AUTOTHERMAL THERMOPHILIC AEROBIC DIGESTION HEAT BUDGETS

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INTRODUCTION

Several investigations of autothermal thermophilic aerobic digesters (ATAD) have been published by the author; the first compared the results of three full scale demonstration studies, (Kelly, (1991), and Kelly et.al. (1993)). A second dealt with the ATAD operation, (Kelly et.al. 1995) and a third provided design criteria, (Kelly, Warren 1995). What has not been reported are the associated heat budgets. The purpose of this paper is to initially provide a brief review of the ATAD process, and finally examine the ATAD heat budget as it relates to air/oxygen addition, chemical oxygen demand (COD), feed solids concentrations (TS) and mechanical energy additions. The paper is intended to further the understanding of the process, and to point to areas of improvement for design and operations.

Simulated digester start-ups with and without heat exchanger, and several types of heat exchangers are examined. The material is based on the author's experience with three different types of aerator mixer installations, reactor construction methods, and heat exchanger approaches.

PROCESS

Flexibility and choice are accessible for today's publically owned treatment works (POTW), ATAD construction. A two reactor minimum made of concrete, steel or fibreglass; provided with mixing and aeration using aspirator mixers, recirculation pumps and venturis, or turbine mixers and diffused air; and operated in batch or semi-continuous modes, comprise the current installations. Ancillary needs such as prethickening to ensure a sufficient concentration of substrate feed, and final storage and dewatering functions to reduce solids handling are normally used in the overall solids handling facilities.

Biologically, the ATAD process responds to a set of seemingly paradoxical conditions. Aerobic biological processes are often gaged by the concentration of dissolved oxygen present in the liquid. The ATAD process, however, functions between an anaerobic and aerobic environment and the concentration of dissolved oxygen is not normally measurable. Although oxygen is necessary, it is provided by the limited addition of air usually coincident with mechanical mixing operation. The mass of oxygen needed is equated to the mass of chemical oxygen demand to be removed. Excess oxygen is not necessary nor desirable. Oxygen transfer efficiency is high since dissolved oxygen is near or below detection limits, ensuring a maximum gradient; and the mixing systems promote fine bubble aeration, providing high surface area to mass ratios to enhance transfer. The high operating temperature of over 50°C (122 °F) lessens oxygen solubility but to compensate, transfer rates increase. A high transfer efficiency is obtained. This means low air volume requirements. Air addition may be equated to volumes of air per reactor volume per hour, (V/V-hr). This is not accurate but is a convenient rule of thumb measure.

The advantage of the ATAD process is its ability to deliver a pasteurized stable product at a relatively short hydraulic retention time. The short operating hydraulic retention time of as little as 5 to 6 days, due to the high operating temperatures and rapid regrowth rates, reduces the size of tankage. Although high mixing power densities are used, the unit energy consumption can be less than conventional processes, especially if energy recovery is included in the design. Conservation of the heat released by the biological breakdown of organics, and the mechanically produced heat released by mixing energy dissipation become important where energy is considered a valuable resource. The heat budget of the ATAD and identification of heat recovery opportunities should therefore be considered during design.

HEAT BUDGET

Vismara (1987) describes an ATAD heat budget model using six heat sources and losses. A seventh and eighth are added for completeness.

The rate of heat change in each reactor may be determined by a second order rate equation which models the following heat transfer relationships:

1. sensible heat change due to rate of addition of influent sludge,
2. heat release from rate of breakdown of organics,
3. heat from mechanical mixing energy,
4. sensible heat loss or gain through the shell of the reactor,
5. sensible heat loss or gain from rates of addition and removal of air flow,
6. latent heat loss from evaporation and subsequent removal through air flow,
7. sensible heat addition or loss through heat exchangers, and
8. heat addition or loss caused by phase changes, cavitation and other unknown factors. (These secondary sources may be significant but are presently unquantified and are not included in the simulations.)

A time step averaged approach can be used to solve the above second order rate equation and simulate a start-up condition or examine effects of operating changes. For steady state, the rate of heat change in the digester is zero and for known or assumed physical, chemical, meteorological, structural, mechanical and biochemical criteria, final reactor temperature can be calculated. For either case, the importance of heat exchangers can be tested. Further, the selection of mechanical mixing power density, air flow, organic heat content (concentration of chemical oxygen demand, COD), liquid loading rate hydraulic retention time, (HRT), insulation and operating temperatures can be examined to evaluate operating strategies and confirm process design. (HRT is the hydraulic retention time or theoretical time required for the flow through the tank. For an ATAD reactor, where thickening and decanting are not practised, this also equals the solids retention time or SRT.)

A two reactor heat budget is simulated in Figures 1 and 2 for an ATAD operating under steady state condition for the criteria shown in Table 1. Ambient temperature is assumed at 0°C and the relative humidity is 50%.

TABLE 1
ATAD SIMULATION CRITERIA

Parameter	Case 1	Case 2
Sludge Feed		
- Daily Sludge Flow	50 m^3/d	58.5 m^3/d
- Total Solids Dry Weight (TS)	3%	2.5%
- Chemical Oxygen Demand/Total Solids Ratio	1.6/l	1.7/1
- Chemical Oxygen Demand	50 g/L	43 g/L
- Sludge Temperature	9°C (48°F)	9°C (48°F)
- Heat content of organics	3500 kcal/kg COD	3500 kcal/kg COD
- Air Flow, V/V-hr	1	2
Reactors		
- Number	2	2
- HRT, each	3.5 days	3 days
- Volume, each (liquid)	175.4 m^3	175.4 m^3
- Mixer-aerator - Power density first reactor	120 W/m^3	120 W/m^3
- Power density second reactor	100 W/m^3	100 W/m^3

W/m^3 - Watts of mixing power per m^3 of reactor volume.

Figure 1 shows results for a 100 mm insulation and an air flow of about 1 V/V-hour. If air flows were doubled, the heat budget would yield a final ATAD temperature below the 55°C target. The increased sensible heat losses from air flow and latent heat losses from evaporation are only slightly above those for the lower air flow, but the effect is sufficient to require an additional 7.5 to 10 kW of mechanical mixing to compensate. The use of a heat exchanger could avoid this extra cost.

Reduced insulation will produce similar results. A reduction of insulation thickness to 50 mm will reduce the Figure 1 final reactor temperature by 4 to 5°C (7 to 9°F) and about 5 to 8 kW of added power would be needed to compensate.

More significant is the effect of changes in organic content and feed sludge rates. For the same mass of feed, as shown in Case 2, an increase in flow to 58.6 m^3/d and a coincidental lower organic concentration of 43 g/L COD, produces a 6 day HRT. This results in final temperatures less than 50°C. To have avoided the temperature loss, supplemental mechanical energy of 20 kW would have been needed.

If a heat exchanger were used to recover heat from the biosolids product and increase the 9°C sludge feed to 22°C, the recovered energy for a 24 hour feed could represent about 30 to 35 kW. This could allow reduction of the mixing power in the first reactor, compensate for lower HRT and thin feed sludge conditions, compensate for excess air flows (2 V/V-hr), give more robustness to the process and recover heat from the final product. The latter is valuable to reduce temperatures for improving dewatering and reducing foul air vapour losses. Figure 2 illustrates the heat balance and the impact of preheating the sludge feed to 22°C. Robustness is important since characteristics of sludge feed are not always at optimum content. Preheating may also reduce problems with foaming.

HEAT EXCHANGER SELECTION

Heat can be recovered from the foul air exhaust and from the final biosolids product. An air to air heat exchanger with condensate recovery is typically used for the exhaust and provides a low cost heat source. For a Temperate Zone winter condition with a heating requirement of 200 to 250 W/m^2 (70-85 $Btu/hr\text{-}ft^2$) of floor area, approximately 1 m^3/d of sludge flow is needed to heat 1 m^2 of area. In the 50 m^3/d example, about 50 m^2 of building space could be heated using a recirculation heating system.

More importantly heat can be recovered from the final digested product through several forms of heat exchange and made available for preheating and other uses. To achieve the recovery, choices for the type of heat exchanger construction, the heat exchange medium, and an approach include:

1. Types of heat exchangers in use include:

    - Spiral (two compartment)
    - Tube-in-tube
    - Tube in shell
    - Complete mix using two (or more) separate compartments

    For the first two for efficiency, counter flow design is normally used. The latter two require mixing energy to assist in heat transfer. In all cases the fluid should have sufficient velocity or be sufficiently mixed to minimize wet film insulation effects. Materials with a high heat transfer coefficient are needed, but selection must also consider corrosion and erosion resistance.

2. The mediums for the heat exchange fluids are typically sludge/sludge or sludge/water (glycol). Sludges may also need to be macerated when using heat exchangers with small flow passages.

3. Common approaches include heat exchange by recirculation of reactor contents, or direct transfer to the feed sludge or discharged biosolids.

A combination of the above should be selected to suit the needs of the process and plant resources.

As an example, a batched process using 24 hour fill and draw, for a 6 or 7 day HRT would generally use a complete mix, multi compartment heat exchanger as shown in Figure 3. The necessary volumes of each compartment would be about one-sixth of the reactor contents to allow the daily discharge to provide heat for the incoming daily feed. This is an example of a typical sludge/sludge medium using a coincident heat exchange by a direct exchange between feed and discharged flows.

Alternatively, a coil or hot water jacket can be installed in or around the final reactor, and water circulated to cool the reactor contents, similar to a tube and shell arrangement. The heated water could be further used to preheat incoming sludge in a tube-in-tube or spiral arrangement as shown in Figure 4. This is an example of a sludge/water medium using both recirculation and direct flow heat exchange approaches. The sludge/water option has the advantage of being independent of sludge feeding schedules since the recirculated water flow can be used for other options. A sludge/sludge heat exchanger can also be used in a tube-in-tube or spiral arrangement but its use will be dependent on feed schedules.

Figure 5 illustrates a recirculation sludge/sludge heat exchanger approach. A recirculation approach is often used with anaerobic digestion to restore the sensible heat losses from the structure but rarely to provide the initial heating. If used for initial preheating two inefficiencies are obvious. Firstly, the gradient to raise the temperature will be less since the first ATAD will be hotter than the feed. Secondly, the temperatures from the hot reservoir will be less for preheating since it will have been steadily cooled by the recirculation.

This is observed in Figure 6 in a start-up simulation where added mechanical energy supplements are used to illustrate the extent of the difference in energy needs for various approaches to heating.

HEAT EXCHANGER APPROACH FOR START-UP

Figures 6a, b and c compare start-up simulation for three cases to meet a 6 day objective for a temperature rise to 60°C (140°F):

- Figure 6a - No heat exchanger - supplemental mechanical mixing of 300 W/m^3 is required.
- Figure 6b - Reactor heat exchanger as in Figure 5 - supplements mechanical mixing of 200 W/m^3.
- Figure 6c - Direct feed heat exchanger as in Figure 3 or 4 - supplemental mechanical mixing of 100 W/m^3 only is required.

All three cases assume a 10°C (50°F) cold start, equal kinetic rates, batch feed (once per 24 hours) and other characteristics as given for Case 1 of Table 1. The direct feed heat exchange is capable of a temperature increase in the feed to 22°C (72°F), and the heat exchange for the recirculation assumes a 60°C (140°F) heat source and a 35 percent transfer efficiency. For each reactor to achieve a 60°C (140°F) operating temperature in seven days, supplemental power requirements are double for recirculation heating and are triple without heat exchanger heating when compared to the direct feed heating.

CONCLUSION

The ATAD process is currently becoming attractive in North America as a means of producing stabilized and pasteurized biosolids. Several process methodologies are available and range in design for mixer-aerator type, construction shape, materials and operations strategy.

In design and operation, the use of heat and energy budgets are valuable for improving process and operational control. The rates of addition of feed sludge and air, concentration of organics, and component design have bearing on the efficiency of the process. The use of a heat exchanger allows energy conservation, provides buffer against feed variations and improves operational flexibility for the process and final product handling.

Types, medium and approach to heat exchanger selections show advantage for specific objectives. For example, a batch process using a once in 24 hour fill and draw sludge/sludge medium is often associated with complete mix, multi-compartment type for feed and final product heat exchange. For greater flexibility however, a water/sludge medium may be used and spiral or tube-in-tube heat exchangers selected. Also, a direct feed as opposed to a reactor recirculation heat exchange appears to be a more efficient approach when considering the use of a heat exchanger.

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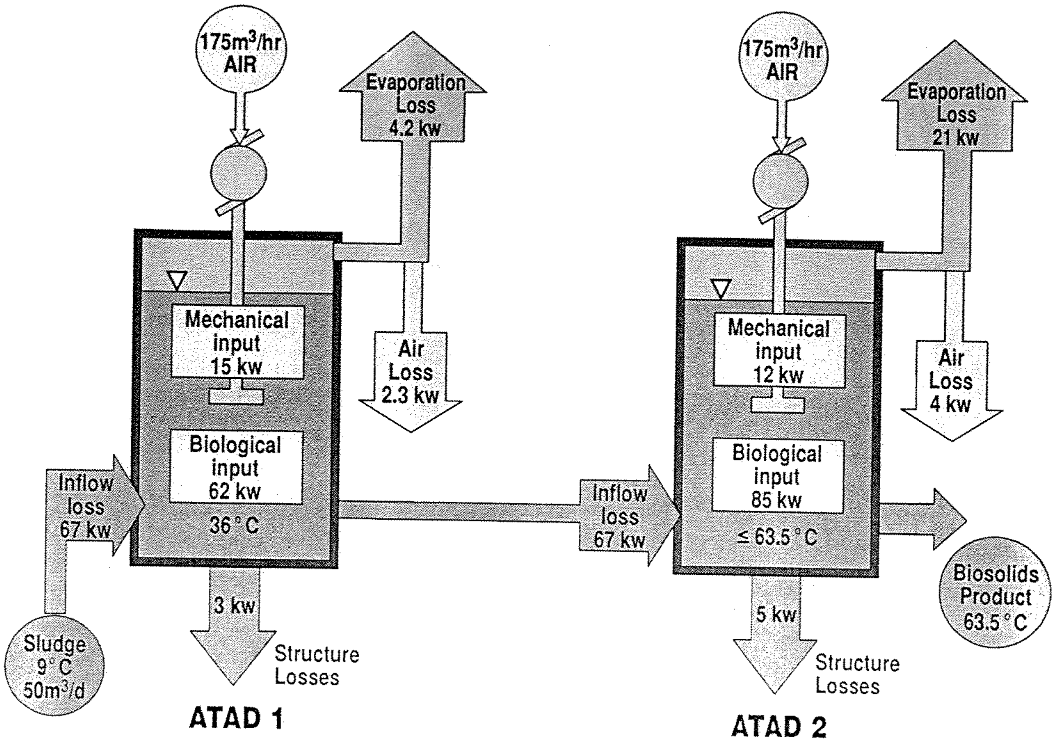
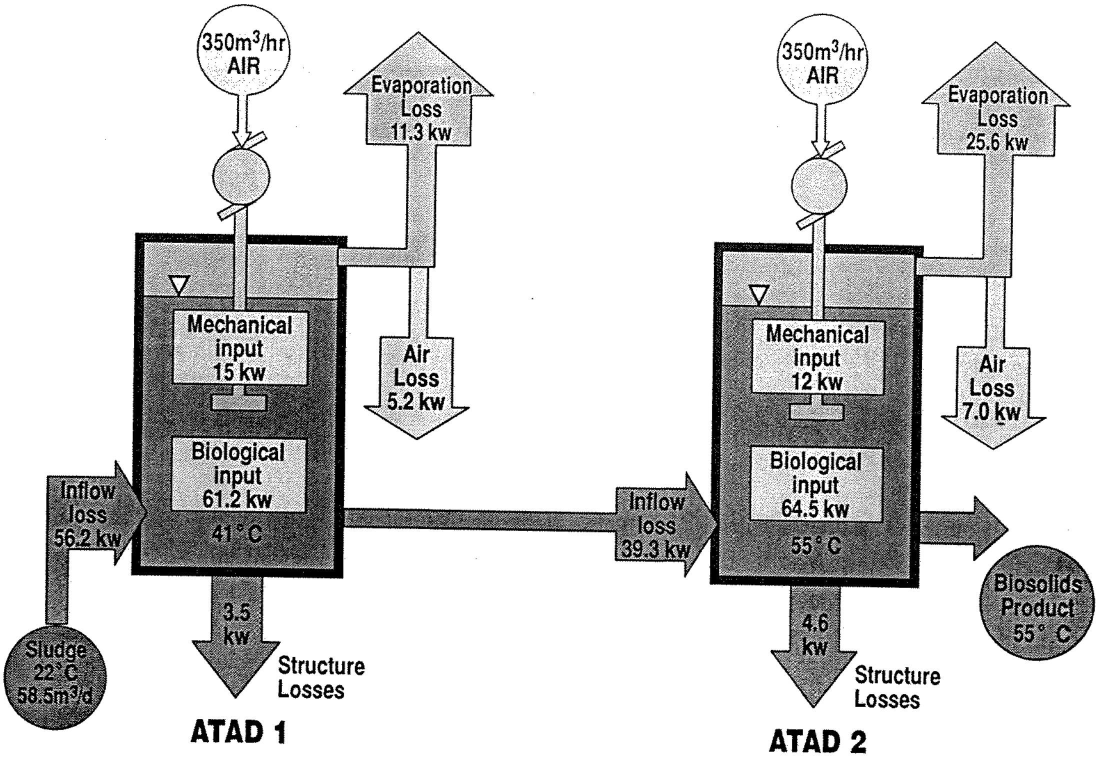


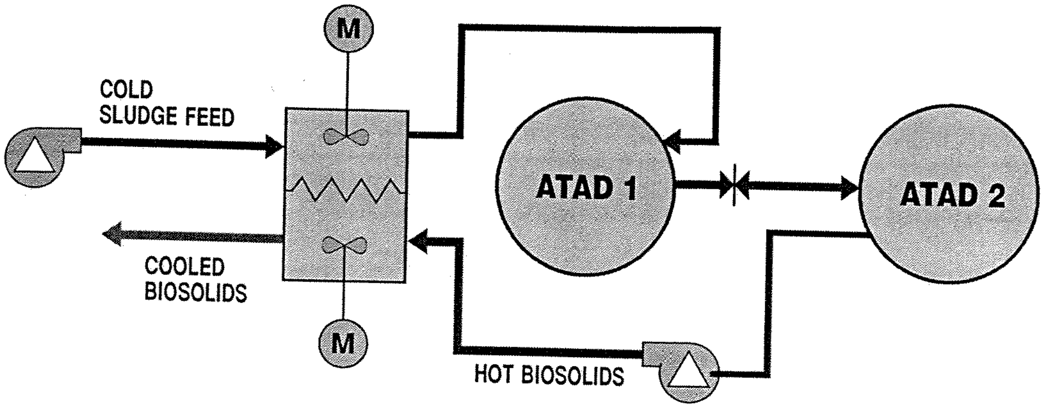
7 DAY ATAD HEAT BALANCE WITHOUT HEAT EXCHANGER

Figure 1



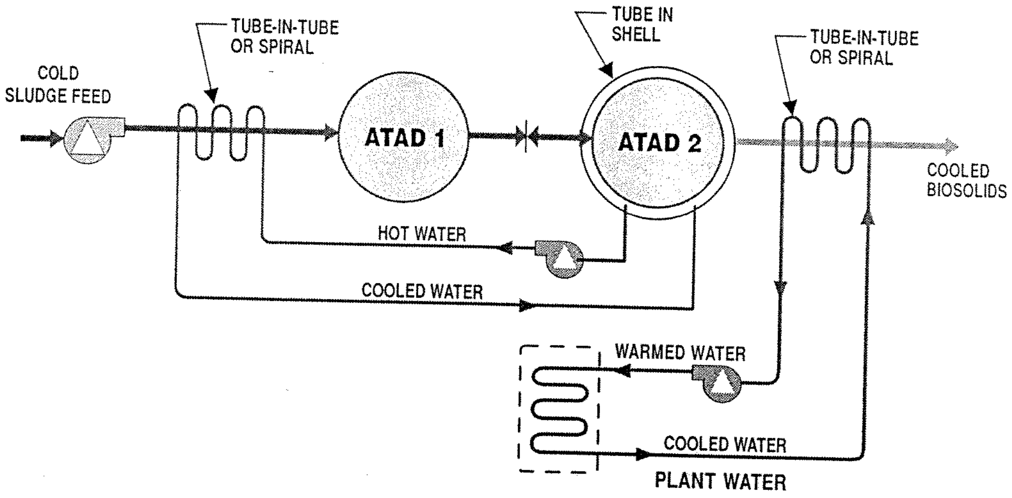
6 DAY HRT ATAD HEAT BALANCE WITH HEAT EXCHANGER DOUBLED AIRFLOW AND REDUCED FEED CONCENTRATION

Figure 2



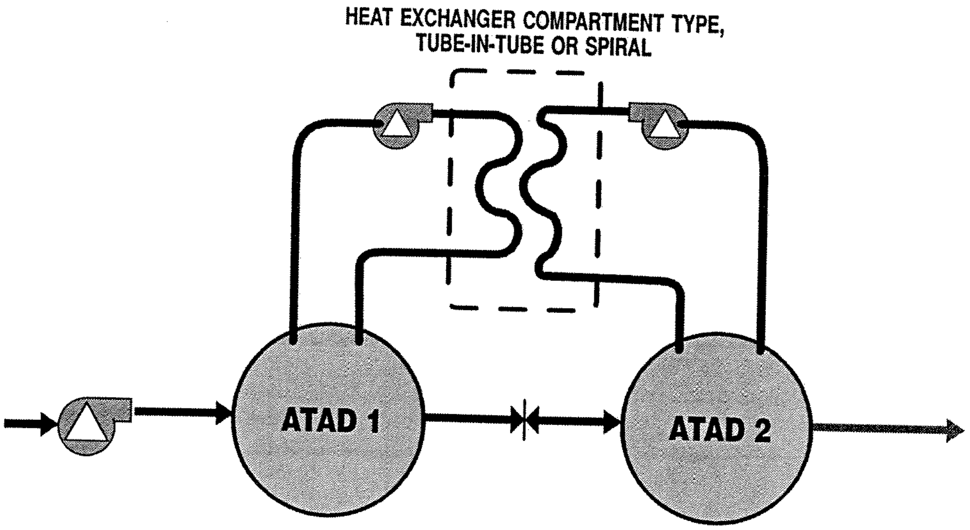
COINCIDENT SLUDGE/SLUDGE BATCH ATAD HEAT EXCHANGER

Figure 3



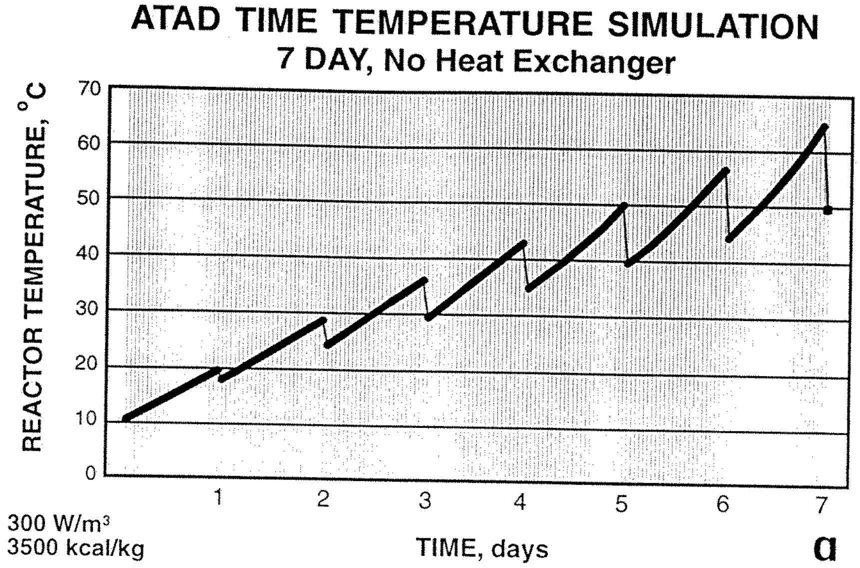
DIRECT INDEPENDENT SLUDGE/WATER HEAT EXCHANGERS

Figure 4

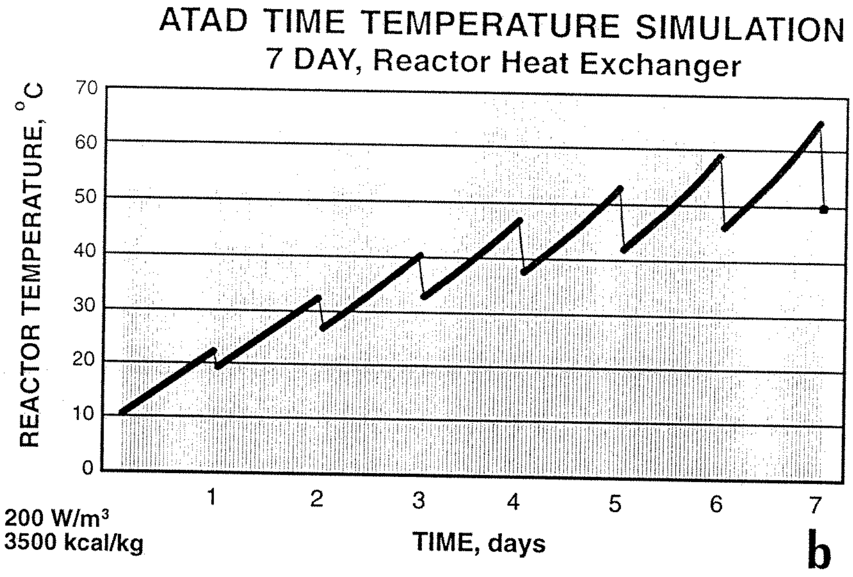


RECIRCULATION SLUDGE/SLUDGE HEAT EXCHANGER

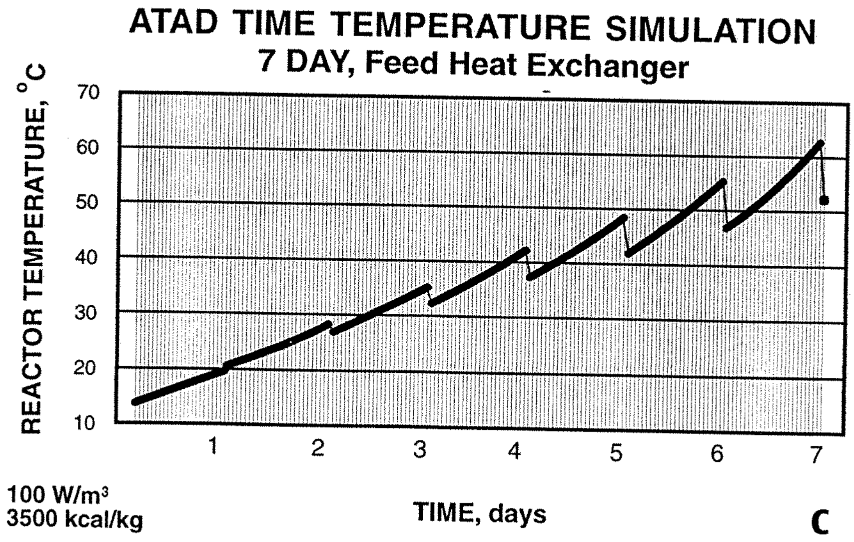
Figure 5



ATAD TIME TEMPERATURE SIMULATION
7 DAY, No Heat Exchanger



ATAD TIME TEMPERATURE SIMULATION
7 DAY, Reactor Heat Exchanger



ATAD TIME TEMPERATURE SIMULATION
7 DAY, Feed Heat Exchanger

Figure 6