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# PULSE COLUMNS IN NUCLEAR FUEL REPROCESSING

## PART 1 – LITERATURE SURVEY

BY

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# PULSE COLUMNS IN NUCLEAR FUEL REPROCESSING

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### Abstract

A survey of relevant literature on the use of pulse columns for the reprocessing of irradiated nuclear fuel has been made. The effects of design and operating variables on flood point and mass transfer and the various methods of correlation are reviewed.

Recommendations are made for further work into some aspects of the design and use of pulse columns.

# CONTENTS

## 1. INTRODUCTION

A programme of investigation of possible solvent extraction methods for use in the reprocessing of HIFAR and other nuclear fuel elements, has been commenced.

Work has previously been done (1), (2), to develop a mixer settler unit suitable for use in the first cycle of reprocessing HIFAR fuel elements. This has enabled the behaviour of mixer settlers to be investigated and the necessary experience for the eventual design of mixer settler units for this or other reprocessing cycles to be obtained.

Since pulse columns offer some advantages over mixer settlers, especially in design for nuclear safety and mechanical simplicity, it was felt that the possibility of using pulse columns for reprocessing should also be investigated.

A literature search on pulse columns has been made covering the effect of design and operating variables on pulse column behaviour. Methods available for predicting this behaviour from a knowledge of the system are presented and recommendations have been made as to which aspects require further investigation.

## 2. EQUIPMENT

Pulse columns, as used in liquid–liquid extraction, normally contain either packing or sieve plates. Sieve plates are discs, containing holes to give a percentage free area, spaced regularly up the column. Packing is not so satisfactory as sieve plates since it tends to dump due to pulsing action. It can have a comparable efficiency to sieve plates but is generally less efficient. The capacity is not so great with packing as it is with sieve plates.

Expanded sections at the top and bottom of the column are often used to provide a relatively quiescent zone for phase disengagement.

Many different types of pulsing mechanism have been used (3), (6), (9), (18), (19), (20). The simplest and most common type is the mechanical pulser. With this system, the bottom of the column is connected to a valveless plunger or diaphragm pump. The motion of the pulser is approximately sinusoidal. Frequency may be varied by means of a gear unit and amplitude by stroke adjustment on the pump. Other mechanical methods, which have been used for pulse formation, are an eccentric operated diaphragm at the base of the column and a neoprene or stainless steel bellows actuated by a lever and cam.

Another more recent method for imparting the pulsation is the use of an air pulse. A dip pipe runs concentrically down the entire length of the column, the bottom end being open and the top end being connected to the pulsing unit. This is simply a cylinder closed by a reciprocating piston. The piston is driven by a double acting air motor using compressed air. During operation the air in the dip pipe transfers the motion of the piston to the main body of liquid in the column. Several modifications of this method have been developed and it has been shown to be applicable to columns up to 6 in. in diameter and 25 ft. high. The main advantage of the method is that the pulsed liquids do not come into contact with the pulsing mechanism, thus preventing its contamination.

A further method of pulse formation, developed mainly as a research tool, is the electronic pulse producer. The base of the column is closed by a flexible diaphragm, connected by means of a metal rod to an electromagnetic transducer. This is fed from an oscillator and power unit designed to give any desired wave form.

## 3. DESIGN VARIABLES

### 3.1 Column Height

The column height required for any given operation is determined by the number of transfer units required and the height of a transfer unit. Some effects due to diffusing component concentration have been noted (19). Height of transfer unit values appear to be higher at the dilute end of the column than at the concentrated end. H.T.U. values also tend to be higher in taller columns. This is believed to be due to increased channelling tendencies with increasing column height.

### 3.2 Column Diameter

Sege and Woodfield (19) found that limiting superficial velocities are not appreciably effected by column diameter. H.T.U. values did increase with column diameter and this was attributed to greater channelling tendencies. The only reported work carried out to evaluate the effect of diameter on column performance is given by Logsdail and Thornton (16). They found that diameter had little effect on flooding characteristics and suggested that this indicated that diameter had no effect on the mean droplet size. Columns could be scaled up geometrically as far as throughput was concerned.

Over the range of diameters studied,(3–12 inches), (H.T.U.) values were found to vary exponentially as $\frac{d_c}{2}$ , where $d_c$ is the column diameter measured in feet. It was considered that the scale up factor was principally due to maldistribution, since the mean droplet size and hence interfacial area of contact was unchanged. Further, since no maldistribution of the dispersed phase was observed, it was considered that the effect was due to backmixing of the continuous phase. Plate design to reduce this tendency has been carried out with some success.

### 3.3 Sieve Plate Form

Sieve plate design, and its effect on column performance has received attention from many investigators (5), (7), (8), (11), (12), (19), (21), (22), (23). Capacity and H.T.U. both increase with increasing hole size and percentage free area. 23% free area has been found to represent the best compromise between the requirements for high capacity and low H.T.U. Greater free area than this results in droplet coalescence on the top surface of the plates, giving a greater throughput at the expense of extraction efficiency. Geier (11), (12) has carried out the most extensive investigation of sieve plate forms. He found that plates with 1/8 inch diameter holes giving 23% free area were a good choice. He also used graded cartridges, in which the hole size was varied down the column length. For example, with the system water – uranyl nitrate – nitric acid, using T.B.P. as the extractant, extraction factors are such that most of the uranium extraction is near the top of the column, while nitric acid extraction occurs mainly near the base. It is found that the dispersion of droplets is coarse near the top, fine in the middle and coarse again near the base of the column. High rates of mass transfer are believed to stabilize large drops. Since flooding characteristics are determined by the region of fine dispersion, Geier devised the graded cartridge which tends to give a uniform dispersion. The method he used was to increase the hole size, free area and/or plate spacing in the region of low mass transfer. The method was quite successful, higher flooding capacities being achieved with mass transfer properties unchanged.

### 3.4 Plate Spacing

Increased plate spacing results in increased flooding capacity and H.T.U. values (7), (11), (12), (19). The best balance appears to be a spacing of about 2 inches for columns up to approximately 3 inches in diameter.

### 3.5 Pulse Amplitude and Frequency

Three distinct types of operation have been observed in pulsed columns (19), (21).

(i) Mixer–settler type operation occurs at low throughput rates and frequencies. The two phases separate into distinct layers above each plate. On the upstroke of the pulse, the light phase is forced through the perforations in the plates and rises in droplets through the heavy phase, and on the downstroke, the heavy phase is forced in a similar manner down through the light phase.

(ii) Emulsion type operation occurs at higher throughputs and frequencies. The dispersion is relatively uniform and the droplets are small. Little change in phase dispersion occurs during the pulse cycle. The small droplet size renders this the most efficient type of operation.

(iii) Unstable operation occurs at still higher frequencies. The column contains both large and small dispersed phase drops due to coalescence of some small droplets. This results in periodic phase reversals of the continuous phase in short sections of the column. Operation is unsteady and generally poorer than with emulsion type operation.

Figure 1 shows how the three types of operation are related to frequency and volume velocity. Volume velocity is defined as the total flow of both phases per unit area of column cross section. Similarly, the pulse volume velocity is defined as the total pulsed volume per unit time per unit area of column cross section. It can be seen by reference to this figure how the flooding capacity varies with the frequency. In the low pulse energy, or mixer–settler range, flooding capacity is equal to the pulse volume velocity. Capacity reaches a maximum in emulsion type operation and then drops off. At higher pulse frequencies as the operation becomes unstable, the capacity continues to decrease. In practice there is no distinct point of demarkation between the various regions.

Emulsion type operation is the only important type, and is the only one considered in the following discussion on extraction efficiency.

H.T.U. values generally decrease sharply with increasing amplitude frequency products until the onset of unstable operation, when they show a slight increase. The shapes of H.T.U. versus amplitude–frequency product curves vary with system and plate design but are normally convex downward. Some typical curves are shown in Figure 2. Griffith, Jasney and Tupper (13) found the overall H.T.U. to be inversely proportional to the frequency and amplitude at low values of these two factors and directly proportional to the frequency at high values. Other workers (3), (5), (6), (9), (10), (11), (17), (18), (19), (20) have also found relationships between the frequency amplitude product and column performance but the correlations are only applicable to the particular system studied.

### 3.6 Pulse Wave Form

The effect of wave form has been thoroughly investigated by Thornton (22). It has been found to have little effect on column performance except for the manner in which it influences the frictional power dissipated in the perforations of the sieve plates.

## 4. OPERATING VARIABLES

### 4.1 Flow Rate

The flow rates of the two phases have a rather complex and interrelated effect on the flooding point and extraction efficiency of a pulse column.

#### 4.1.1 Effect on Flooding Point

At any fixed continuous phase flow rate, increasing the dispersed phase flow rate will eventually result in flooding of the column. The holdup of dispersed phase increases as the dispersed phase flow rate increases. The flow ratio has been found to exert considerable effect on the total flooding acpacity. Swift (21) has carried out quite an extensive study of this aspect. He showed that for a given frequency amplitude product, the total volume flow of both phases at the point of flooding increased as the ratio of continuous to dispersed phase increased. As this ratio approaches infinity the total flow rate at flooding also approaches infinity as the flow of continuous phase is only determined by pressure drop requirements. On the other hand, as the flow rate of continuous phase approaches zero, the total flow rate at flooding becomes entirely a function of the dispersed phase flow rate, which is limited by the rate of passage of dispersed phase droplets.

At the flooding point there is a definite relationship between the flow rates of continuous and dispersed phases which results in a straight line plot of $(V_c)^{1/2}$ against $(V_d)^{1/2}$ at values of $(V_c/V_d) < 2$.

At low values of $(V_c/V_d)$ flooding takes place over the entire length of the column simultaneously or from the dispersed phase outlet back through the column while at high values, flooding occurs due to removal of small drops to the dispersed phase inlet end.

The flood point is very sensitive to variations in either phase flow rate, since altering one phase flow rate changes the value of the flow ratio, thus effecting the total possible flow before flooding.

Thornton, Pratt and others (22), (23) have shown that the effect of the two flow rates on flood point can be combined into what they call "the characteristic droplet velocity". This is determined only by the volume velocities of the continuous and dispersed phases and the percentage holdup of dispersed phase. At the flood point holdup is a maximum for the particular continuous phase flow rate, which enables it to be calculated simply from a knowledge of $V_c$ and $V_d$ at flooding. The effect of the two flow rates can be included in a correlation by means of a single variable.

Unfortunately, all the work mentioned above applies only to systems containing no solute. As soon as extraction starts to take place, all the correlations become invalid although the general principles remain unaltered.

### 4.1.2 Effect on Mass Transfer

Many workers have considered (H.T.U.) to be a function of the total flow rate of both phases. Plotting extraction efficiency against the total flow rate of both phases generally results in curves with highest efficiency as a value between 75% and 95% of the value at flooding.

Other workers have shown (H.T.U.) to be dependent on a power of the flow ratio. At high pulse frequency, the data appear to be a unique function of the flow ratio regardless of the actual values of the individual flow rates, while at lower frequency separate straight line relationships between $(H.T.U.)_o$ and flow ratio are obtained for different flow rate values.

Thornton has shown that extraction efficiency is a function not only of the flow rates and ratios, but also of the characteristic droplet velocity, and has developed a correlation on this basis.

### 4.2 Choice of Continuous Phase

Most reported work has been carried out with an aqueous continuous phase, and very few investigators have interested themselves in the effects of changing the continuous phase. Durandet et al carried out work using an aqueous solution of uranyl nitrate in nitric acid as one phase and a solution of tri-butyl phosphate in kerosene as the other. They investigated the effect of the choice of continuous phase on the extraction of uranium and found that they could not achieve as high an extraction efficiency with the aqueous phase dispersed as they were able to with the organic phase dispersed. Flooding capacity was also considerably reduced. They used stainless steel plates in all experiments.

Geier, (11), (12), has studied this effect more fully, using both stainless steel plates, which are wet preferentially by the aqueous phase, and teflon plates which are wet preferentially by the organic phase. As a result, he found that flooding capacity and extraction efficiency were greatly reduced when the continuous phase did not wet the plates. Capacity was nearly identical when the aqueous phase was continuous using stainless steel plates, and when the organic phase was continuous using teflon plates. The maximum extraction efficiencies in the two cases also appeared to be comparable but when the organic phase was continuous, using the teflon plates, column efficiency was found to be less sensitive to changes in flow rate, indicating that this choice may be more desirable from the point of view of the higher rangeability.

### 4.3 Physical Properties

The physical properties which have a bearing on column behaviour are density, viscosity and interfacial tension. Most work has been carried out with pulse columns using two definite phases of fixed physical properties for all experiments. Any relationships found in these investigations are, therefore, only applicable to the particular system used.

Geier states that flooding capacity has been shown to be approximately proportional to 0.7 power of the density difference, 0.4 power of the interfacial tension and the minus 0.3 power of the continuous phase viscosity.

In their recent work, Thornton, Pratt et al have incorporated the relevant physical properties with all the other design and operating variables into a correlation obtained in its general form by dimensional analysis. The powers of the various groups in this function have then been evaluated by experimental work using a number of different phase combinations.

### 4.4 Temperature

H.T.U. values have been found to decrease with increased temperature to a much greater extent than would be predicted due to equilibrium shift (4). In fact, in some cases, increased extraction efficiency has been achieved even when an adverse equilibrium shift has accompanied the increased temperature. This is probably due to changes in viscosity, interfacial tension and resistance to mass transfer.

## 5 CORRELATION METHODS

### 5.1 Flood Point

As previously stated, most work has been carried out using specific solutions and correlations apply only for the particular system used in a particular column. Practically all the investigators have given plots relating the flood point to frequency and amplitude, and have shown the effect of the individual flow rates and the flow ratio on the flood point. Very few have actually attempted to correlate the data. Even those who have attempted a correlation have been able to do this only in the absence of a distributed solute and in the case when each phase is mutually saturated with the other.

Swift (21) has given one such correlation which relates the effect of cartridge geometry, pulse characteristics and volume flow variables in the region of emulsion type flooding for a non-coalescent system. The equation is empirical and does not include the physical properties of the system used. The effect of these properties appears in the two constants used. The correlation is:

$$\mathrm{Log}\left(\frac{(U_c + U_d)\ F^{0.34}\ C_1}{d^{0.64}}\right) \cdot \mathrm{exp.}\left(C_2\ \frac{f.a.d.^{0.28}}{1^{0.32}\ F^{0.82}}\right) = \phi\,\frac{U_c}{U_d}$$

At a constant flow ratio, this reduces to

$$\mathrm{Log}\left(\frac{(U_c + U_d)\ F^{0.34}}{d^{0.64}}\right) = C_1 - C_2\ \frac{f.a.d.^{0.28}}{1^{0.32}\ F^{0.82}}$$

To use this correlation for predicting flooding behaviour, two runs have to be made, after which the whole flooding curve can be established.

The nomenclature used by Swift is:

| | |
|---|---|
| a | pulse amplitude (inches) |
| d | perforation hole diameter (inches) |

| | |
|---|---|
| F | fraction open area |
| f | pulse frequency (cycles/minute) |
| l | plate spacing (inches) |
| U | Volume flow rate, based on overall column cross section (gals/(hr) (sq.ft.) |

Subscripts

| | |
|---|---|
| c | continuous phase |
| d | dispersed phase |

Thornton (22), in his correlation, has included all design and operating variables in combination with the "characteristic droplet velocity", which is given by:

$$\frac{V_d}{x} + \frac{V_c}{1-x} = \bar{V}_o \;(1-x) \tag{1}$$

The flow rates at the flood point can be determined by differentiating (1) with respect to x and setting the differentials equal to zero.

$$V_{d(f)} = 2\,\bar{V}_o x_f{}^2 (1-x_f) \quad \text{when} \quad \frac{(dV_c)}{(dx)} = 0$$

$$V_{c(f)} = \bar{V}_o \;(1-x_f)^2 \;(1-2x_f) \quad \text{when} \quad \frac{(d\,V_d)}{(dx)} = 0$$

whence:

$$x_f = \frac{(L_r{}^2 + 8L_r)^{1/2} - 3L_r}{4(1-L_r)} \quad \text{where } L_r = \frac{V_{d(f)}}{V_{c(f)}}$$

$x_f$ can thus be determined from the flow rates at flood point and $\bar{V}_o$ determined from a plot of $V_{d(f)}$ versus $x_f{}^2(1-x_f)$.

By dimensional analysis, the general form of the correlation was established and the powers were evaluated by experimental work with six solvent water systems containing no distributed solute. The final form of the correlation was:

$$\left(\frac{\bar{V}_o \mu_c}{\gamma}\right) = 0.60 \left(\frac{\psi_f \mu_c^5 \; g_c}{\rho_c \gamma^4}\right)^{-0.24} \left(\frac{d_o \rho_c \gamma}{\mu_c{}^2}\right)^{0.90} \left(\frac{\mu_c{}^4 g}{\Delta \rho \gamma^3}\right)^{1.10} \left(\frac{\Delta \rho}{\rho_c}\right)^{1.80} \left(\frac{\mu_d}{\mu_c}\right)^{0.30}$$

Thus a knowledge of all the design and operating variables enables the characteristic velocity at flood point to be found and hence the holdup and flow rate of dispersed phase for a given continuous phase flow rate. The nomenclature used by Thornton is given in Appendix I.

### 5.2 Mass Transfer

Mass transfer behaviour is effected by changes in any of the operating and design variables. Practically all the work done has been carried out with most of the variables held constant. In general only the effect of flow rates, with all the other variables held constant have been correlated. Consequently, there are limitations on the application of the correlations so developed. Some of the more recent correlations are given below.

(i) Rubin and Lehman used the systems water – uranyl nitrate – cyclohexane and water – uranyl nitrate – pentaether in a ½ in. diameter column 3 ft. long with teflon plates. They agreed with other workers that $(H.T.U.)_{o.d.}$ is relatively constant with respect to flow rate but concluded that $(H.T.U.)_{o.c.}$ was a function of the individual flow rates rather than the flow ratio. This led to their H.T.U. – surface concept in which $(H.T.U.)_{o.c.}$ was plotted in three dimensions with $(H.T.U.)_{o.c.}$ on one axis, the flow rate of one phase on a second axis, and the reciprocal of the flow rate of the other phase on the third axis. Their correlations were:

$$(H.T.U.)_{o.d.} = \gamma$$

$$(H.T.U.)_{o.c.} = \alpha\ G + \beta \frac{G}{L}$$

By mathematical manipulation, they derived expressions for individual H.T.U. values.

$$(H.T.U.)_{d.} = \gamma'$$

$$(H.T.U.)_{c.} = \alpha\ G$$

Where $\alpha$, $\beta$, $\gamma$, $\gamma'$ are constants

G = the flow rate of continuous (organic) phase

L = the flow rate of dispersed (aqueous) phase

$(H.T.U.)_{o.c.}$ = Overall height of a transfer unit based on the continuous phase.

$(H.T.U.)_{o.d.}$ = Overall height of a transfer unit based on the dispersed phase.

$(H.T.U.)_{c.}$ = Individual height of a transfer unit for continuous phase.

$(H.T.U.)_{d.}$ = Individual height of a transfer unit for dispersed phase.

(ii) Lehman later used trace concentrations of plutonium between aqueous nitric acid and thenoyltrifluoroacetone (T.T.A.) solvent to obtain individual H.T.U. values by varying the distribution coefficient, using the following relationships:

$$(H.T.U.)_{o.c.} \doteq (H.T.U.)_{c.} + \frac{mG}{L} (H.T.U.)_{d.}$$

$$(H.T.U.)_{o.d.} = (H.T.U.)_{d.} + \frac{L}{mG} (H.T.U.)_{c.}$$

Where m is the distribution coefficient.

No general correlations of individual H.T.U. were made but the overall (H.T.U.) values were correlated by the (H.T.U.) surface concept mentioned above.

(iii) Cohen and Beyer, using the system isoamyl alcohol – boric acid – water in a 1 in. diameter column, 20 in. tall found that at a given pulse amplitude and frequency, the effect of flow rates on overall H.T.U. was correlated by

$$(\text{H.T.U.})_{\text{o.c.}} = \propto \frac{G^{0.39}}{L}$$

(iv) A number of other workers have shown the effect of the frequency amplitude product and developed empirical correlations relating this to (H.T.U.) and H.E.T.S. with all other variables fixed.

(v) Thornton et al are the only investigators who have attempted to develop a general correlation relating (H.T.U.) values to all the possible system variables. The correlation requires that at least two experimental runs be carried out on model tests to determine the two constants before extraction behaviour over the whole range of full scale operation can be predicted.

It is interesting, since this is the most complete investigation yet carried out on extraction in pulse columns, to trace the method used by Thornton to develop his correlation. Mass transfer data were correlated in terms of the overall (H.T.U.), based on the continuous phase.

This is defined as:

$$(\text{H.T.U.})_{\text{o.c.}} = \frac{V_c}{K_{\text{o.c.}}a} \tag{1}$$

If the droplets can be assumed to be spherical,

$$a = \frac{6x}{d_{vs}} \tag{2}$$

Hence

$$\frac{(\text{H.T.U.})_{\text{o.c.}}\,x}{V_c} = \frac{d_{vs}}{6K_{\text{o.c.}}} \tag{3}$$

Theoretically, it should be possible to correlate the mass transfer data by means of equation (3), but since determinations of $d_{vs}$ and $K_{\text{o.c.}}$ were not made directly, it was necessary to relate these variables to the physical properties of the system. Visual observations showed that the droplet size was in the region where the drag coefficient for solid spheres is approximately proportional to $(Re)^{-0.5}$, and hence from the usual drag coefficient – Reynolds number relationship it was shown that:

$$d_{vs} \propto \left(\frac{\mu_c^2}{g\rho_c^2}\right)^{1/3} \left(\frac{\rho_c}{\Delta\rho}\right)^{2/3} \left(\frac{\bar{V}_o^3\,(1-x)^3\,\rho_c}{g\mu_c}\right)^{1/3} \tag{4}$$

Also, in single droplet experiments it has been shown that mass transfer data for a given system can be correlated by a simple plot of the modified Stanton number against Reynolds number giving an expression of the form:

$$\frac{K_{\text{o.c.}}}{\bar{v}_r} \propto \left(\frac{d_{vs}\,\bar{v}_r\,\rho_c}{\mu_c}\right)^m \tag{5}$$

where $\bar{v}_r$ is the velocity of droplets relative to the continuous phase.

By substituting equations (4) and (5) in equation (3)

$$\frac{(\text{H.T.U.})_{o.c.}}{(\mu_c{}^2/g\rho_c{}^2)^{1/3}} \propto \left(\frac{\mu_c g}{\bar{V}_o{}^3(1-x)^3\rho_c}\right)^{2m/3} \left(\frac{\Delta\rho}{\rho_c}\right)^{\frac{2(m-1)}{3}} \left(\frac{V_c{}^3\rho_c}{g\mu_c x^3}\right)^{1/3}$$

The plotting of experimental data in accordance with this equation showed a significant drift of points of varying flow ratio. This was corrected by introducing the term $\left(\frac{V_d}{V_c}\right)^{0.5}$ to the right hand of the equation on a purely empirical basis. It was believed that longitudinal mixing in the continuous phase was the cause of this drift.

The final form of the correlation was:

$$\frac{(\text{H.T.U.})_{o.c.}}{(\mu_c{}^2/g\rho_c{}^2)^{1/3}} = K\left(\frac{\mu_c g}{\bar{V}_o{}^3(1-x)^3\rho_c}\right)^{2m/3} \left(\frac{\Delta\rho}{\rho_c}\right)^{\frac{2(m-1)}{3}} \left(\frac{V_c{}^3\rho_c}{g\mu_c x^3}\right)^{\frac{1}{3}} \left(\frac{V_d}{V_c}\right)^{0.5}$$

## 6. CONCLUSIONS AND RECOMMENDATIONS

It is apparent from the search which has been carried out that the design variables have been quite fully investigated. Of the operating variables, most attention has been paid to the effect of the flow rates. Flood point correlations are limited strictly to systems where no mass transfer is occurring and flood point data relating to systems in which mass transfer is occurring are very limited. The only comprehensive work reported on the choice of continuous phase has been done by Geier, and even this is limited. The effect of the physical properties of the feed solutions has received limited attention and the ranges of investigation are small.

With relation to physical properties, those of particular interest in the reprocessing of HIFAR type fuel elements are viscosity and density. It is anticipated that the feed solution will be a basic aluminium nitrate containing the uranium and fission products as nitrates. The viscosity of this solution may range up to 10 centipoises and the density to 1.4 g/ml. In such a system, it seems probable that the choice of continuous phase may have a considerable effect on column behaviour. Due to the lack of information on such a system and the possibility that it may need to be handled, it is proposed that a pulse column be set up to study the behaviour of simulated HIFAR fuel element solutions over a range of densities and viscosities and with either phase continuous.

## 7. NOMENCLATURE

| | |
|---|---|
| a | Superficial area of contact of phases (ft.$^2$/ft.$^3$) |
| $d_{vs}$ | Mean volume – surface diameter of droplets (ft.) |
| K | Constant |
| $K_o$ | Overall mass transfer coefficient (ft./hr.) |
| V | Superficial velocity of phase in column (ft./hr.) |
| $\bar{V}_o$ | Characteristic droplet velocity (ft./hr.) |
| $\bar{v}_r$ | Mean droplet velocity relative to the continuous phase (ft./hr.) |
| x | Fractional holdup |
| $\gamma$ | Interfacial tension (lb./hr.$^2$) |

| | |
|---|---|
| $\mu$ | Viscosity (lb./ft.hr.) |
| $\rho$ | Density (lb./ft.$^3$) |
| $\psi_f$ | Frictional power absorbed per unit mass of fluid in the perforations in the sieve plates. (ft.$^2$/hr.$^3$). |

Subscripts

| | |
|---|---|
| c | Continuous phase |
| d | Dispersed phase |
| f | Value at floodpoint |
| m | Mean value |

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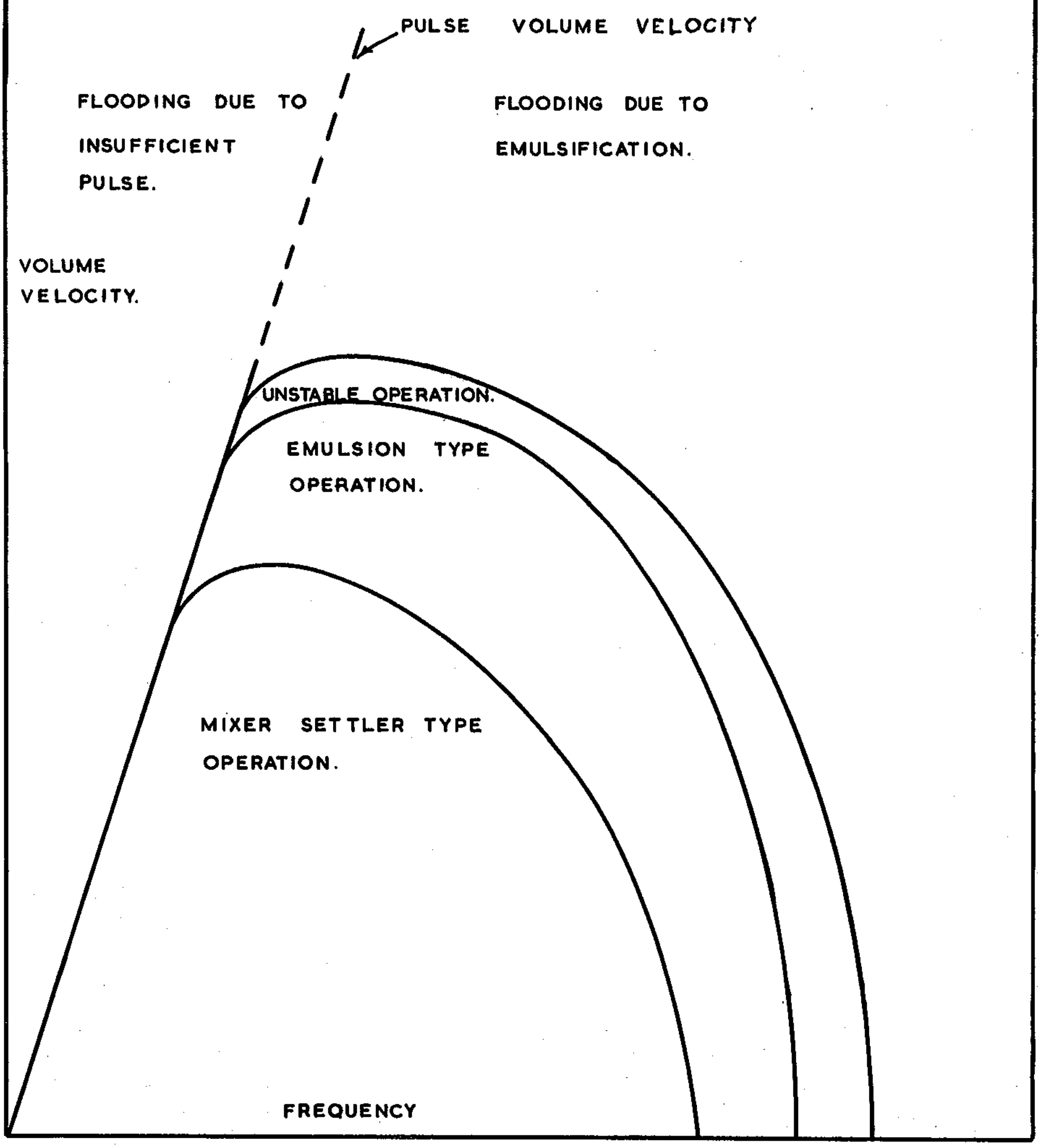
**FIGURE 1.**

REGIONS OF PULSE COLUMN OPERATION.



AMPLITUDE = CONSTANT

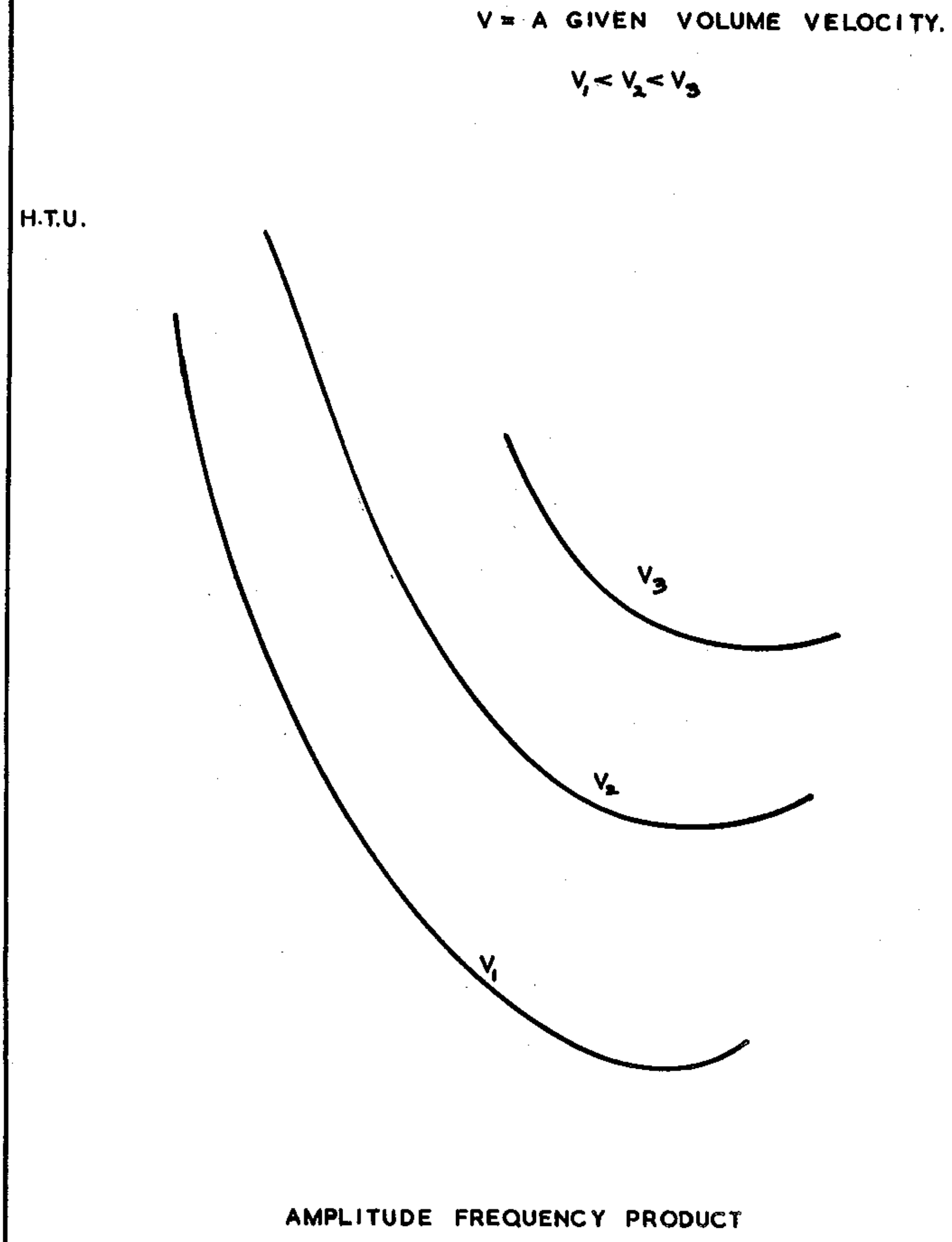


FIGURE 2.

H.T.U. AS A FUNCTION OF AMPLITUDE FREQUENCY PRODUCT.