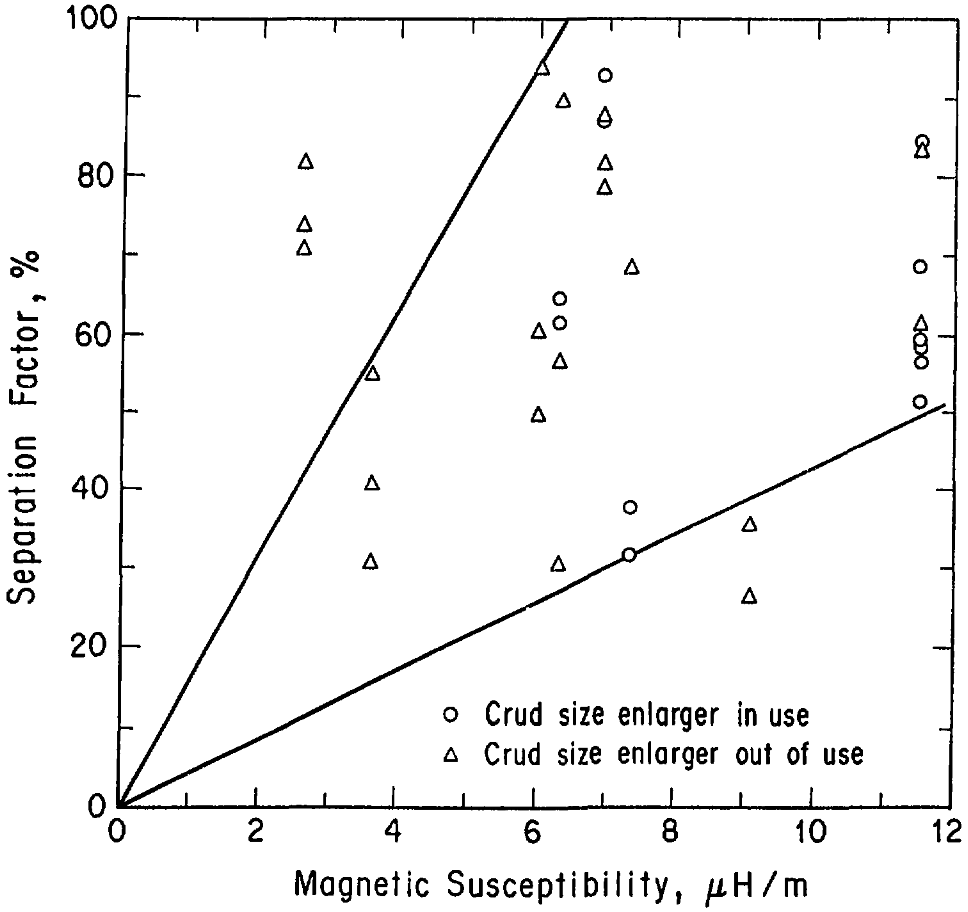

Fig. 4 Relation between separation factor and magnetic susceptibility. It is suggested that higher magnetic susceptibility of crud gives better separation factor (separation efficiency).

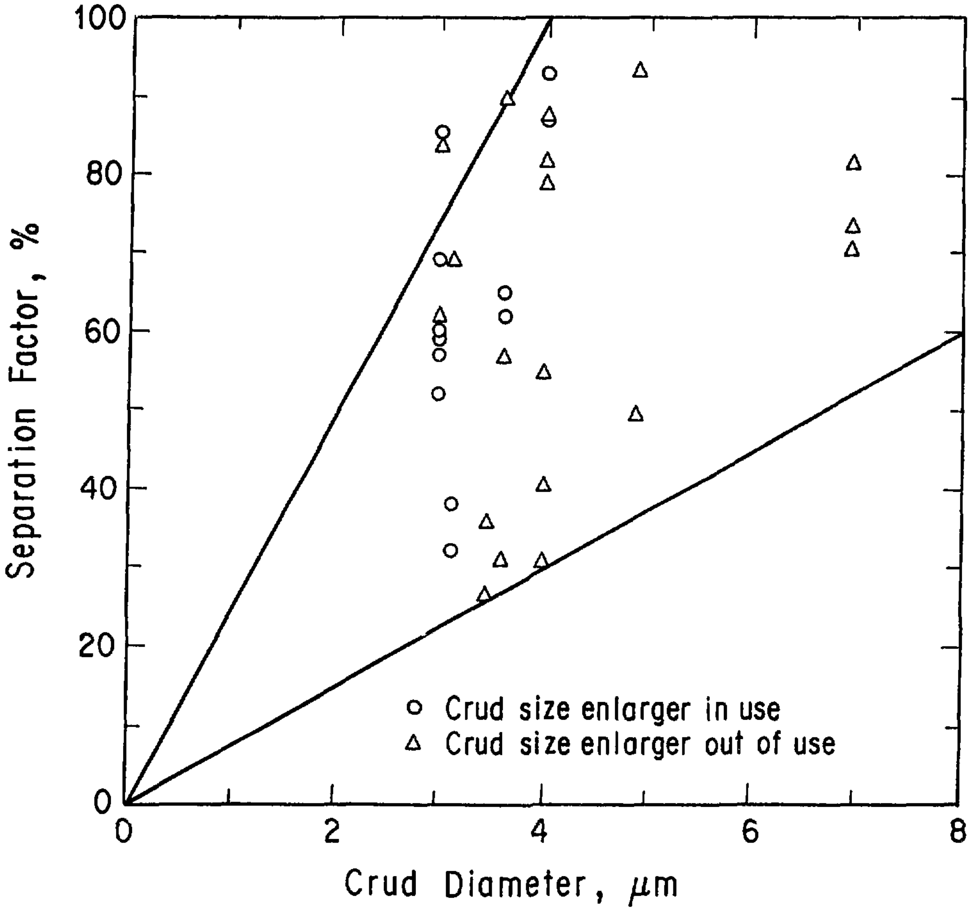

Fig. 5 Relation between separation factor and crud diameter. Separation factor tends to increase with increasing crud diameter.

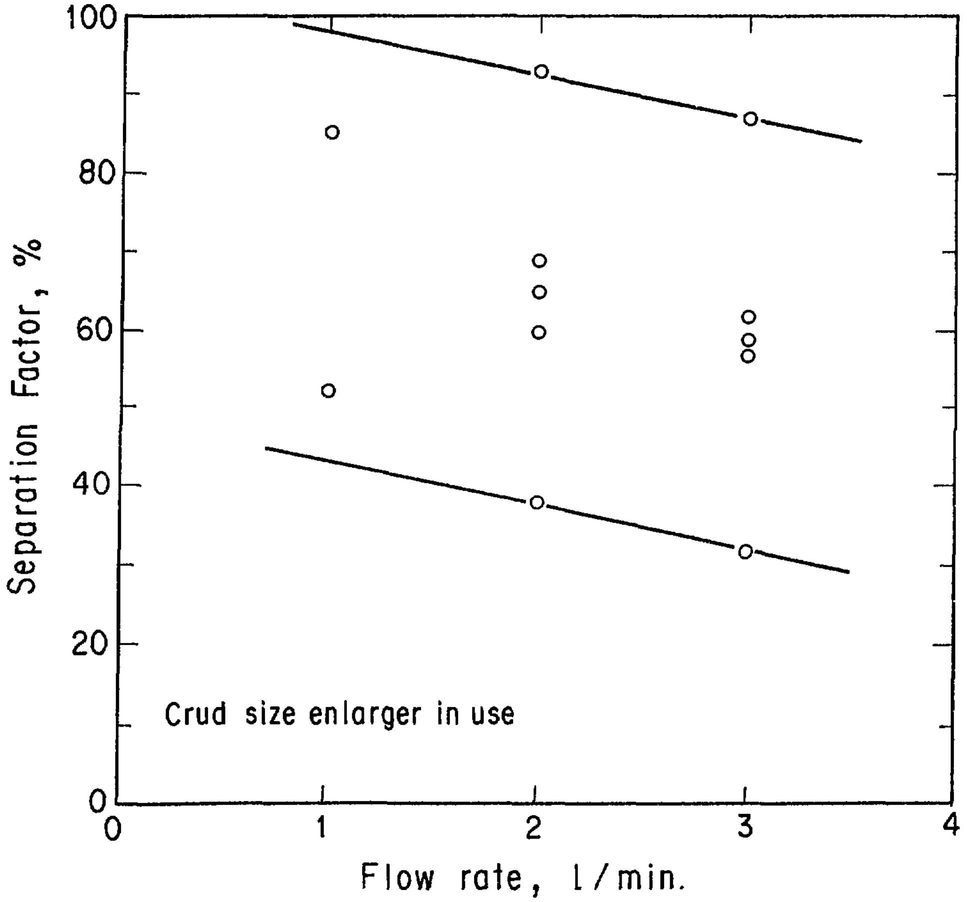

Fig. 6 Relation between separation factor and flow rate when crud size enlarger is in use. Separation factor tends to decrease with increasing flow rate.

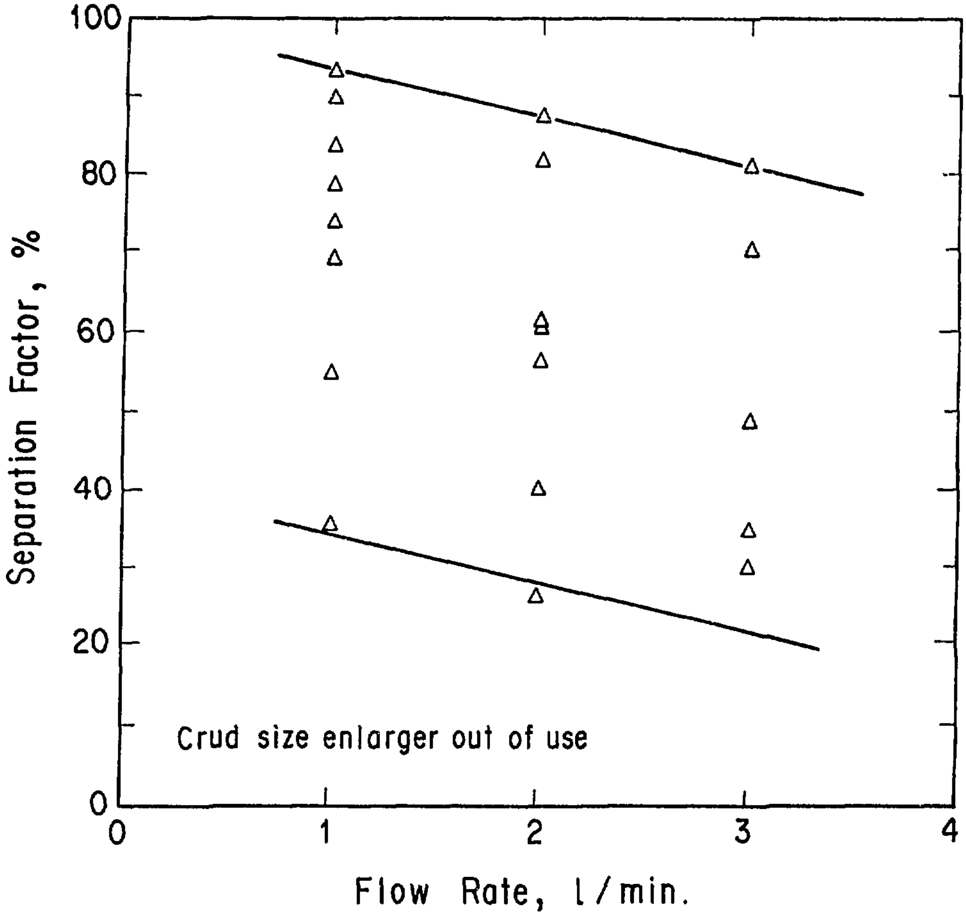

Fig. 7 Relation between separation factor and flow rate when crud size enlarger is out of use. Separation factor shifts down to to lower factor side apploximately 5-10% in this case when compared to the case of Fig. 6.

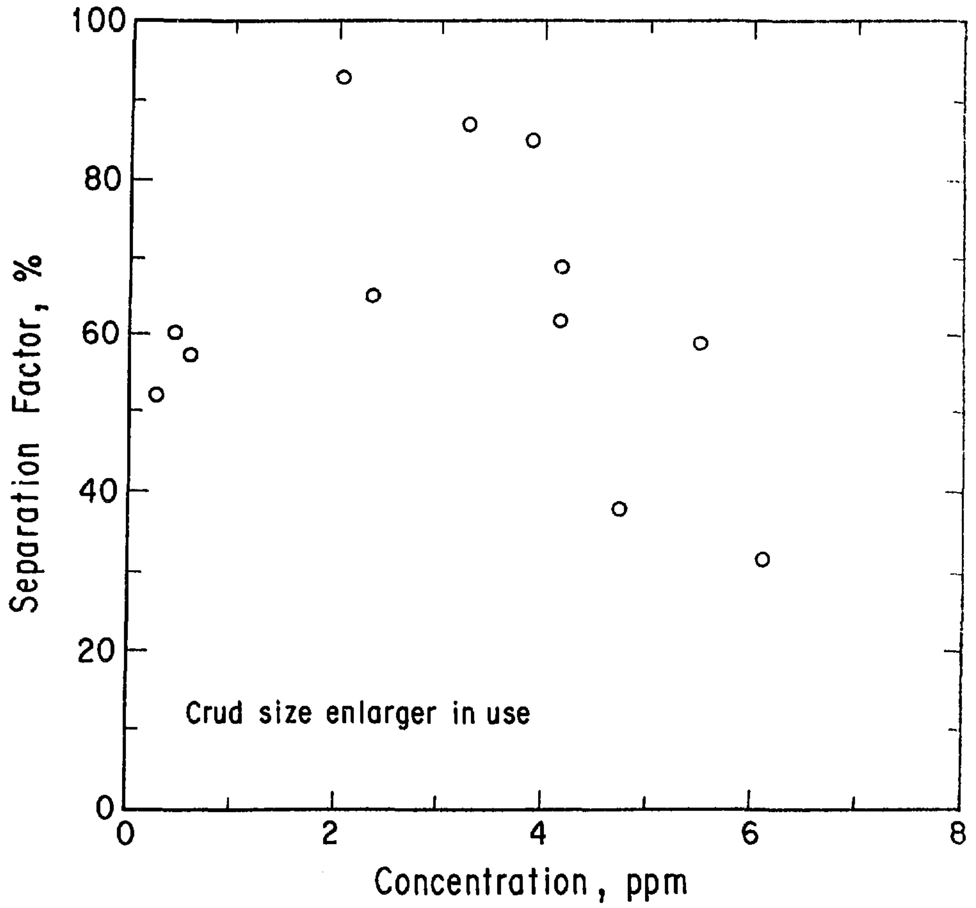

Fig. 8 Relation between separation factor and crud concentration when crud size enlarger is in use. There seems to be no correlation between separation factor and crud concentration.

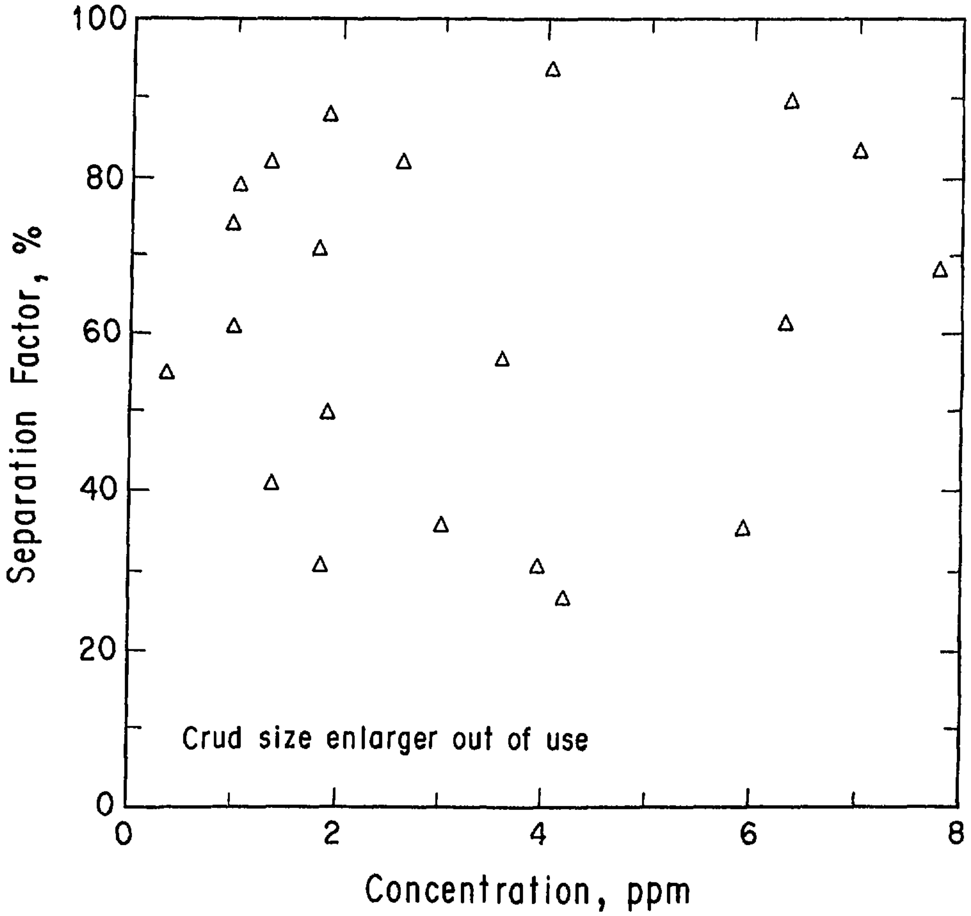

Fig. 9 Relation between separation factor and crud concentration when crud size enlarger is out of use. There seems to be no correlation between separation factor and crud concentration also in this case.

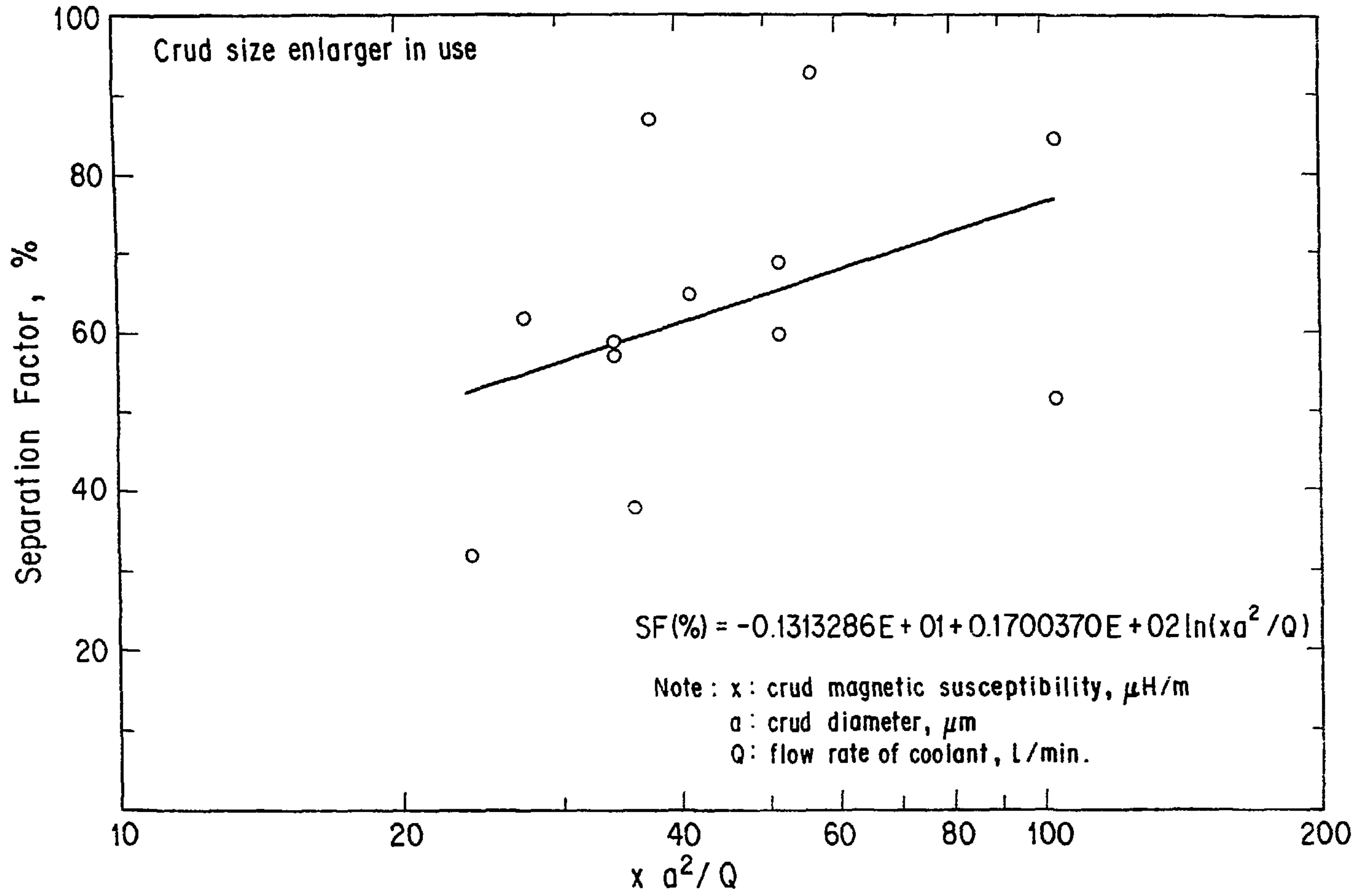

Fig. 10 Crud separator characteristics when crud size enlarger is in use. The best fitting line was derived by the least square method. See also Fig.11.

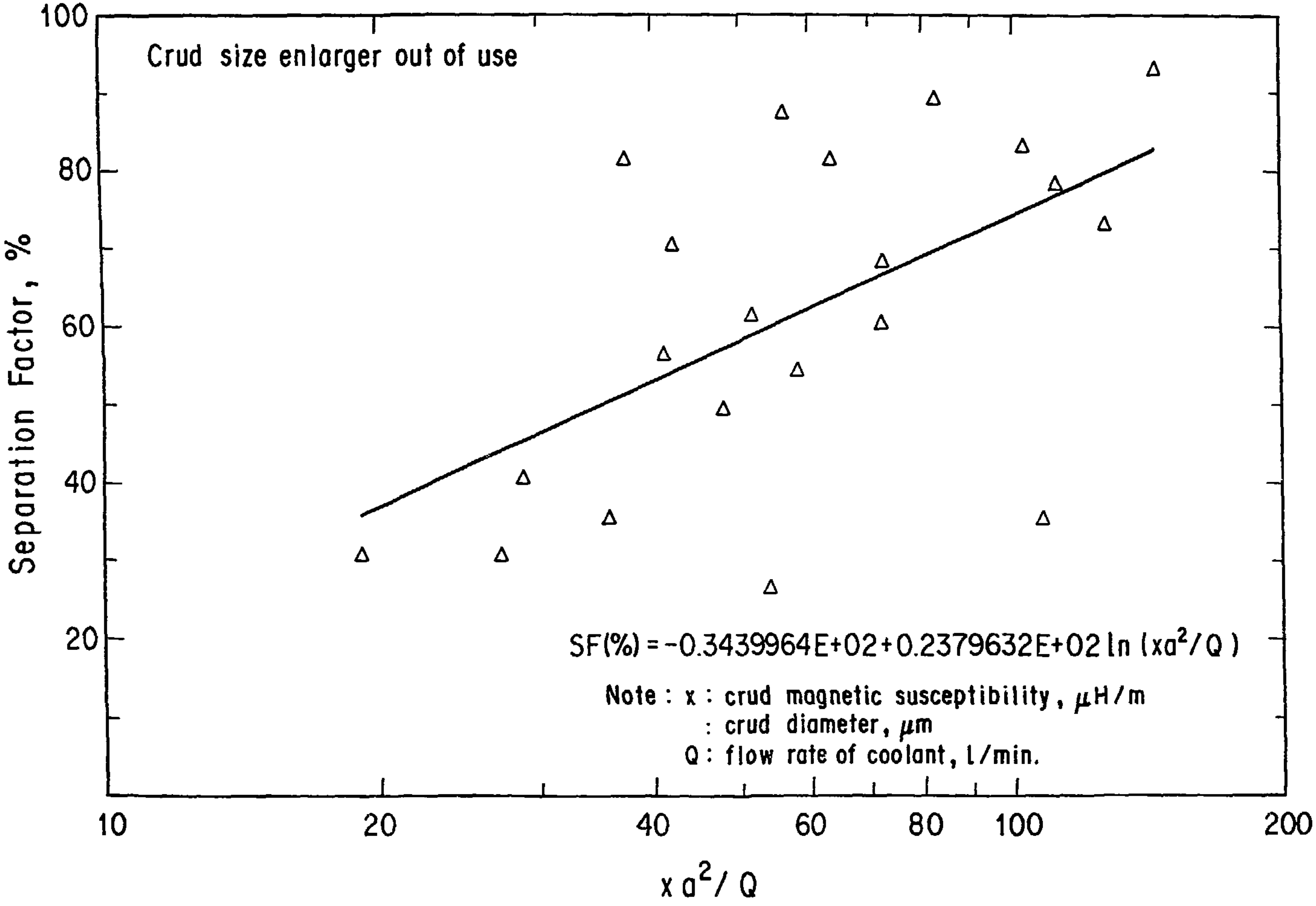

Fig. 11 Crud separator characteristics when crud size enlarger is out of use. As same as the relation shown in Fig. 10, separation factor tends to increase with increasing the parameter of $\chi a^2/Q$.

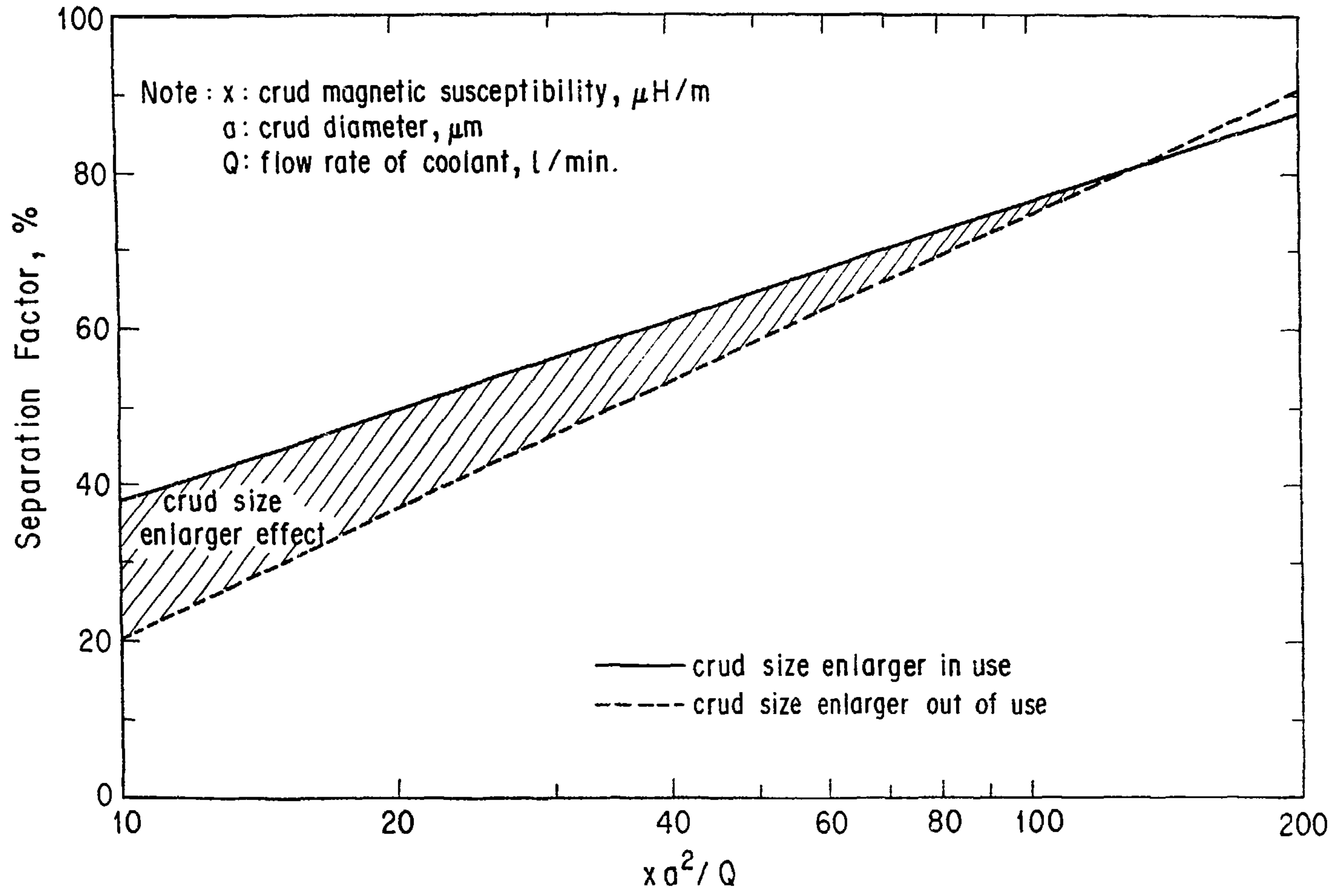

Fig. 12 Effect of crud size enlarger on separation factor. Higher gain of separation factor is expected in utilizing crud size enlarger when the parameter ($\chi a^2/Q$) has low value.