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A THREE-PHASE CENTRIFUGE TO MINIMIZE WASTE FROM PRODUCTION TANK BOTTOMS AND SLUDGES: AN ECONOMIC ANALYSIS

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ABSTRACT

The performance of a three-phase centrifuge process in separating tank bottoms into salable oil, brine and solids was scaled using the sigma method. The profitability was analyzed for a range of processed volumes for three business scenarios: producer owned, service company and a disposal facility. Centrifuge processes operated at full capacity in these situations may be very profitable investments but any investment decision should be heavily influenced by the annual volume to be processed, the quality of the feed and the price received for separated oil.

INTRODUCTION

Oilfield sludges and production tank bottoms present major waste management problems in the petroleum industry both from the cost of disposal and due to the perceived noxiousness of the waste by the public and regulatory personnel. The best waste management solution would be to minimize such wastes, maximize recovery of salable product and in doing so maximize profits.

Tank bottoms and sludges are usually three-phase (solid, liquid hydrocarbon and brine) emulsions of varying degrees of stability[1]. There are many ways to treat tank bottoms to recover oil: a major industry supplies chemicals to the oilfield to break

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References and illustrations at end of paper emulsions to minimize the volume of tank bottoms from accumulating or to recover oil from those which have accumulated, microwaves have been used to irradiate the emulsion and cause separation of the phases with recovery of salable oil, a sizable service industry has evolved to provide hot oil treatments to break out oil from tank bottoms and in parts of the U.S., tank bottoms are stored in immense, open earthern pits where solar heating, evaporation, gravity and time allow some oil to be separated and recovered. These treatment operations take place either at the producing site or at oil reclamation sites and the processes are operated by the producing organization using mobile or fixed equipment, a service company with mobile equipment, or by personnel whose only job is to treat sludges using fixed equipment at disposal or reclamation sites.

In a recent project to demonstrate centrifuge technology to producers in southeast New Mexico, a Wyoming based, commercially available, trailer-mounted, three-phase centrifuge process was used to separate oil from very difficult to separate tank bottoms at a nearly break even cost to the revenues generated from the sale of oil[2]. In the analysis of the demonstration it was noted that easily implemented improvements could reduce the costs of the process and that the throughput of the process was inadequate for processing the millions of barrels of tank bottoms which had been accumulated at the disposal site where the demonstration was conducted. However, the throughput of the centrifuge was thought to be adequate for meeting the industry needs for separating oil from new tank bottoms being generated in the nation if multiple units were available. Other studies have reported on the cleanup of petroleum sludges using two-phase centrifuges.[3,4] In this paper we examine the effects of the size of the centrifuge unit, and the type of application, whether owned by a producer and located at a fixed site, owned and operated by a service company using mobile equipment or owned and operated by a commercial Treatment, Storage and Disposal (TSD) site using a fixed installation, on the economic result from using a centrifuge to separate salable oil from production tank bottoms. The parameters we examine include the maintenance costs due the severity of operating stress on the centrifuge, quality of the feed, the price received for separated oil, the disposal cost, fees charged on throughput, the cost of utilities, and the interest rate charged on the capital investment.

SCALING THEORY

Ambler[5] introduced the sigma (Σ) factor which is useful for scaling of two-phase centrifuges. For a given settling velocity, which is related to the goodness of separation, one centrifuge may be scaled to another by

$$\frac{Q_1}{\mu_1 \Sigma_1} = \frac{Q_2}{\mu_2 \Sigma_2} \qquad \text{............(1)}$$

where: μ_1 and μ_2 are empirical efficiency factors for different centrifuges, reported to have a value of 60% for decanter centrifuges[6]
Q_1 and Q_2 are the volume flow rates through the centrifuges, and
Σ_1 and Σ_2 are the sigma factors relating the two centrifuges with area dimensions.

The values of sigma are related to the geometry of the centrifuge; the relationship is:

$$\Sigma = \frac{2\pi\omega^2 l_1}{g}\left(\frac{r_2^2 + 3r_2r_1 + 4r_1^2}{8}\right) + \frac{2\pi\omega^2 l_2}{g}\left(\frac{3r_2^2 + r_1^2}{4}\right) \qquad \text{....(2)}$$

where: r_1 is the radial distance to the free liquid surface
r_2 is the radial distance to the solid-liquid interface
l_1 is the length of the centrifuge at the free liquid surface in the conical part
l_2 is the length of the centrifuge at the free liquid surface in the cylindrical part, and
ω is the angular velocity of the centrifuge.

The exact relationship for Σ used in this study is related to the geometry of the centrifuge from which the data is scaled and is proprietary information, but the relationship used was very similar to Equation (2).

The sigma factor has been demonstrated to be valid for scaling three-phase centrifuges as well[7].

Knowing the flow rate of feed to the centrifuge, the quality of separated streams, the angular velocity, and the geometries of the centrifuge used in the previous demonstration project, flow rates through the centrifuge were scaled for centrifuges of other sizes and turning at different angular velocities.

SYSTEM DESCRIPTION AND ASSUMPTIONS

Centrifuge Type; There are many configurations of centrifuges which could conceivably be used to separate oil from tank bottoms. This paper does not address which type is best for these applications. A three-phase decanter configuration is used because we have data from such a centrifuge from which we could scale to other sizes and this type of centrifuge works in our application. Descriptions of centrifuges and, in particular, three-phase decanter centrifuges may be found in Polston's thesis[8]. Figure 1. is a schematic of the centrifuge system configuration used. Tank bottoms are pumped from a storage tank through heat recovery exchangers in the intermediate storage tanks containing separated brine, oil and solids, through an electric heater and into the three-phase, decanter centrifuge. Separated water, oil and solids are diverted to the respective intermediate storage tanks from which they are periodically transferred via progressive cavity pumps to disposal or sales. The centrifuge is driven by an electric motor.

Business Scenarios; Figure 2. is a diagram showing the matrix of operating scenarios which were considered in this study. This matrix takes into account the business type and location of operation, the quality of the tank bottoms being processed, how the centrifuge is being operated and the size of the centrifuge. Business types include producer owned and operated centrifuge systems at a fixed site, a service company operated system at the producing site, and a system located at a TSD site which receives tank bottoms from many producers. After separating the tank bottoms into salable oil, water and solids, both the producer owned and TSD owned scenarios must still consider the disposal of solids and brine. In the producer owned scenario it was assumed that solids and brine could be disposed for the same charge per volume as tank bottoms, or $2 per barrel. In the TSD owned scenario, it was assumed that the facility received a fee of $2 per barrel of tank bottoms and the separated solids and brine were then processed as part of the TSD operations with no additional charge. For the service company scenario, it was assumed that a service was performed but no change of ownership of the tank bottoms occurred. It was thought that these business situations covered the spectrum likely to be encountered.

The quality of the feed is an important parameter which affects the profits directly; if the feed has a low proportion of oil, then a greater volume of tank bottoms must be processed to obtain the same volume of oil as a feed with a higher proportion of oil, lower quality tank bottoms are more difficult to separate into component phases, and there are greater quantities of brine and solids which must be disposed. The quality of tank bottoms is measured as the Basic Sediment and Water (BS&W). In this study, two cases, a light tank bottoms, or fluid, and a heavy tank bottoms, or fluid, were considered. The quality of the heavy fluid was set at 65% BS&W (62% water and 3% solids) while the quality of the light fluid was set at 5% BS&W (2.5% water and 2.5%) which is a reasonable range of qualities based on observations during the demonstration project. For purposes of this study, a clean oil gravity of 25 °API was assumed.

The centrifuge system in the demonstration project was operated at lower speeds than those suggested by the fabricator[9] because the operator felt that maintenance costs were reduced[10]. Based on the scaling relationships presented above, the higher the bowl speed, the higher the volume flow rate for a given level or degree of separation, but also the higher the stress for a given size centrifuge. To evaluate the economic effect of the speed of operation, two speeds were chosen: the first being the speed at which a critical Relative Centrifugal Force (RCF) is achieved (the criteria used by the operator in the demonstration) and the second being the speed at which a critical mechanical stress is achieved (the criteria suggested by the centrifuge fabricator). Tests using a laboratory centrifuge indicate that a minimum RCF of 2000 is necessary to separate tank bottoms emulsions and that value was used as the critical value for the RCF limited cases in this analysis. The maximum stress suggested by the centrifuge fabricator for each centrifuge size was used in the stress limited cases in this analysis.

As indicated by Equations (1) and (2), the capacity of a centrifuge is related to size. For this analysis commercially available centrifuges 18, 24, 34, and 44 inches in diameter were considered. Lengths were specified to be 2.5 times the diameter. Both smaller and larger centrifuges are also commercially available, but the range of sizes used was considered sufficient to establish any economic trends due to size. The systems were numbered for convenient reference based on the size with system 1 being the 18 inch diameter, system 2 the 24 inch diameter, system 3 the 34 inch diameter and system 4 the 44 inch diameter. Table 1 is a summary of the capacities calculated by scaling for the four systems operating at either the RCF limited or stress limited condition. The throughput rates varied from 4 to 24 gpm for the RCF limited operation and from 6 to 30 gpm for the stress limited operation.

In each system a standard layout of equipment was used. Each system was assumed to require two full-time operators and an air conditioned control house was included. Costs of a trailer mounted system were used for all systems, even though two of the three systems could be fixed facilities, as the cost for the trailer was not great and it was felt that suitable fixed foundations and structures would cost about the same.

Table 2 is a summary of the estimated costs of construction for the four systems. Assuming there is no additional investment required for real estate, the initial investment varied from about $350K for system 1 to $585K for system 4. Comparing the construction cost data in Table 2 with the rate data in Table 1, a five or six times increase in throughput rate may be achieved by building a larger centrifuge at an initial cost of approximately two-thirds more than the cost of the smallest unit.

Associated equipment, such as pumps, heaters, and motors, were sized based on the estimated flow capacities, estimated thermal properties of fluids and the size of the centrifuge for each system. Heaters were sized with a ten percent safety factor. Two inch diameter steel piping was assumed. Power requirements were calculated for each system based on the flow rates and the size of equipment and the centrifuge. Further details may be found in Polston[8].

The producer owned and TSD owned systems were assumed to operate 300 days per year and 24 hours per day with a 2.5 hour period for daily maintenance. Service companies were assumed to be 24 hour per day operations for a total of six months per year.

Maintenance and Operating Costs; Decanter centrifuges will operate indefinitely if overhauled at periodic intervals. Overhaul intervals suggested by the centrifuge fabricator were used in this study[5]: every 10,000 hours for stress limited operations and 15,000 hours for RCF limited operations. During an overhaul of a standard design of a large centrifuge, it is common to exchange a refurbished unit for the unit requiring work. With such an exchange, a one day down time was assumed. Costs for replacement suggested by the fabricator were used; $15,000, $17,500, $28,000, and $55,000 for systems 1 through 4 respectively.

Maintenance of the progressive cavity pumps was assumed to occur at the same time as the centrifuge exchange. For estimation purposes, it was considered that at that time the stators would be replaced. This life of stator replacement was felt to be very conservative and adequate to include rotor and seal maintenance as well. Heater elements were also assumed to be replaced during the centrifuge exchange. Parts costs for pump and heater maintenance were based on the manufacturers quoted prices. Labor costs for centrifuge exchange and pump and heater maintenance were included in operating labor costs described below. Motor replacement costs were estimated at 1% of income.

Electric power costs were estimated at $0.04849 per kWh.

Table 3 is a summary of the procedure for calculating labor costs which has also been used to estimate costs in the petrochemical industry[11]. Operation of all systems was assumed to require two operators. Wages were estimated to be $10/hour. Extra labor for maintenance items was estimated at six percent of maintenance costs. Supervisory costs were estimated to be 20% of operating and maintenance labor costs and administrative costs (vacations, down-time, FICA, and other benefits) were estimated to be 60% of labor and supervisory costs. Total labor costs were then estimated to be the sum of labor, supervisory and administrative costs.

Annual insurance costs were estimated to be 10% of the capital investment. This rate is based on actual experience with a similar system operating in hazardous waste clean up situations[10]. The estimate is probably conservative for the producer owned scenarios since most producer owned sites will not be classified as hazardous waste sites. Service companies and TSD facilities are more likely to require the higher insurance rates.

Table 4 is a summary of marketing, R&D, and analytical cost rates for each scenario which were derived from values suggested by Peters and Timmerhaus[12]. Obviously a service company will have to spend a relatively high amount on marketing while in the producer owned scenario the marketing cost is really an overhead associated with oil sales. Likewise, for the R&D costs, in the producer owned scenario, these costs are most likely corporate overheads but for the TSD and service company they are necessary functions to stay in business. Analytical costs are assumed to be less for a service company since they are performing a service and not taking ownership of the separated streams and the tests necessary for good operation of the centrifuge are simple and can be done in the centrifuge control house. The total of the Other Operating Costs (OOC) estimate came to 18%, 8% and 16% of the total of labor, maintenance, operations and insurance costs.

Interest, Oil Prices and Taxes; For this study, it was assumed that the initial investment was financed with a bank loan at 10% annual interest compounded monthly for the base case with variations from 0 to 30% used in sensitivity analyses. The price received for separated oil for a base case was set at $20 per barrel variations in the price of oil were examined in sensitivity analyses. Taxes were allocated as a stand alone enterprise at corporate rates based on the 1993 Federal Code[13] and the MACRS method of depreciation.

PROFITABILITY AND SENSITIVITY ANALYSIS

To assess the economic viability of each of the operating scenarios, common profitability indicators were computed for the 48 cases of the matrix of Figure 2. For this work, only the discounted Internal Rate of Return (IRR) and payout time will be reported. Results using other indicators may be found in Polston[8]. For the producer owned and the TSD scenarios, the IRR was calculated using the base case assumptions as functions of the quality of the feed and stress condition under which the centrifuge was operated. For the service company operation, profits were generated by throughput fees so IRR values were calculated as a function of those fees. The sensitivity of the calculated values of the IRR to changes in the interest rate, utilities rate, disposal rate and the price received for oil was examined for the producer owned scenario. The sensitivity to variations in parameters for other scenarios may be found in Polston[8].

Figure 3 is a plot of the calculated values of IRR as a function of the project life for the four size systems operating on both light and heavy tank bottoms under the base case parameters and RCF limited capacity at a producer owned facility. The solid lines are for the light (higher oil concentration) tank bottoms and the dashed lines are for the heavy tank bottoms. A curve is not plotted for the small system, system 1, processing heavy tank bottoms indicating that a positive cash flow was not projected under those conditions. In general, the larger the size of the system, the greater the value of the estimated IRR. At ten years of operation, the IRR values estimated when processing light tank bottoms was about 40% or greater for the smallest system with an IRR of about 180% for the largest system. Between five and ten years the estimated IRR values were very close to the maximum values. Plots with similar features were obtained for the stress limited, producer owned facility and for the TSD facility under both stress operations conditions.

Table 5 is a summary of the estimated values of IRR after ten years of operation for the producer owned and TSD facilities using the base case parameters. In all cases the estimated IRR values were greatest for the largest size centrifuge operating under the stress limited condition. For system 1 processing heavy (low oil concentration) tank bottoms, a positive cash flow was not projected. For system 2, only the TSD facility operating on a light feed in the stress limited regime was profitable. Unsurprisingly, higher concentrations of oil in the feed produced greater estimated IRR values with everything else being equal.

Figure 4 is a plot of calculated values of IRR, using the base case parameters, as a function of throughput charges for a service company scenario with all four systems at both the stress limited and RCF operating modes. Solid lines represent RCF limited operation and dashed represent stress limited operation. The curves are nearly linear with IRR increasing as throughput charges increase with slopes that increase as the size of the centrifuge increases. Table 6 is a summary of service company throughput charges necessary to achieve a 20% IRR at ten years of project life for all four size systems at both RCF and stress limited operations. Because the throughput calculated from the scaling procedure did not vary with the quality of the feed, and because service companies derive revenue from throughput alone, there was no need to include the quality of the feed in this analysis. The required throughput charges varied from $3.30 per bbl to $19.00 per bbl. The smaller sized units operating at RCF conditions were associated with the higher charges and the stress limited conditions and the larger units were associated with the lower charges.

Sensitivity Analysis; Figures 5 and 6 illustrate how calculated values of IRR vary with changes in parameters, chosen as likely to affect the IRR, for the producer owned scenario using the largest system at stress limited operations for both heavy and light tank bottoms. In the figures, the percent change in IRR is plotted against the percent change in the parameters. Parameters investigated include the price received for separated oil, interest rate, disposal rate, utility rate and OOC rate. In both cases, the value estimated for IRR was most sensitive to changes in the price received for separated oil. Suppose the price received for oil was only $15 when the base case (0% deviation) price was $20 per bbl. Referring to Figure 6, at a -25% deviation in the price, the reduction in the IRR was about 15%. Since the value of IRR calculated for the base case was about 210 %, the IRR value estimated using $15 per bbl would be 178%. For the case representing the light tank bottoms feed, the IRR was relatively insensitive to changes in the other parameters.

In the scenario for operations on heavy tank bottoms, the value of the calculated IRR was more sensitive to changes in values of disposal rate, OOC rate, and utility rate than did the same unit operating on light tank bottoms. Calculated values of IRR were relatively insensitive to interest rates.

DISCUSSION

The objective of this study was to determine under which conditions of volume of tank bottoms to be processed, quality of the tank bottoms, size and stress level of operation of centrifuge, and business structure that a centrifuge system for separating production tank bottoms into salable oil, brine and solids might be profitable. Using the base case parameters and all three business scenarios, the results clearly indicate that profitability is improved if the centrifuge is operated at the maximum allowable stress. Under these operating conditions, the centrifuge must be overhauled more often, but the greater throughput and revenues generated outweigh the greater maintenance costs.

The results also clearly indicate that for all three business scenarios, the larger the volume to be processed the more attractive the investment in a centrifuge system. And, if the volumes of tank bottoms are large enough, all scenarios present very attractive investment opportunities. As noted above, from a comparison of the estimated costs for constructing a system (Table 2) and the throughput rates for the systems (Table 1), the throughput rate from the smallest to the largest system may be increased by a factor of 5 or 6 for a two-thirds increase in the initial investment. Thus for the best return on investment, one should chose the largest centrifuge to handle the volume, not multiple smaller units.

In the producer owned scenarios, the results indicate that a minimum annual accumulation of tank bottoms volume is necessary to support a profitable, fixed centrifuge system especially if the concentration of oil in the tank bottoms is not high. For 24 hour per day, 300 day per year operation using the base case parameters, the minimum volume of heavy tank bottoms which must be processed to be profitable is between 41,000 bbls (4 gpm X 60 in/hr X 24 hr X 300 days /42 gal/bbl) and 72,000 bbls. For scenario including light (high oil concentration) tank bottoms, a profitable operation may be achieved processing accumulations of less than 41,000 bbls. Many small operators have locations for which 41,000 bbls is greater than the total annual production of crude oil. For producer operations in which less than the profitable volume is accumulated, a service company using mobile equipment might be justified or the tank bottoms could be transported to a TSD facility for processing.

The results of the sensitivity analysis for the largest centrifuge in a producer business situation were most dependent on the price received for the separated oil. The price used in the base case was $20 per bbl. At the time of preparation of this paper, the price of West Texas Intermediate (WTI) crude oil is less than $20. Further, it is not unusual for tank bottoms to be subjected to heating and chemical treatment with an accumulation of tank bottoms which are difficult to separate and missing volatile components. Such oil, even when separated might not command the same price as the oil taken from the stock tank. Thus, even if the location of a producer owned centrifuge were in a WTI producing area, it is likely that one might see a 25% reduction (-$5) in the price received. When the oil concentration is high (light tank bottoms) a 25% reduction would cause a 20% reduction in the estimated

IRR, or an IRR of 165%. For the heavy tank bottoms, low concentration of oil, the same - 25% deviation in the price of oil would cause a 50% reduction in the estimated IRR, or an IRR of 38%. While these adjusted values of IRR indicate a favorable investment, it is obvious that the quality of tank bottoms and the price of oil should be considered in any investment decision.

Finally, the Σ method for scaling provides a convenient tool for studies such as this evaluation. Future work includes an effort to determine the empirical efficiency factors, μ of Equation 2, with sufficient accuracy so that the results of laboratory tests on a particular tank bottoms sample could be used to project the economic viability of separating that fluid with any configuration of centrifuge.

CONCLUSIONS

1. The Σ method for scaling centrifuge performance is a convenient method for performing economic analyses on centrifuge systems.

2. Three-phase centrifuges for separating petroleum tank bottoms into salable oil, solids and brine may offer quite attractive investment opportunities, particularly if the concentration of oil in the tank bottoms is high. If the concentration of oil in the tank bottoms is not high, then the volume of tank bottoms to be processed becomes more critical in determining the profitability of these processes. In those cases, the volume of tank bottoms required to support a producer owned facility may be more than the total volume of crude oil produced annually at some locations but processing by a service company on site or transport to a TSD for processing may be a viable alternative.

3. The estimated profitability of all the scenarios in this study was more sensitive to variations in the price received for separated oil than any other parameter studied. If the oil concentration in the feed is high, then the disposal rate, utility rate, and OOC rate did not greatly affect profitability. If the oil concentration is low, then disposal rate, utility rate and OOC rate become more important. Profitability was not greatly affected by the interest rate.

4. For the scenarios of this analysis, the centrifuge should be operated at the maximum stress condition suggested by the manufacturer to maximize profits.

5. The largest centrifuge necessary to process the volume should be used.

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Table 1. Scaled Capacities of Centrifuge Systems Operating at Both RCF and Stress Limited Conditions

	Throughput Rate, gpm	
System	RCF	Stress Limited
1	4	6
2	7	11
3	14	18
4	24	30

Table 2. Estimated Costs to Construct the Four Centrifuge Systems

Component	System 1 (18x45)	System 2 (24x60)	System 3 (34x85)	System 4 (44x110)
Centrifuge				
Includes:	$195,000	$252,000	$292,000	$369,000
Centrifuge				
Drive motor				
Hydraulic Clutch				
Differential drive unit				
Heater				
Electric, Circulation	$10,535	$12,460	$15,350	$30,700
Pumps				
Feed	$6,765	$6,765	$6,765	$6,765
Oil	$3,272	$3,272	$3,272	$3,272
Water	$3,272	$3,272	$3,272	$3,272
Solids	$27,853	$27,853	$27,853	$27,853
Trailer				
40' Lowboy	$15,500	$15,500	$15,500	$15,500
Plumbing				
2" Tubing	$200	$200	$200	$200
Misc. Fittings	$300	$300	$300	$300
Holding Tank Material	$200	$200	$200	$200
Control Room				
Materials	$1,000	$1,000	$1,000	$1,000
Furnishings	$1,000	$1,000	$1,000	$1,000
Electric Heater	$80	$80	$80	$80
Air Conditioner	$300	$300	$300	$300
Electric				
200 Amp Wire	$277	$277	$277	$277
100 Amp Wire	$166	$166	$166	$166
Service Boxes	$750	$750	$750	$750
Labor				
50% of non-centrifuge equipment	$35,735	$36,698	$38,184	$45,983
Subtotal	$302,205	$362,093	$406,552	$506,949
Contingency				
15% of Subtotal	$45,331	$54,314	$60,983	$76,042
Grand Total	$347,536	$416,407	$467,535	$582,991

Table 3. Procedure for Calculating Labor Costs

Base employee salaries	$20/hr
Maintenance personnel expense	0.06(Maintenance expense)
Salary base	**$20/hr + maintenance**
Supervisory expense	20% of **salary base**
Subtotal	**salary base + supervisory**
Administrative expense	60% of **subtotal**
Grand total	subtotal + administrative

Table 4. Summary of Rates Used in Calculating OOC as a Percentage of the Sum of Labor, Maintenance, Operations and Insurance Costs

Expense	Producer Owned	TSD Owned	Service Company Owned
Marketing	2%	2%	10%
R&D	5%	5%	5%
Analytical Analyses	11%	1%	1%
Total	18%	8%	16%

Table 5. Summary of Calculated IRR Values After Ten Years of Operation Using the Base Case Parameters

		Light Fluid				Heavy Fluid			
		1	2	3	4	1	2	3	4
Producer Owned	RCF	43.1%	87.7%	148.5%	185.0%	-	-	23.0%	58.9%
	Stress	84.2%	133.1%	175.3%	209.1%	-	34.0%	45.4%	76.8%
TSD Owned	RCF	49.3%	91.6%	151.0%	186.9%	-	-	52.6%	84.6%
	Stress	88.6%	136.1%	177.6%	210.9%	-	37.1%	74.0%	103.9%

Table 6. Minimum Service Company Throughput Fees Required to Achieve an IRR of 20%

	System 1	System 2	System 3	System 4
RCF Limited	$19.00/bbl	$11.90/bbl	$ 6.00/bbl	$ 4.20/bbl
Stress Limited	$12.00/bbl	$ 7.00/bbl	$ 5.00/bbl	$ 3.30/bbl

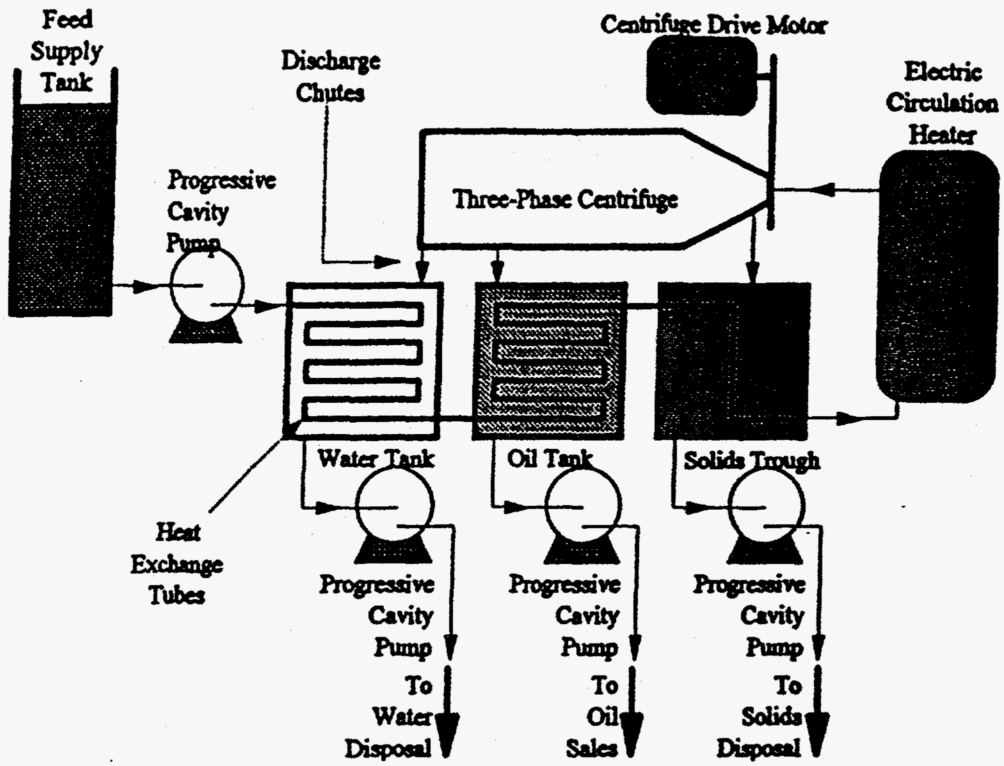

Figure 1. Schematic of the three-phase centrifuge process.

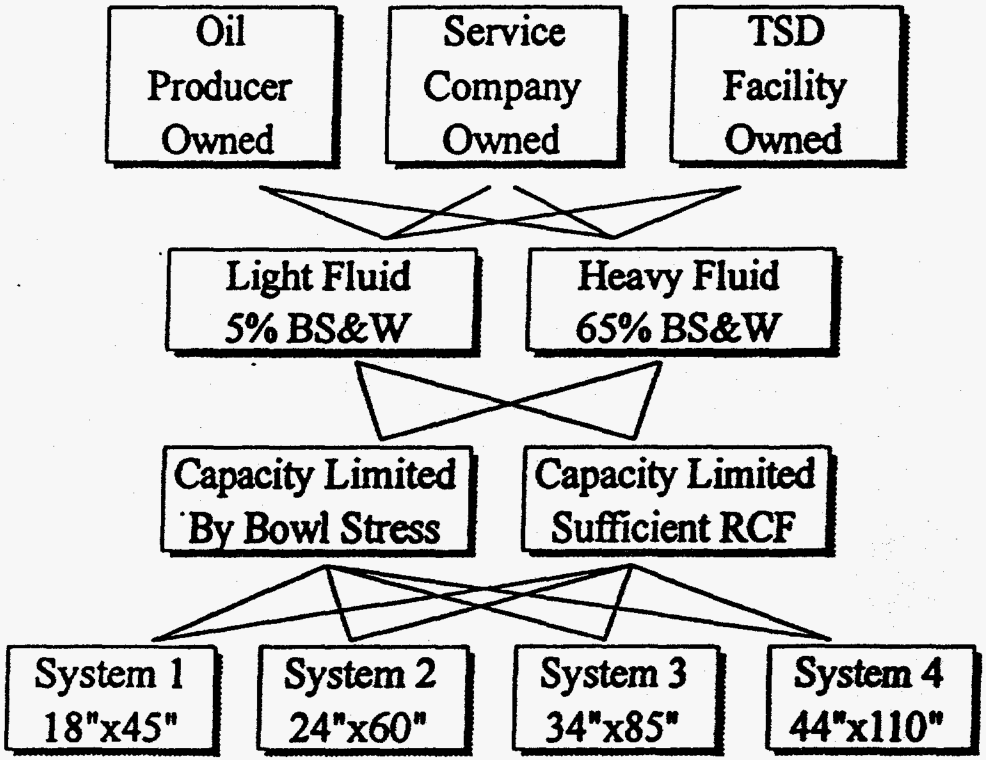

Figure 2. Matrix of operating scenarios.

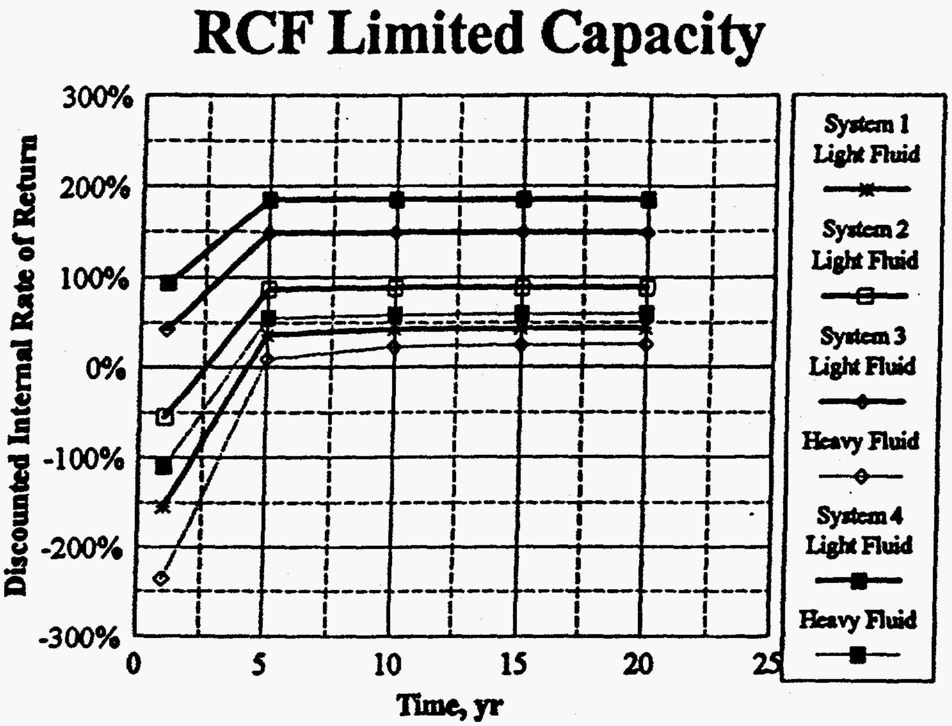

Figure 3. Calculated values of IRR as a function of project time for the producer owned scenarios for all four size centrifuges at the RCF limited operating mode.

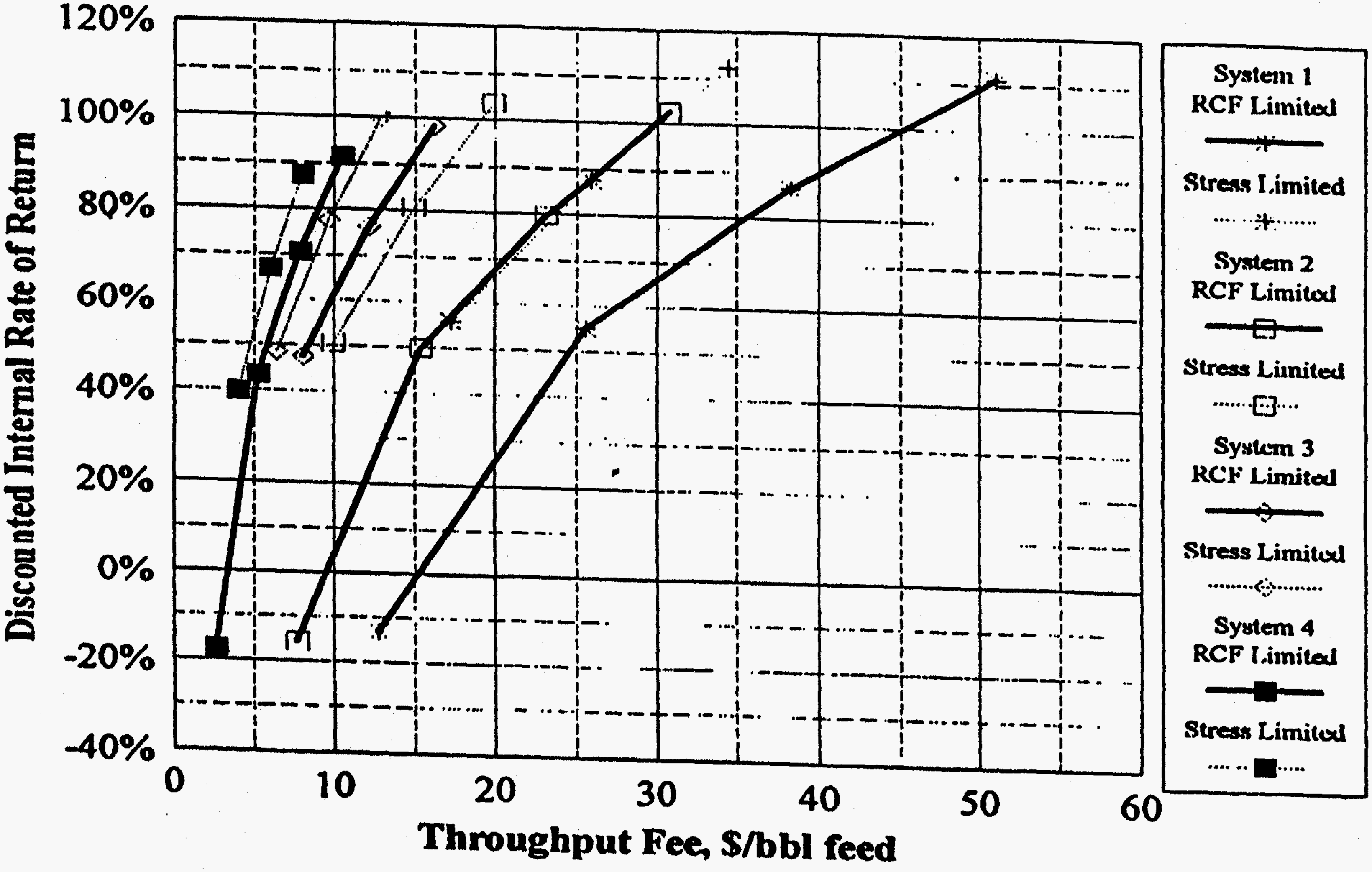

Figure 4. Calculated Values of IRR vs Throughput Fee for a Service Company Operation.

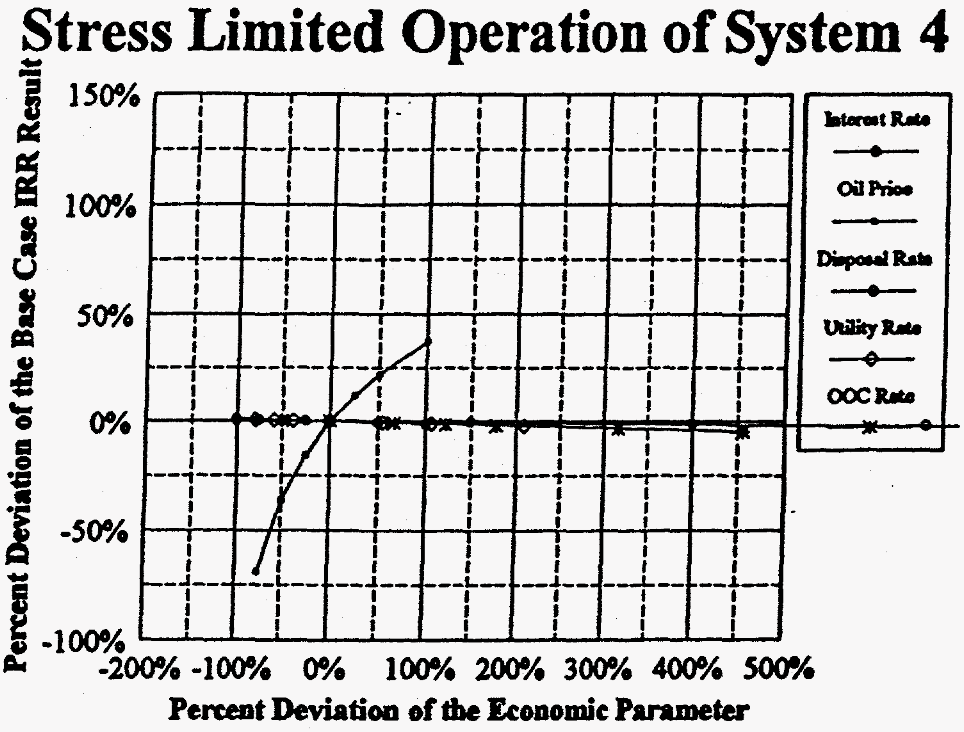

Figure 6. Sensitivity of the IRR as a function of the percent deviation in selected parameters for a producer owned system with the largest size centrifuge operating at the stresslimited condition on a light feed.