A Simulation Study on The Operation of Laboratory Scale Anaerobic Digesters

GEOFFREY S. HANSFORD
Department of Chemical Engineering, University of Cape Town, Rondebosch 7700

Abstract

This paper reports results of simulation studies of the operation of laboratory scale anaerobic digesters at constant sludge age and at constant sludge concentration. This method of operation permits the determination of the kinetic parameters in a much shorter period of time than is required when the experimental system is operated at constant sludge age. The simulation studies show that at constant sludge age the response of the system to changes in the operating conditions is very slow, of the order of three to five times the sludge age. For anaerobic digestion this is so long as to make it impractical for experimental purposes. On the other hand under conditions of operation at constant sludge concentration, the response time is short, being of the order of the hydraulic residence time. The results of these simulation studies confirm earlier experimental observations and suggest that operation at constant sludge concentration is a valuable technique to expedite the measurement of kinetic constants for anaerobic digestion.

Nomenclature

F	feed rate	ℓ/d
k_D	decay constant	d^{-1}
K_SS	saturation constant	mg COD/ℓ
S	substrate concentration	mg COD/ℓ
S_I	feed substrate concentration	mg COD/ℓ
t	time	d
V	digester volume	ℓ
W	sludge wastage rate	ℓ/d
X	sludge concentration	mg VSS/ℓ
Y	yield constant	mg VSS/mg COD
μ	specific growth rate	d^{-1}
μ_M	maximum specific growth rate	d^{-1}
τ_H	hydraulic residence time	d
τ_S	sludge age	d

Introduction and Background

The kinetic parameters for the design of both aerobic and anaerobic sludge digester systems can be obtained from the operation of laboratory scale apparatus. This is achieved by operating the laboratory digesters at the design loading rate and feed strength and varying the sludge age so as to produce effluents of differing quality. From the well-known plots of: $\frac{S_I - S}{X \tau_H}$ versus $1/\tau_s$, and $\frac{\tau_s}{1 - \tau_s k_D}$ versus l/S, the four kinetic parameters: maximum growth rate, μ_M; saturation constant, K_S; yield, Y; and decay constant, k_D can be evaluated (Hansford and Richter, 1975). Normal experimental operation is to set the sludge age and allow the system to reach steady state. After the data have been recorded a new sludge age is set. Usually a period between three and five sludge ages is allowed to elapse before the next steady state is expected. This is in accordance with process dynamics theory for first order systems subjected to a step change in input, and regarding the sludge age as the characteristic time of the system. The above operating procedure is adopted widely for aerobic systems where sludge ages rarely exceed ten days. However, for anaerobic systems with sludge ages of a minimum of ten days and more likely about thirty days up to one hundred days the above method of operation requires periods of several months between strictly valid steady state readings.

As such long periods of operation are impractical for experimental purposes, another method has been investigated experimentally and by means of digital computer simulation. The method involved variation of the loading rate and attempting to maintain a constant sludge concentration by varying the sludge age i.e. the amount of sludge removed daily.

Because the sludge concentration is maintained constant by varying the sludge removal rate a new steady state would be achieved as soon as the effluent COD concentration reached a steady value. This would occur in a time scale related to the hydraulic residence time. Under these circumstances the response of the system would be more closely related to the hydraulic residence time, τ_H, rather than the sludge age, τ_S. For anaerobic systems this would mean the attainment of new steady states within 10 to 15 days following a step change in feed conditions and would permit kinetic data to be obtained within a reasonable time period. Using computer simulation, Curds (1973) has compared the stability of aerobic digesters operating at constant sludge age with those at constant sludge concentration. He found that those operated at constant sludge concentration gave more consistent effluent quality when subjected to sinusoidal loading. He also claimed that sewage plant operation at constant sludge concentration gave better operation.

Materials and Methods

The operating method described above was tested during the course of an experimental investigation on the anaerobic digestion of yeast factory effluent. The experimental apparatus and procedures are fully described elsewhere by Hansford and Richter (1975) and will only be summarized here.

The digesters consisted of a well mixed section separated from a quiescent settling section by a slanted moveable baffle, as shown in Figure 1. This is an adaptation of the laboratory activated sludge units described by Ford (1969). The units were made air-tight by means of a lid with O-ring seals. Agitation is by means of gas recirculation. The system was operated by withdrawing sludge daily in quantities such that the sludge concentration was forced to a constant value. Conditions were varied by operating the systems at different feed strengths and feed

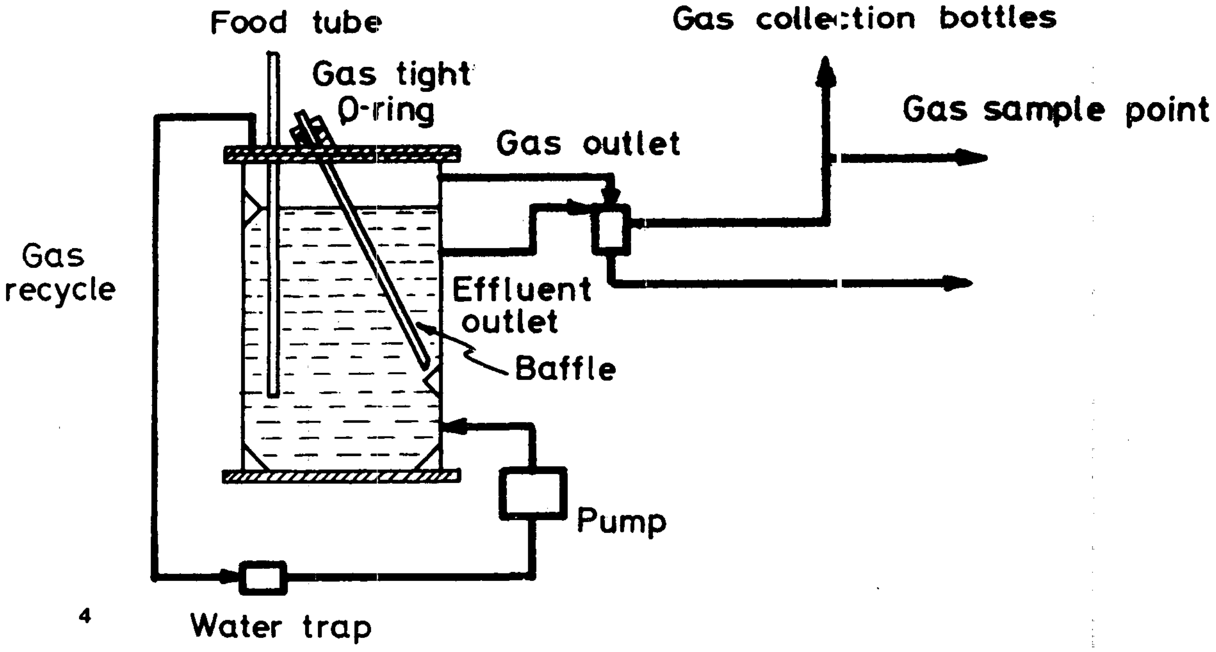

Figure 1
The Laboratory Anaerobic Digester

rates. Steady state was assumed to have been obtained when the following criteria remained constant for several days: effluent COD, gas production, and CO_2/CH_4 ratio with constant sludge removal rate required to keep the sludge concentration constant. Some typical operating conditions are shown in Table 1.

TABLE 1
TYPICAL OPERATING CONDITIONS

τ_H day	τ_s day	S_I mg COD/ℓ	S mg COD/ℓ	X mg VSS/ℓ
1,7	104	7 000	2 600	13 000
	56	10 000	3 500	13 000
	26	19 000	6 300	13 000
3,5	65	13 000	4 000	13 500
	54	16 000	4 700	13 500
	46	19 000	6 900	13 500

In going from one steady state to another, the inlet substrate concentration was changed gradually from one level to the next following a ramp function over ten days. Figure 2 shows the response of the laboratory digester to such a change from a feed strength of 7 000 to 10 000 at a τ_H of 1,70 days. In order to maintain a constant cell concentration the sludge age had to be lowered from 104 to 56 days. As can be seen, the gas production

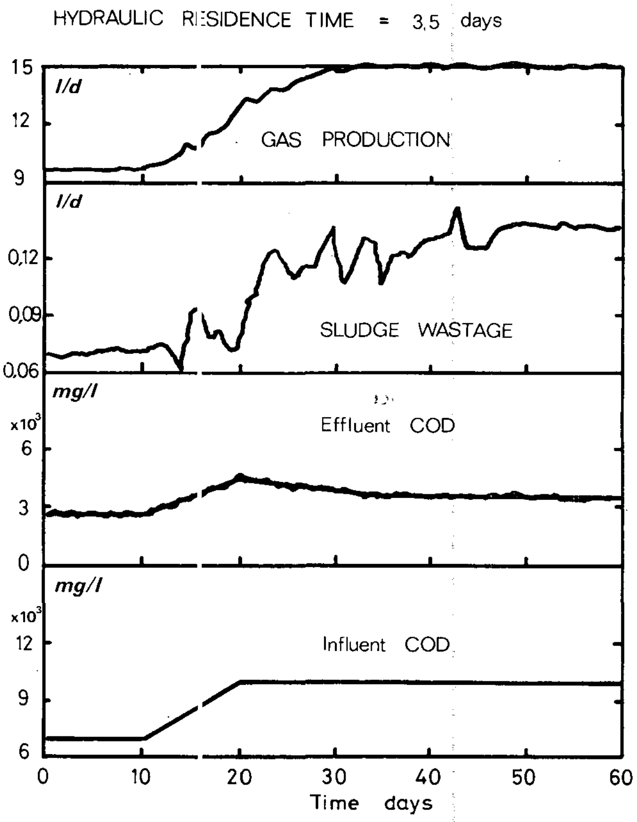

Figure 2
Experimental Response to a Ramp Change in Feed Strength from 7 000 to 10 000 mg COD/ℓ at a constant X of 13 000 mg MLSS and a hydraulic residence time, T_H, of 3,5 days

stabilized within about 12 days and the sludge wastage rate had stabilized at its new value within 27 days. All quantities remained constant thereafter. The response was typical of that which accompanied each change of loading rate with the qualification that the time to stabilize appeared to be proportional to the hydraulic residence time.

Theory

In order to test the validity and applicability of this method of operation, computer simulation studies were carried out. For this purpose an adaptation of the IBM 1130 CSMP, Continuous System Modelling Program, for use on the Univac 1108 was used.

As was reported by Hansford and Richter (1975) this method has been used successfully to obtain data on anaerobic digestion which could be used to determine kinetic constants for the system. The simulation studies reported here show that the rapid attainment of steady state conditions under this method of operation can be predicted using a simple kinetic model for the system.

Consider a digester, as shown in Figure 3, of volume, V, fed at rate F with feed of strength S_I. The sludge wastage rate, W, is adjusted to keep the sludge concentration constant.

As the main objective was to show, in principle, that operation at constant sludge concentration rather than constant sludge age allows more rapid attainment of steady state, a simple model was used to describe the biological kinetics. Inclusion of terms to account for endogenous respiration or substrate inhibition will not alter the validity of the assumptions drawn.

The material balances for sludge and substrate are as follows:

$$V\frac{dX}{dt} = \mu VX - WX \tag{1}$$

$$V\frac{ds}{dt} = F(S_I - S) - \frac{\mu VX}{Y} \tag{2}$$

where

F = feed rate
S = substrate concentration in digester
S_I = substrate concentration in feed
V = volume of digester
X = sludge concentration in digester
Y = yield constant
t = time
μ = growth rate

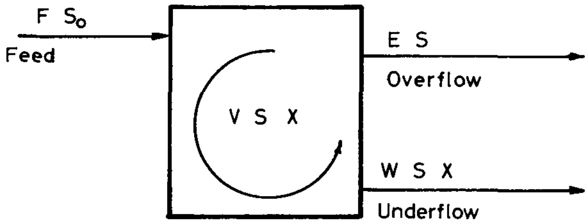

Figure 3
A Diagrammatic Representation of the Anaerobic Digester

From the Monod equation the growth rate can be calculated in terms of the substrate as follows:

$$\mu = \frac{\mu_M S}{K_S + S} \tag{3}$$

where μ_M = maximum growth rate
and K_S = saturation constant

Defining the sludge age,

$$\tau_S = \frac{VX}{WX} \tag{4}$$

and the hydraulic retention time

$$\tau_H = \frac{V}{F} \tag{5}$$

equations (1) and (2) can be written as:

$$\frac{dX}{dt} = \mu X - \frac{X}{\tau_S} \tag{6}$$

$$\text{and} \quad \frac{dS}{dt} = \frac{1}{\tau_H}(S_I - S)\frac{X}{\tau_s Y} \tag{7}$$

Equations (3), (6) and (7) are used to draw up the block diagrams for the CSMP simulation. Operation at constant sludge concentration is performed by setting $\frac{dx}{dt} = 0$ so that equation (6) gives $\mu = \frac{1}{\tau_s}$. For comparison a simulation was also carried out with τ_s set constant.

Results and Discussion

A set of simulations were carried out at the following initial conditions: Feed concentration, S_I = 20 000 mg/ℓ; hydraulic residence time, τ_H = 2,0 days; sludge age, τ_s = 30 days, which gives a sludge concentration, X, of 14 600 mg/ℓ and an effluent quality, S, of 560 mg COD/ℓ. Simulation runs at constant τ_s and at constant X each showed that these steady values were maintained.

The response to a 50 percent increase in feed strength (20 000 to 30 000 mg COD/ℓ) was then simulated. For the digester operated at constant sludge age, the new steady state was reached after 300 days (i.e. 10 times τ_s) while for the digester operated at constant sludge concentration, the new steady state was reached after 1,1 days (i.e. 0,55 times τ_H). The 99 percent levels of recovery were attained after 145 days (*ca* $5\tau_s$) and 0,32 days respectively. The results of these simulations are shown in Figures 4, 5 and 6.

Figure 4 shows operation under constant sludge concentration leads to a steady and rapid response in the effluent COD concentration to the new steady state value in 1,1 days which is of the same order of magnitude as the hydraulic residence time. This is as expected because no change occurs in the concentration of the slow growing sludge and theoretically the Monod equation predicts an immediate response in sludge growth rate and substrate utilization rate. Experimentally one might expect a somewhat slower response due to lags within the biological system.

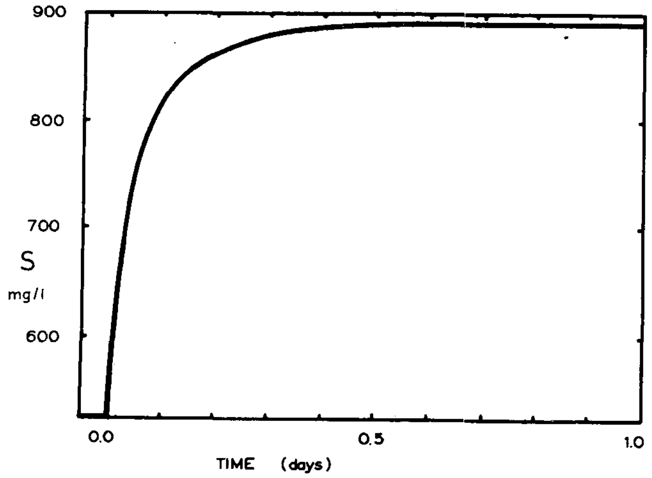

Figure 4
Simulated Response of Effluent Concentration to a Step Change in Feed Strength from 20 000 to 30 000 mg COD/ℓ at a constant sludge concentration of 14 600 mg/ℓ (τ_H = 2,0 d, μ_M = 0,33 d^{-1}, K_s = 5 000 mg/ℓ, Y = 0,05)

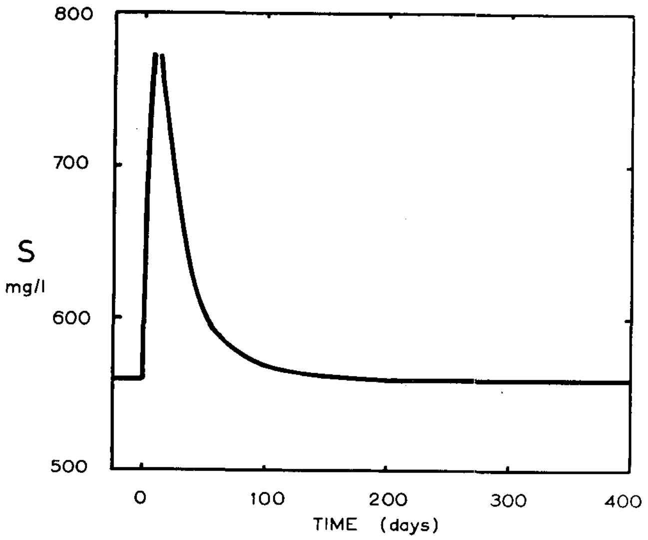

Figure 5
Simulated Response of Effluent Concentration to a Step Change in Feed Strength from 20 000 to 30 000 mg COD/ℓ at a constant sludge age of 30 days (τ_H = 2,0 d, μ_M = 0,33 d^{-1}, K_s = 5 000 mg/ℓ, Y = 0,05)

In contrast, Figure 5 shows that operation under constant sludge age leads to a very much slower response to the step change in feed concentration. The effluent COD concentration rises steeply over the first ten after the step change and then as the sludge concentration begins to increase the effluent COD concentration decreases slowly to the new steady state value in a time of the same order of magnitude as the sludge age τ_s = 30 days.

A further set of simulations was run at a hydraulic residence time of four days. At constant sludge age the new steady state was again attained after 300 days, 99 percent after 145 days, while at constant sludge concentration the new steady state was attained after 2,1 days (i.e. 0,525 τ_H).

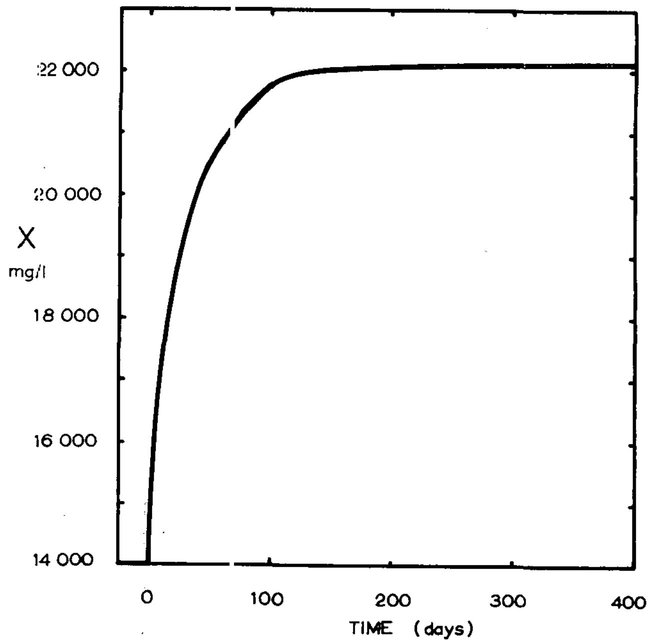

Figure 6
Simulated Response of Sludge Concentration to Step Change in Feed Strength from 20 000 to 30 000 mg COD/ℓ at a constant sludge age of 30 days (τ_H = 2,0 d, μ_M = 0,33 d^{-1}, K_s = 5 000 mg/ℓ, Y = 0,05)

A third set of simulations was carried out at operating conditions reported by Hansford and Richter (1975) and using the experimentally determined kinetic parameters *viz:* μ_M = 0,084 day^{-1}, K_s = 3 100 mg COD/ℓ, Y = 0,073. The simulated system was subjected to a step change increase in feed strength of 43 percent (7 000 to 10 000 COD) while operation at a sludge age of 104 days and an hydraulic retention time of 1,70 days. The results, shown in Figures 7, 8 and 9 once again indicate a much more rapid response when operated under conditions of constant sludge concentration.

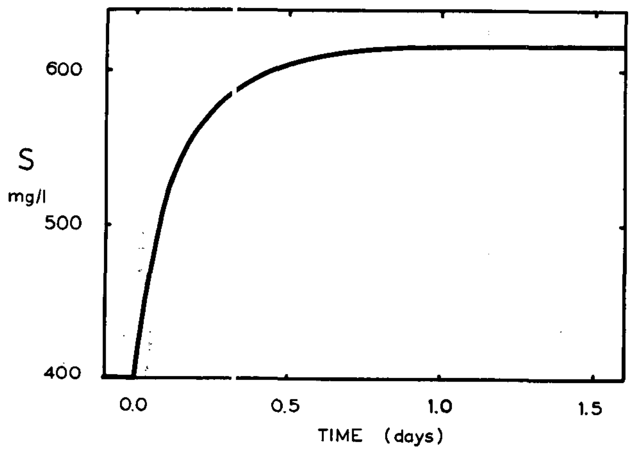

Figure 7
Simulated Response of Effluent Strength to a Step Change in Feed Strength from 7 000 to 10 000 mg COD/ℓ at a constant sludge concentration of 29 000 mg/ℓ (τ_H = 1,70 d, μ_M = 0,084 d^{-1}, K_s = 3 100 mg/ℓ, Y = 0,073)

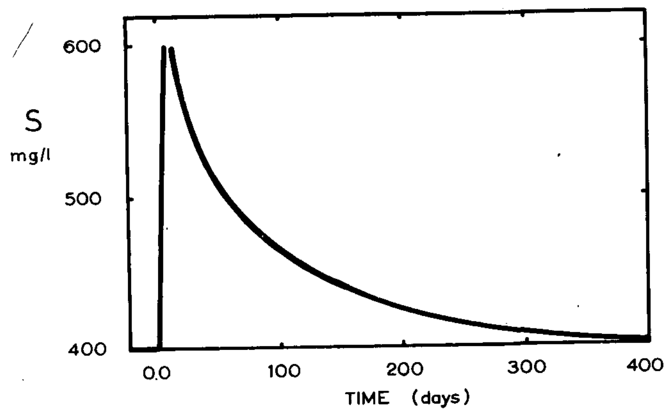

Figure 8
Simulated Response of Effluent Strength to a Step Change in Feed Strength from 7 000 to 10 000 mg COD/ℓ at a constant sludge age of 100 days (τ_H = *1,70 d,* μ_M = *0,084* d^{-1}, K_s = *3 100 mg/ℓ, Y = 0,073)*

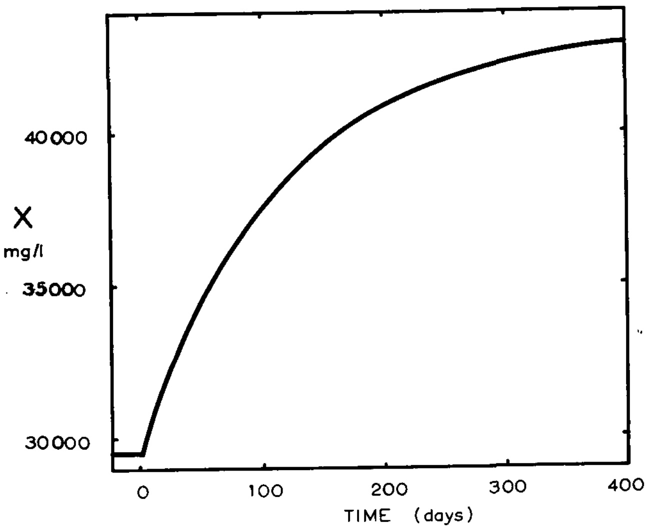

Figure 9
Simulated Response of Sludge Concentration to a Step Change in Feed Strength from 7 000 to 10 000 mg COD/ℓ at a constant sludge age of 100 days (τ_H = *1,70 d,* μ_M = *0,084* d^{-1}, K_s = *3 100 mg/ℓ, Y = 0,073)*

They follow a similar pattern to the simulations presented in Figures 4, 5 and 6. By comparison the experimental system was subjected to a ramp change in influent concentration from 7 000 to 10 000 mg COD/ℓ. The experimental system reached a new steady state within 15 days of reaching the new influent concentration. This is considerably longer than the 1,0 days taken by the step change simulation at constant sludge concentration, and is probably due to the lag inherent in the real biological system which is not accounted for in the Monod model. However it was much less than the response time of 300 days taken by the simulated system operated under conditions of constant sludge age.

Conclusions

The results of experiment and computer simulation have shown that, after a step change in feed rate, a digester operated at constant sludge concentration attains a new steady rate much more rapidly than one operated at constant sludge age. This permits the experimental determination of the kinetic constants for digestion in a much shorter period of time.

For operation at constant sludge age the time to reach steady state appears to be related to the sludge age, while at constant sludge concentration it is more closely related to the hydraulic residence time. The results presented in this paper, however, do give an indication of the validity. The simulation work has examined those microbial systems which obey a simple Monod kinetic model. The conclusions drawn from these may not be valid necessarily for those systems which are subjected to inhibition, particularly if the substrate concentration following the step change approaches toxic levels. This is particularly true if the sludge is being controlled at a low rather than high level or if the hydraulic residence is short. Current studies using the model of Andrews and Graef (1971) are being carried out to investigate this effect.

Acknowledgements

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