THE HEAT PATH DIAGRAM FOR ENERGY MANAGEMENT

by

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ABSTRACT

The paper first defines energy management as a large scale optimization problem. We then identify the subproblem of adjusting the heat flow between each of several processes and a common utility system as one which can be studied using recent work by Cerda and coworkers (Doldan et al, 1983a, Doldan et al, 1983b). We decribe the use of a diagram which shows the flow of heat in such processes. With it one is able to see when improving the utility consumption of one or more of the processes may only result in the generation of more low pressure powerhouse steam. The diagram allows one to accomplish the analysis by hand methods. A linear programming model can also be written which corresponds to it. Finally we show how one can locate the more energy efficient relative production rates among the processes.

INTRODUCTION

This paper has been prepared at the invitation of the session chairman, Jerry Robertson. He requested a paper that would think of energy management as a large scale optimization problem with perhaps many competing objectives. The idea was to explore this viewpoint to see where future challenges might exist in the area of energy management.

The area of energy management is not an area in which I would claim any expertise. However, within my research group we have done work on energy conservation and on the setting up and solving of large-scale optimization problems. Thus the request did seem to present an interesting, albeit, somewhat risky one to accept.

In preparing this paper, it seemed first prudent to define the term "energy management". Making up a list of possible objectives that one would use to measure the degree of success that one has had in managing energy was the next challenge. These steps led to an attempt to think of the various degrees of freedom one is free to manipulate for this problem. Putting all these ideas together suggested that the problem is about as complete an optimization problem as one would ever care to formulate. BUT it also suggested that, with tools recently developed by Cerda and coworkers (Doldan et al, 1983a, Doldan et al, 1983b), it is possible to develop considerable insight into some aspects of the proper management of energy using very simple models that can be set up and solved by hand.

We shall therefore spend the bulk of the paper exploring how to attack a limited version of the problem of energy management with these simple tools.

A DEFINITION OF ENERGY MANAGEMENT

The following definition resulted from observing the titles of the other papers in this session and the earlier one, session 5, and from conversations with Jerry Robertson when trying to overcome the panic that was setting in as the deadline approached. The earlier session considers how one can modify an existing process or set of processes to improve their energy efficiency. The changes considered in particular involve altering the structure of the processes being examined. An example would be to restructure the heat exchanger networks.

In contrast the papers in the second session labeled energy management tend to take the process structure as being fixed and ask how best to manage the process to conserve the use of energy. Therefore one could consider the problem at hand to be the one where process structure is essentially fixed, and one is interested in operating in an energy efficient manner. To make the problem more challenging we can consider the managing of several processes which are tied together through the use of a common utility system. We shall, however, not ignore using the ideas that may come up in considering this problem to suggest where energy use could be significantly reduced by making obvious structural changes.

One can also consider time varying changes that occur within a process, where one will have to alter the running of the process with time to account for these changes. For example, often a catalyst will deactivate with use, and the process operation will have to be altered with time to maintain production. This alteration may have a significant impact on the utility system which in turn may have an impact on the other processes tied it. Clearly the deactivation of catalyst is a form of maintenance problem. One paper (Jackson, 1983) in this session considers scheduling maintenance problems. Such problems add the dimension of time to the problem.

One could imagine that scheduling the operation of several interacting processes whose products and/or raw materials may change periodically as being a problem in energy management. This type of problem has considerable conceptual overlap with the operation of batch processes.

Finally one could consider the managing of energy conservation projects within a company (McMahan and Roach, 1982), deciding which projects to reject, which to accept, and in which order to execute those accepted. We will not consider problems in this last class in this paper.

OBJECTIVES

It would appear that the nature of the problem of operating a set of interacting processes is one in which economics might dominate; however, one can imagine that the political aspects to this problem could overshadow the economic ones. For example, one may have to ask a plant manager to operate in a manner he views as suboptimal so his operation blends in better with the operation of a total set of interacting processes. It could be a challenge to convince him to cooperate. While obviously very important, we will not spend time considering this aspect of energy management further.

Obviously dollars are important. One can easily think of other objectives which are difficult to put into terms of dollars, however. For example, suppose one proposes operating a set of processes in a manner, which although energy efficient, is insufficiently flexible to tolerate expected process upsets. The flexibility of a system of interlinked processes thus becomes a second objective one has to consider. Can one see the tradeoffs in any reasonable way? Can one even model what one means by flexibility? Recent works by Grossmann and coworkers and by Morari and coworkers (Grossmann and Morari, 1983) are coming to grips with how to pose the flexibility (resiliency) problem. Grossmann and coworkers show that one must formulate a feasibility requirement which has the unpleasant characteristic of introducing an infinite number of constraints into the problem. They show how to convert the problem of handling this set of constraints into an optimization problem which must be solved within the outer optimization problem.

Other objectives one can consider are related to the safety of the processes, their dynamic characteristics for control (Morari and coworkers), and so forth. If one is to prognosticate about where future work is needed, it is in how to model processes so these characteristics can be measured in some quantitative way, thus allowing one to say that this alternative to a process is, for example, safer than another and by how much.

THE DEGREES OF FREEDOM

What can we manipulate to "improve" the operation of the processes? Given that the processes are to operate concurrently, one could consider the following adjustments as being reasonable:

1. adjusting the level of production for each of the processes,
2. adjusting utility temperature levels,
3. scheduling the use of different feedstocks and/or product manufacture versus time so the processes operating concurrently at any one time will blend together better, and
4. adjusting internal flows inside processes within the limits that are allowed.

Other alterations that one could consider, but which will require that the equipment be modified within the processes, are to change the heat integration structure, to change the pressures across which power is being generated in the utility system, etcetera.

APPROACHES TO SOLVING

An approach to solving the above energy management problems is to turn them into mathematical programming problems with, for example, a present worth objective function competing with a flexibility index objective function (competing with a safety objective function ...) subject to constraints which state that the equipment in the processes exist in fixed configuration. Operational degrees of freedom would include such variables as reflux rates, etc. To solve requires the use of multicriteria techniques, the solution of which is an entire family of solutions which show the tradeoffs possible among the competing criteria. The family of solutions is valuable because it gives sensitivity information about the problem, but clearly to obtain it also requires considerable computation. The problem in its most general formulation will be a mixed integer nonlinear, time varying multicriteria programming problem subject to an infinite number of inequality contraints. It could somewhat difficult to solve.

- It is clear that one can only solve aspects of the above problem and then only after looking for ways to reduce the problem size based on physical insight. An example of reducing the problem size in this manner is shown in Figure 1 where two distillation columns have been heat integrated on a T-Q diagram. The columns are represented by an area (Andrecovich and Westerberg, 1983L Heat is degraded from the high temperature required by the reboiler (top of the diagram) of the hotter column. This heat is expelled out of its condenser and used as part of the heat needed by the reboiler of the second colder column. Some of the heat needed by the reboiler of the second column is also shown as coming from the same hot utility which supplied heat to the hotter column. An insight is that the reflux ratio of the hotter column does not affect the consumption of energy for the total process whereas the reflux ratio of the colder one does. Thus one could set the reflux ratio of the hotter column by some reasonable heuristic and optimize only over the reflux ratio of the colder one. One could imagine reducing the size of the problem considerably in this manner (an approach consistent with the work of Douglas and coworkers in setting up and solving design problems (Dotglas, 1977, Douglas et al, 1983)).

AN ENERGY MANAGEMENT PROBLEM

This next section will present an approach to solving the particular energy management problem of operating several steady-state processes which are tied to a common utility system. The approach will use recent ideas presented by Cerda and coworkers (Doldan et al, 1983a, Doldan et al, 1983b).

To present this section we will use an example which consists of two processes that we wish to operate efficiently and which are tied to a common utility. The problem is particularly interesting if we assume that one of the processes requires the generation of work and only a modest amount of heal from the utility system while the other process is a large heat consumer and only a small consumer of work. By work, we mean shaft work such as would be required to drive compressors. Obviously one is hoping that the two processes together can make more efficient use of the energy produced by the utility system than they could if operated separately.

The Cerda papers consider the problem of improving the energy efficiency of an existing process tied to a utility system which is servicing not only the process of interest but also other processes. They wished to discover the potential for reducing the consumption of utilities subject to the constraint that the configuration of the utility system was to remain unaltered.

The obvious approach is to discover the thermodynamic minimum utility requirements for the process by itself, using the analysis originally suggested by Hohmann (Hohmann, 1971) and later by Linnhoff and Flower {Linnhoff and Flower, 1978), The heat exchanger system for the process can then reconfigured to attempt to reduce the required utility consumption to this minimum, making the fewest changes possible in an attempt also to minimize capital investment. Cerda and coworkers discovered that this approach was incomplete. The main result of their savings within the process being studied was to force the utility system to generate more low pressure steam. Low pressure steam was already in abundance and was being condensed using cooling water.

Their paper presents how to analyze correctly such a problem to discover the maximum amount of energy that can be saved for a process tied to a fixed utility system. Obviously the analysis requires looking at both the process and the utility system. Our goal here will be to show how these ideas, essentially without modification, allow one to to analyze the energy management of several processes tied to a common utility.

Figure 2 illustrates a minimum utility analysis which might be done for a process. It consists of developing the heating curves for all "cold" streams which are to be heated within the process and merging them into a single "merged heating curve"; and similarly developing the "merged cooling curve" for all the "hot" streams which are to be cooled within the process. These two merged curves are adjusted with respect to one another such that the cooling curve is everywhere at least AT_{mm} above the merged heating curve on this figure. The point where the curves are exactly this minimum temperature driving force apart is called the "pinch point" for the process. The portion of the merged heating curve not covered by the merged cooling curve'(to the upper right side of the figure) represents the minimum amount of hot utility needed to operate the process. The portion of the merged cooling curve which does not cover any of the heating curve (to the lower left) represents the minimum amount of cold utility needed.

Figure 3 presents an alternate way (Linnhoff et al, 1982) to think about the heat flow in a process. A process which has a pinch point within it can be partitioned into two parts: (1) a high temperature heat sink above the pinch point and (2) a low temperature heat source below the pinch. Clearly the low temperature heat source portion cannot provide its heat to the high temperature heat sink portion of the process unless thermodynamic work is done. To satisfy the heating deficiency of the high temperature heat sink portion of the process, heat must normally be obtained from hot utilities. Similarly, the excess heat produced by the low temperature heat source will normally be dumped into the cold utilities. Any utility heat input which is in excess of the minimum required will result in that same amount of excess heat flowing from the high temperature heat sink portion of the process to the low temperature heat source portion and then into the cold utilities. Thus, as pointed out by Linnhoff and coworkers, minimum utility use corresponds to a zero flow of heat across the pinch.

THE HEAT PATH DIAGRAM

To illustrate the concepts put forward by Cerda and coworkers, we consider a "Heat Path Diagram" (HPD) for the process and utility system shown in Figure 4. The key idea is simply that one cannot reduce overall utility consumption by reducing the heat flow Q_{12} across the pinch point if (1) there exists an alternate path, Q_{34}r for heat to flow to the cold utility heat sink from the utility heat source and (2) the reduction in Q_{12} only results in an equal increase in the heat flow Q_{34}.

Figure 5 illustrates a Heat Path Diagram for two processes tied to a common utility system. The combustion of fuel provides the highest temperature heat input into the utility system. Three steam headers are illustrated, one each at high, intermediate and low pressures (and thus high, intermediate and low temperatures). The utility system also generates shaft work for the processes using backpressure turbines between the high and intermediate and the intermediate and low steam headers. Each of the processes has been analyzed to discover where it pinches. Also we assume that the heat flows which are illustrated have been found by using plant data.

Consistent with the approach taken by Cerda and coworkers, we note that a reasonable goal could be to operate the processes in a manner which uses the minimum utility consumption. This goal is the same as minimizing the heat flow from the fuel to the high pressure steam header, Q_{12}. The Heat Path Diagram allows one to see just where heat flows are going and how to reduce them if it is ones goal to reduce the heat flow Q_{12}. Clearly we must reduce the heat flow along each path to the least value it can have while not allowing any of the flows to become negative. As pointed out by Cerda and coworkers, one of the flows Q[illegible], Q[illegible] and Q_{45} must be reduced to zero. Where the analysis becomes interesting is when the flow Q_{e} is large because of the requirement to produce shaft work W_e. Then one has the option to send any excess heat from the IP steam header as heat into Process 1 along path Q_{3g} or along the path from the intermediate steam header to the low temperature steam header, Q[illegible]. The heat may be more than the minimum required by Process 1 from the intermediate steam header, but, if it is not sent to Process 1, it will simply be cascaded to the low pressure steam header and then to the cold utility.

The problem to reduce the flow Q_{12} to a minimum can be formulated approximately as a linear program. We first have to analyze each of the processes to obtain the amount of heat that each needs to import from or that each can export to each of the steam headers. Figure 6 illustrates how such an analysis can be done for Process 1 using its merged heating and cooling curves. (The HDA representation of Itoh et al (Itoh et al, 1982), which is the same as the Grand Composite Curve representation of Linnhoff and coworkers (Linnhoff et al, **1982)** is also easily used to get the same information.) The heats $Q^*_{9}9$' ^3^*9 ^{anc*} ^*Q_{1}4 ^{re}P^{resent} bounds on the amount of heat that should be imported and exported in a minimum "cost" utility use solution for Process 1. In particular, the process must import at least $Q^*_{2,9}$ units of heat from the high pressure header to operate. As much as $Q^*_{3,}$g units of heat can be imported from the intermediate pressure header, which one should expect is of lower cost since it is at a lower temperature. Finally, **for** the case when no heat is transported across the pinch in Process 1, $Q^*_{10,}$4 units of heat from Process 1 can be used to generate steam for the low pressure steam header (whether it is needed or not).

A LINEAR PROGRAMMING MODEL

The formulation of a crude linear model for reducing $Q_{1,2}$ is as follows.

$$\text{MIN } Q_{12}$$

Process 1

$$(*5 * {}^{\circ}2.9 - Q^*_{2,9}$$

$$Q«^{x}_{3,9} \cdot Q_{3.9} - <^{\circ}3.9 ** {}^{Q}2.V$$

$${}^{Q}9.10 » {}^{c}*3*9$$

$${}^{Q}10.5 \; {}^{s} \; {}^{Q}10.5 + {}^{Q}9.10 * {}^{Q}10.4$$

Process 2

similar to the equations for Process 1

High Pressure Steam Header

$${}^{Q}1.2^{S}\,{}^{Q}2.9 + {}^{Q}2.11 + {}^{Q}2.3 + {}^{Q}2.6$$

High/Intermediate Pressure Turbine

$${}^{W}A \; {}^{s} \; {}^{Q}i<5 \text{ " } {}^{Q}c? \quad <^{w}e \text{ given})$$

$$Q_{ft}o \; {}^{s} \; (1 \text{ " } ?)*Q\text{-}_{c}$$

etcetera

where $Q_{i,j}$ = heat flow along path from subsystem i to subsystem j

$Q^{*}_{i,j}$ = heat flow for min utility cost solution for process

$Q??_{i,j}$ = heat flow in excess of min utility cost solution flow

W_{fc} = work produced by a turbine

Tf = thermodynamic efficiency times turbine efficiency (fixed)

OTHER USES OF THE HPD

The Heat Path Diagram in Figure 5 gives us considerable insight into our processes and their joint operation with the common utility system. For example, suppose we wish to scale the relative level of operation of the two processes so their utility needs blend in an optimal manner. From the diagram we see that a candidate for the best relative level of operation is when the heat flow $Q_{g\,1Q}$ is reduced to zero while the heat flow Q_{-Q} is at its best value Q^{*}_{Q}. We would also want both the flows across the process pinch points to be zero, if • possible. At this level of operation the two processes are just balanced in the sense that the work load W_6 is degrading exactly the amount of heat needed by the intermediate steam header to allow that header to supply Process 1 with Q^{*}_{-} units of teat along path OL_{Q}. We can see this just by looking at this diagram.

We can add contraints to the above linear programming formulation for the problem to allow the processes to operate with an adjustable scale between them. Each of the heat flow variables which appear for Problem 1 can defined as follows.

$$Q_{i,j} = S_1 * Q^{+}_{i,j}$$

In addition the work required from each of the turbines can be scaled as follows.

$${}^{w}{}_{k} \bullet {}^{s} , \bullet < i^{+} \, {}^{w}W$$

where $Q^{*}_{i,j}$ = heat flow for base case along path i,j

$W^{+}_{k,1}$ = work needed by process 1 from turbine k

S_1 = size of process 1 relative to its base case size

The problem thus remains linear, but it is formulated so the size of Process 1 is allowed to vary to improve whatever objective is selected.

If one sets the value of S_1 to a number of different values and for each solves the above linear program, a plot of the results should have the form shown in Figure 7. The point marked 'a' on that figure would correspond to the point where Process 1 has just become large enough that there is no continued inexpensive heat coming into it from the intermediate steam header, heat which is being used first to drive the turbine that creates the work W_6 or is coming from Process 2 along path $Q_{12,3}$. The point 'a' is an excellent candidate for where the two processes are operating at their best combined level of operation from a utility use point of view.

One can of course invent other objective functions to optimize. If one knows the profit coming from each of the processes per unit of production, when neglecting the operating costs due to fuel consumption and cooling utility costs in the utility system, then one could use the objective function form

$$C_{1,2}Q_{1,2} + C_{CW}*(Q_{10,5} + Q_{4,5} + Q_{12,5}) - P_1S_1 - P_2$$

where $C_{1,2}$ = cost per unit of heat from fuel

C_{CW} = cost of cooling water per unit of heat transferred to it

P_i = profit of process i at base case level of operation less the cost of associated utilities

The cost and profit values above can include such items as warehousing costs if the production rates are higher that the demand for the period of time the two processes are scheduled to operate together or they could include a penalty for producing less that the amount needed.

Another issue we can address at least superficially is the issue of flexibility of heat integrated processes. If we analyze two processes together to decide their combined minimum utility use, we shall almost certainly find that some heat must be transferred between them. Figure 5 shows that Process 2 could give heat to Process

1 since the heat source portion of Process 2 occurs at a high enough temperature that it could give heat to the heat sink part of Process 1. The question is whether it makes sense for this transfer to occur indirectly through the utility system (as shown) or whether it should occur directly. The former arrangement offers the advantage of decoupling the two processes, making the total system more flexible. Direct transfer will mean that if one process must shut down, it will likely severely impact the operation of the other, perhaps causing it to shut down too. Seeing where this transfer must occur can suggest where to establish the intermediate pressure steam header temperature level; ie, such that Process 2 can give steam to the header and then Process 1 can get this heat by using steam from this header. Of course an alternative to maintain the desired flexibility is to place an extra steam heater as a standby in Process 1 and an extra utility cooler in Process 2.

We could spend lots of time playing with the Heat Path Diagram. The essential point is, however, to see that this diagram is a very useful tool for analyzing a set of heat integrated processes. It offers considerable insight into how the processes can be operated in an efficient manner with respect to the utility system. It is simple enough that it appears that one can often successfully manipulate it by hand to find the better solutions.

IN CONCLUSION

We have discussed briefly various aspects of energy management for processes. Motivated by the excellent work by Cerda and coworkers, we have presente the Heat Path Diagram for processes tied to a common utility and have shown it usefulness for understanding the flow of heat among the processes and the utility system. In particular we have shown that one can see from this diagram how to reduce heat flows in a manner fhat reduces the fuel consumption for the utility system while still allowing processes to use utility flows within them in excess of their predicted minimum requirements if reducing these flows is of no benefit to the overall utility consumption of the process. We have also discussed briefly how one might adjust the relative production rates of the processes so their combined utility use is the most efficient, and finally we have discussed even more briefly one aspect of the tradeoffs between utility savings and flexibility one must consider when heat integrating two processes.

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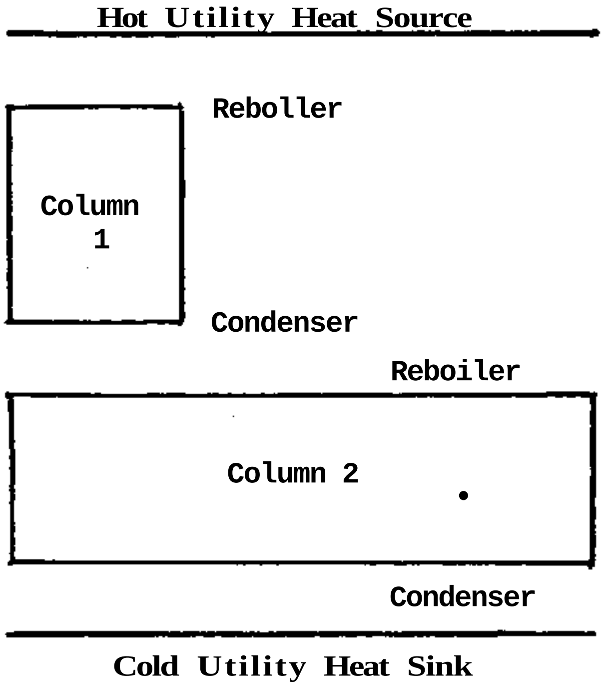

Figure 1, Heat Integrated Distillation Columns

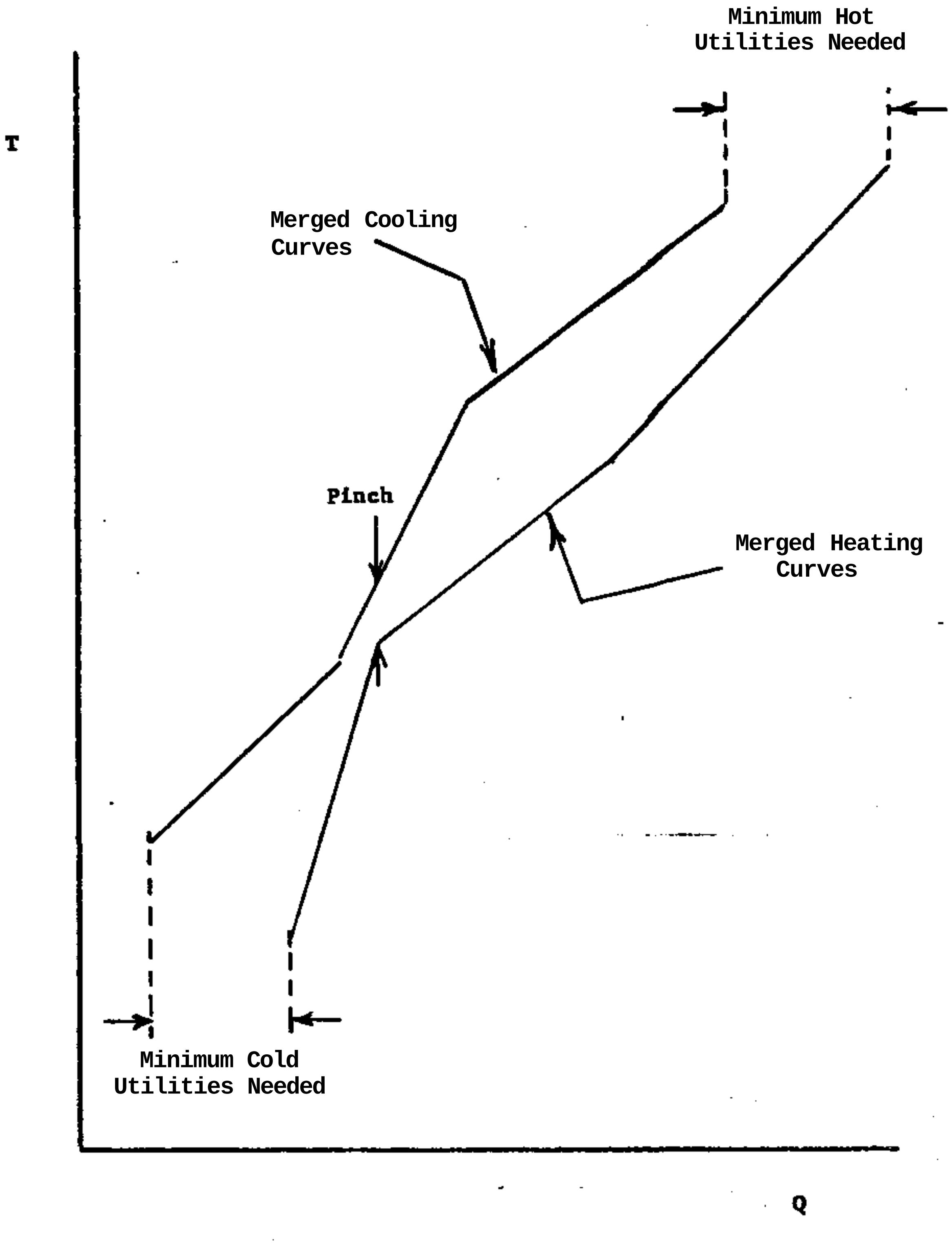

Figure 2. Minimum Utility Analysis for *m* Process

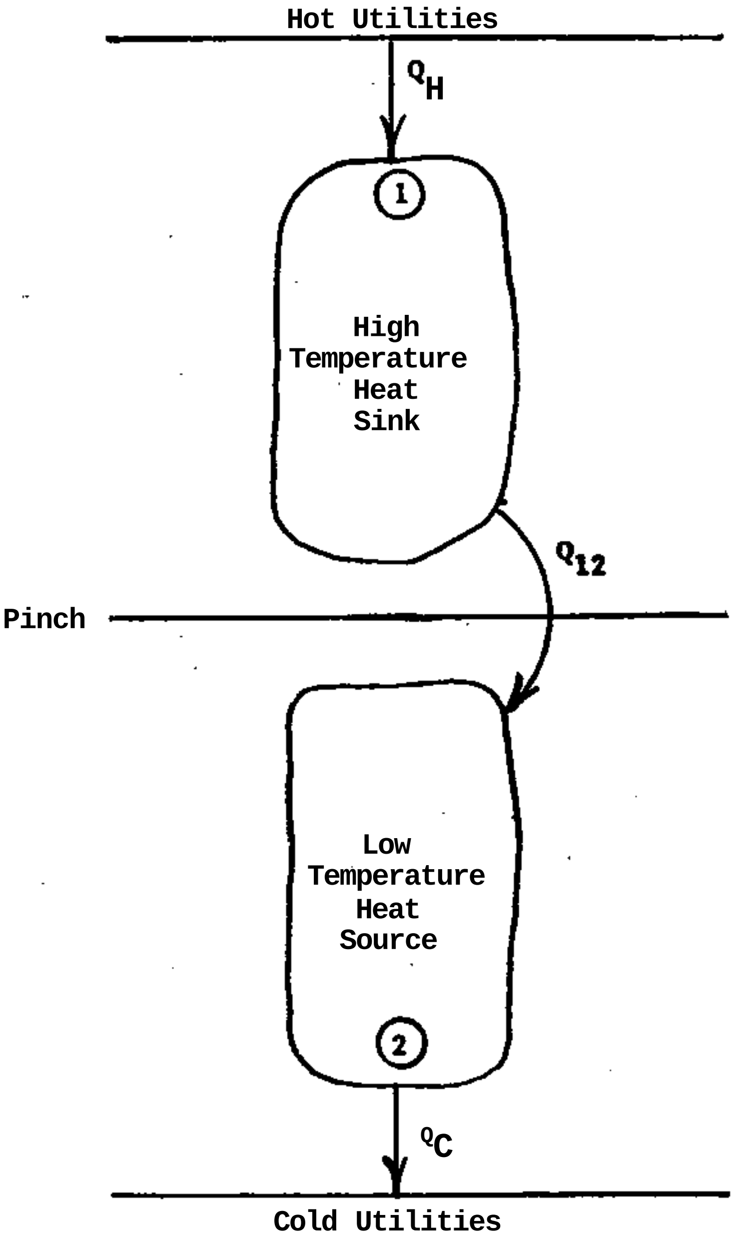

Figure 3. Heat Sink/Heat Source View of a Process Having a Pinch Point

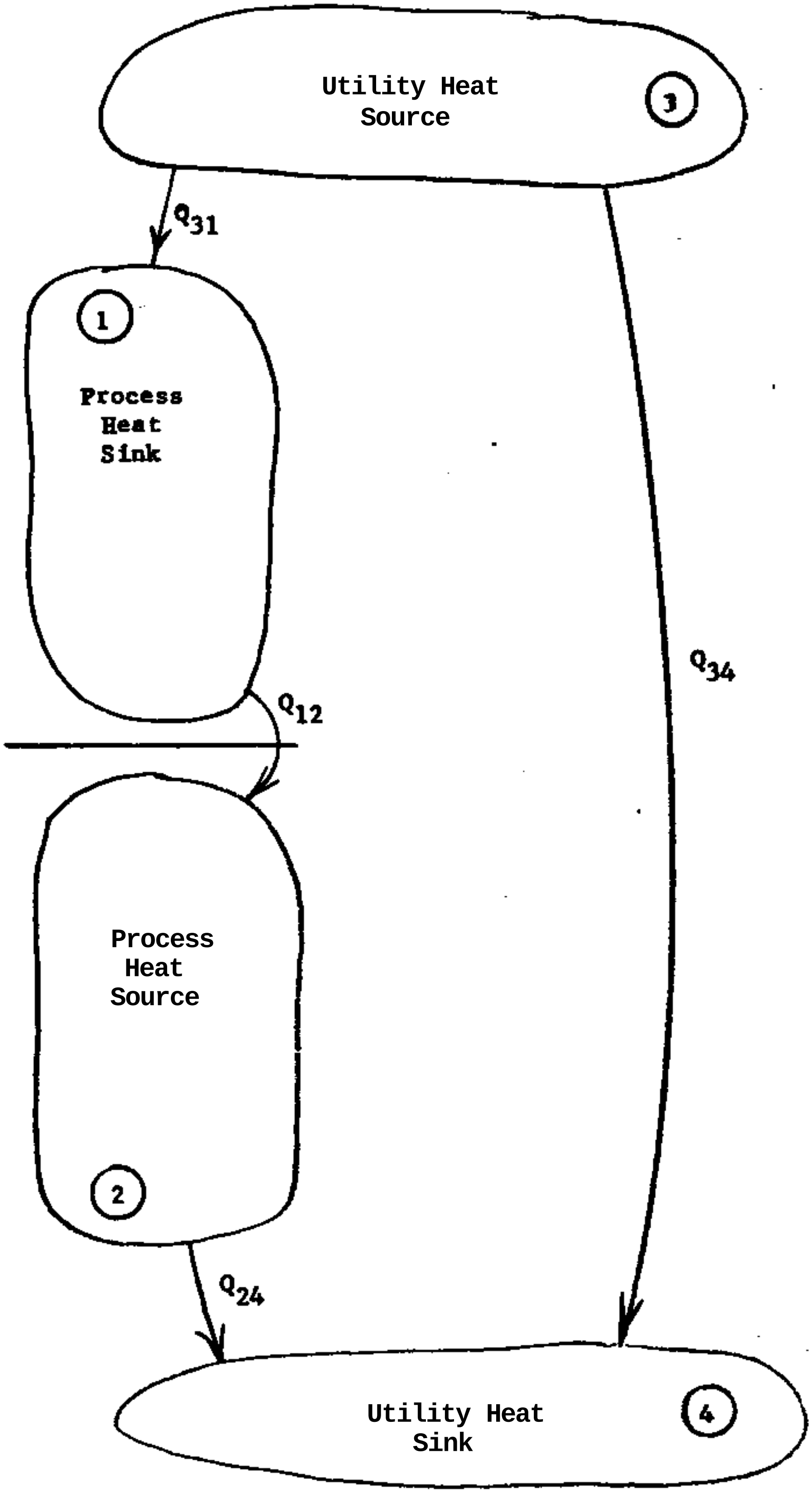

Figure 4. Bypass Heat Path in Utility System

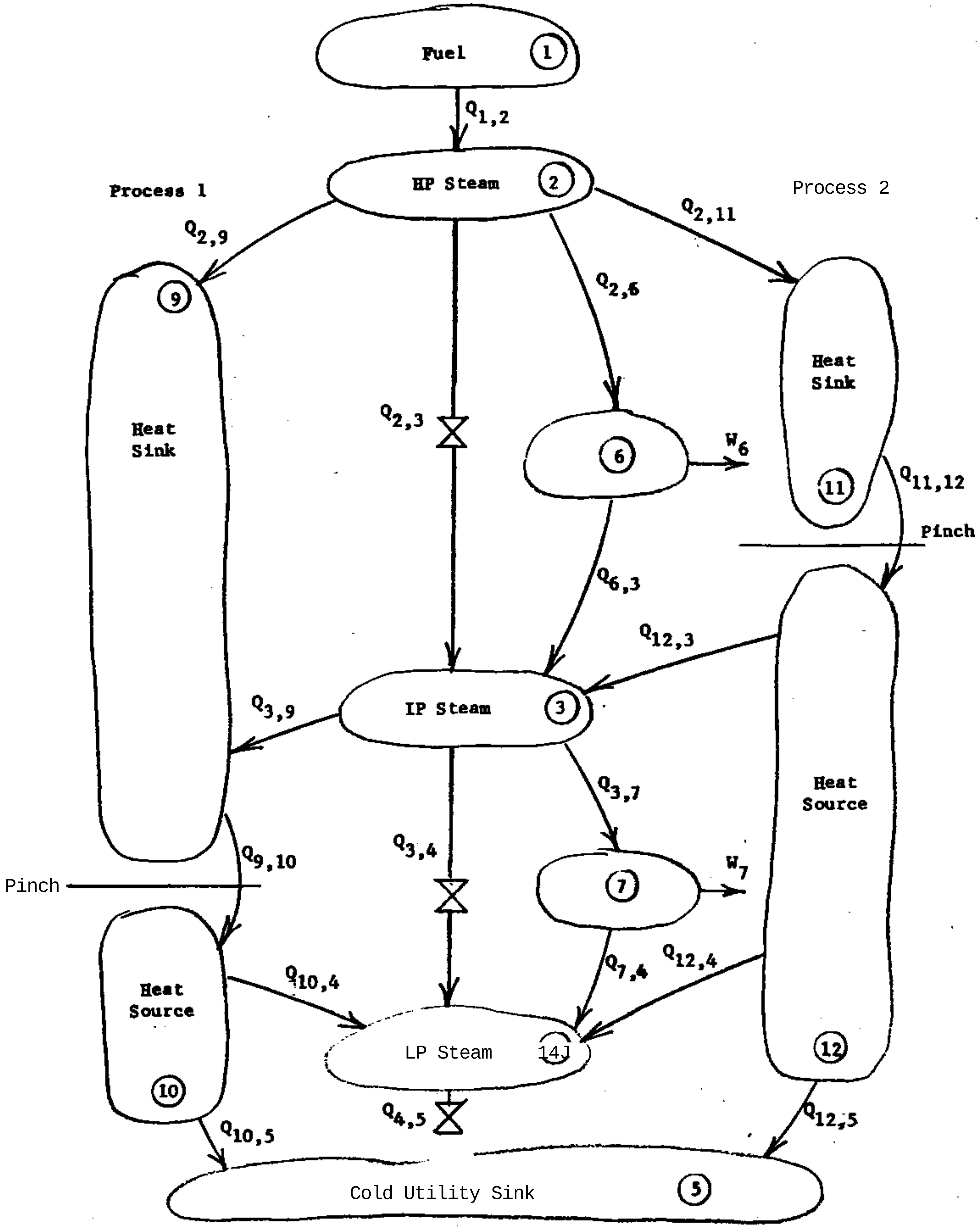

Figure 5. Heat Path Diagram for Example Processes

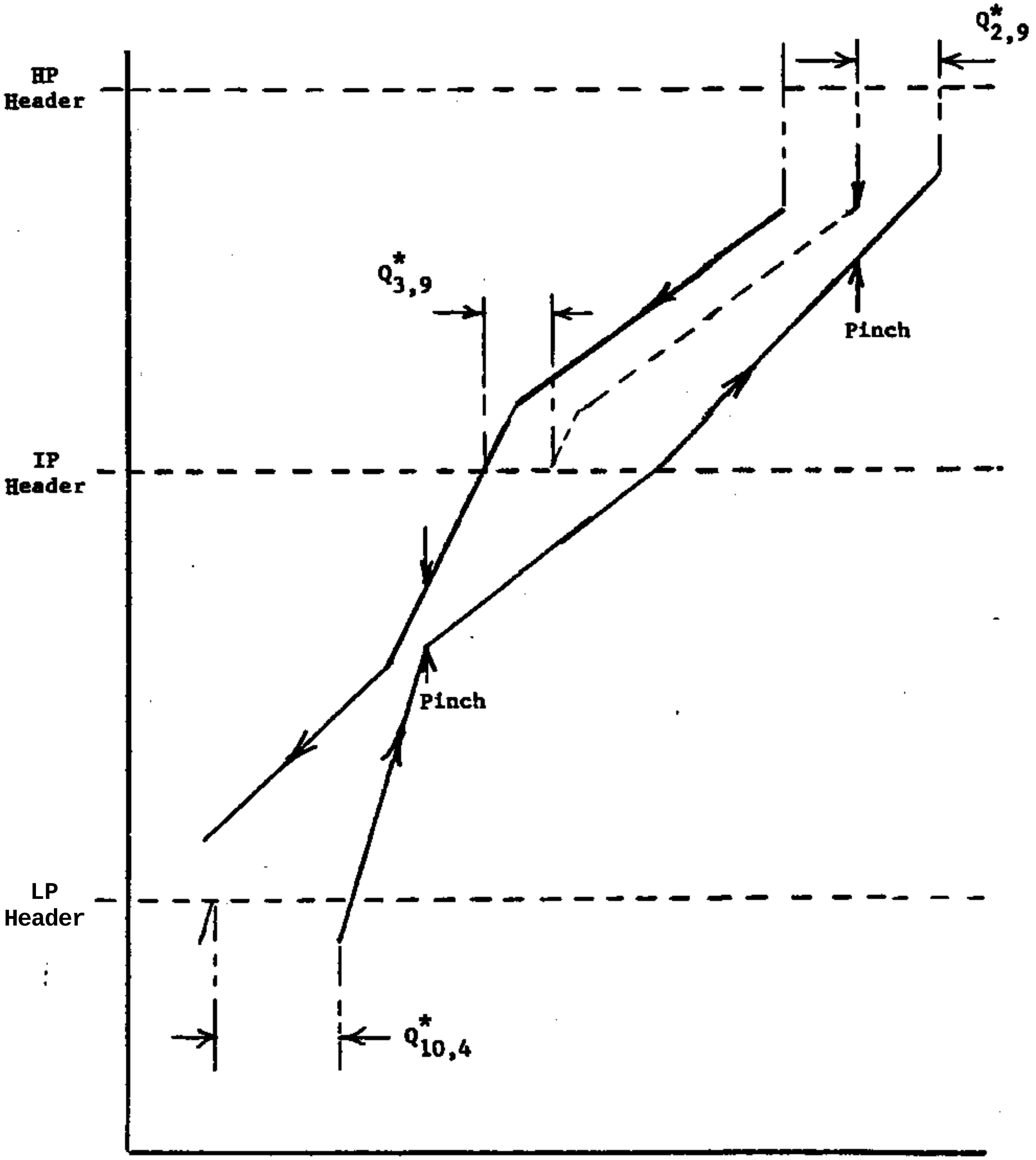

Figure 6. Establishing Bounds on Heat **Exchange Between Steam** Headers and Process 1

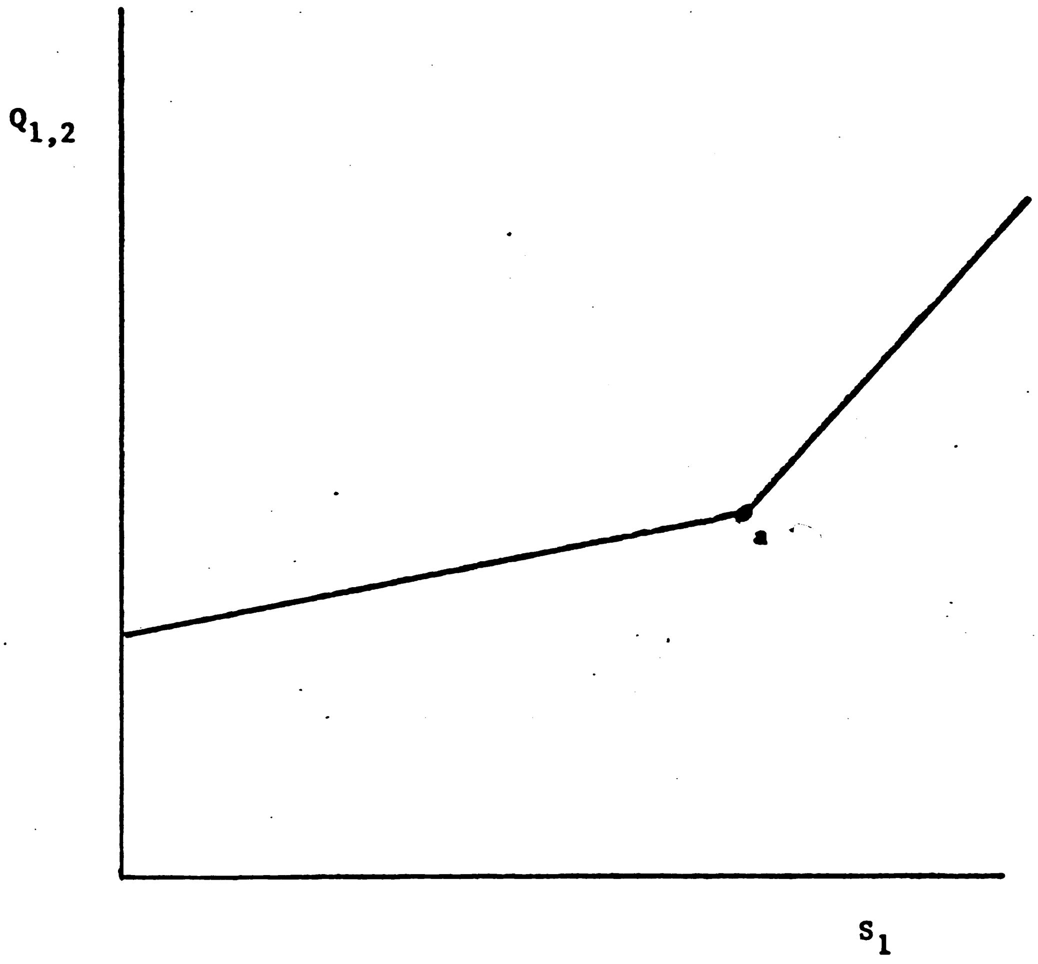

Figure 7. The Expected Behavior of Fuel Consumption Versus the Size of Process 1