MASS INTEGRATION AND POLLUTION PREVENTION

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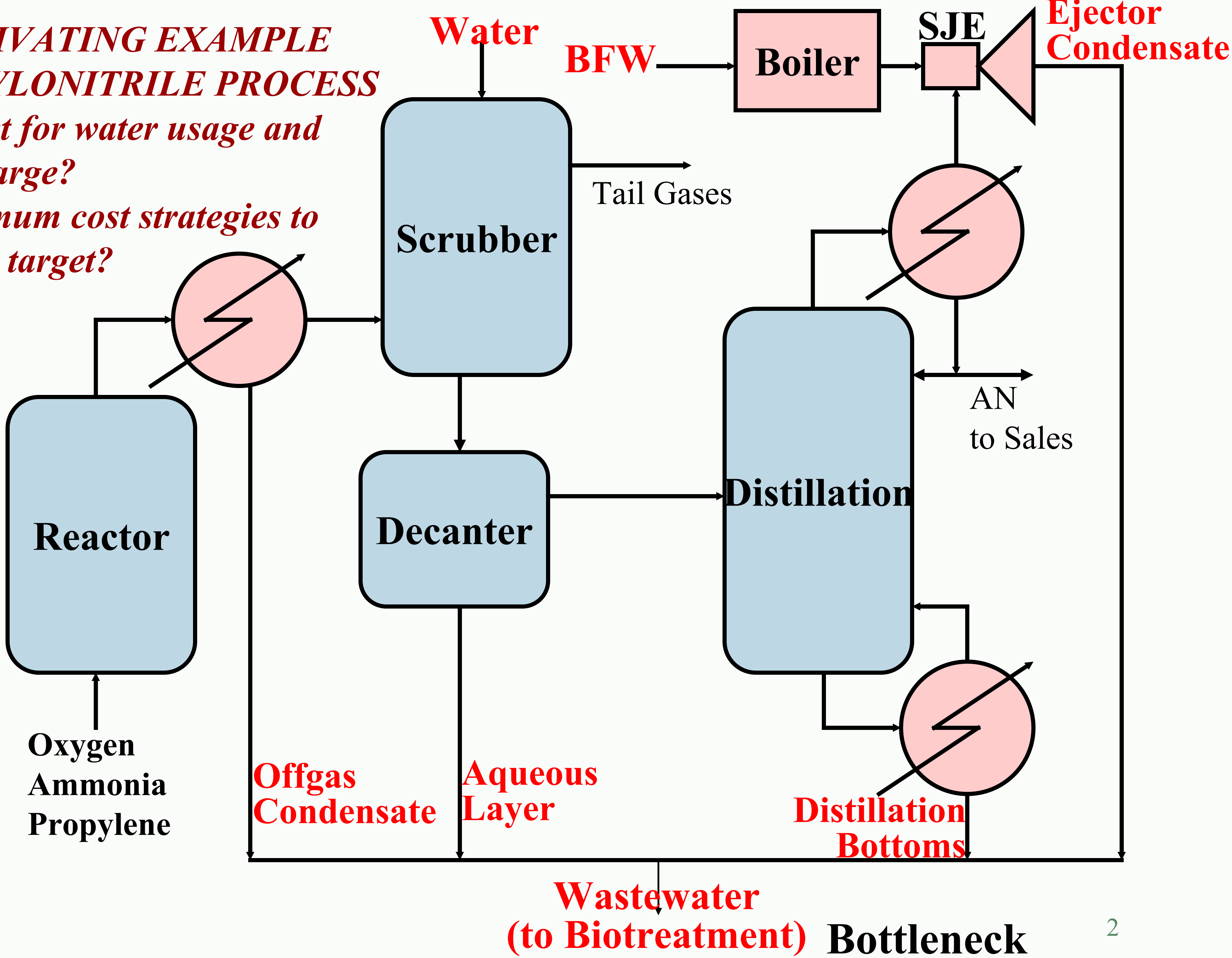
MOTIVATING EXAMPLE
ACRYLONITRILE PROCESS

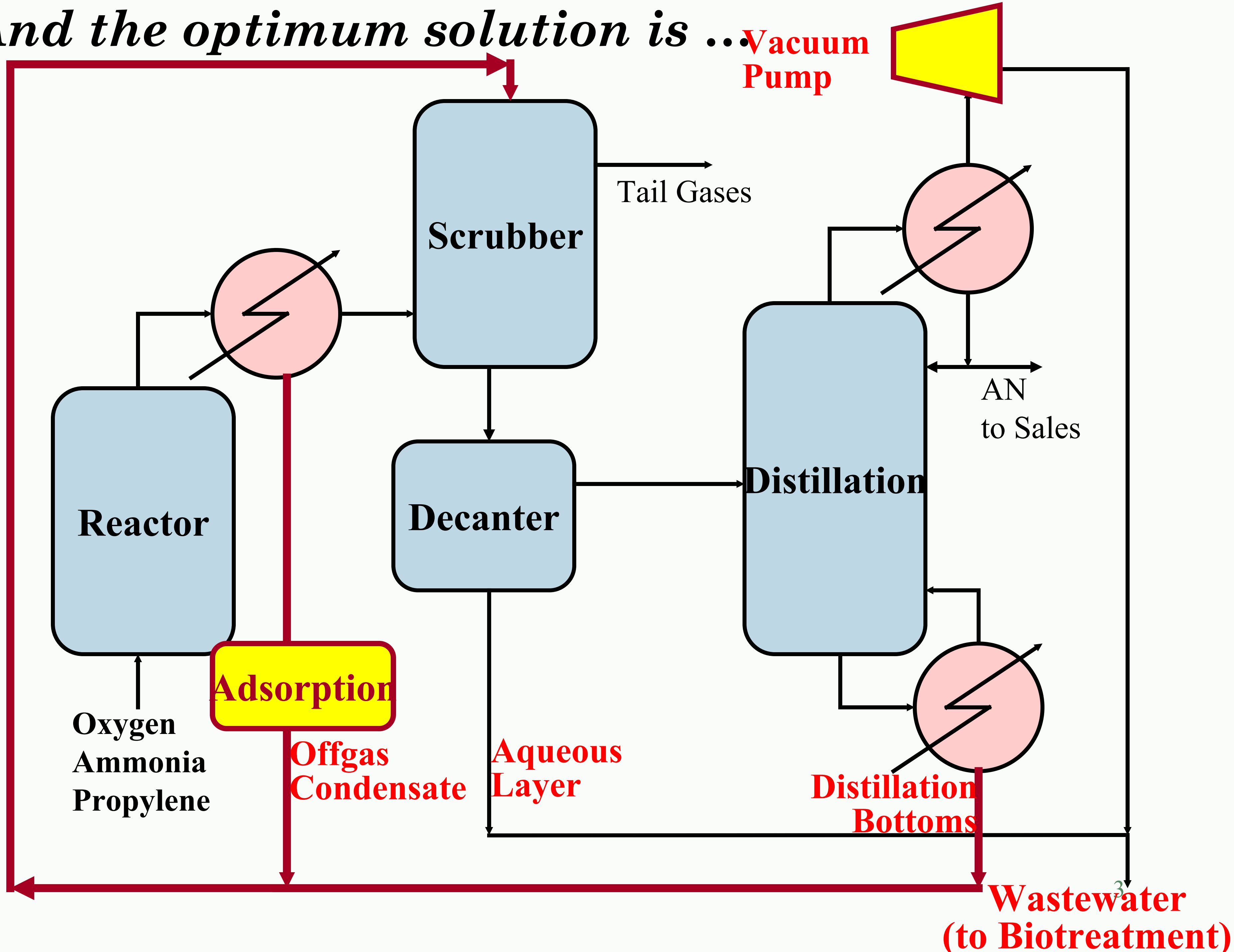
Target for water usage and discharge?

Minimum cost strategies to attain target?



Ref. El-Halwagi, M. M., "Pollution Prevention through Process Integration: Systematic Design Tools", Academic Press (1997)

And the optimum solution is …



OBSERVATIONS

- **Numerous alternatives**
- **Intuitively non-obvious solutions**
- **Focus on root causes not symptoms, must go to heart of process**
- **Need a systematic methodology to extract optimum solution**
- **Process must be treated as an integrated system**

Conventional Engineering Approaches

- Brainstorming among experienced engineers
- Evolutionary techniques: copy (or adapt) the last design we or someone else did
- Heuristics based on experience-based rules

State of the art:

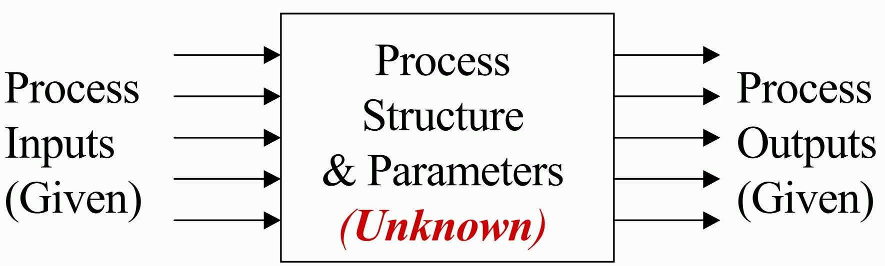
Systematic, fundamental, and generally applicable techniques can be learned and applied to synthesize optimal designs for improving process performance.

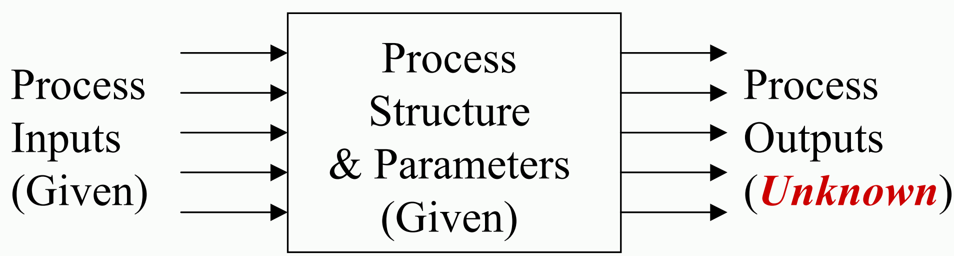
This is possible via *Process Synthesis and Integration + Optimization*:

You will learn the fundamentals and applications of process synthesis, integration, and optimization

Process Design =

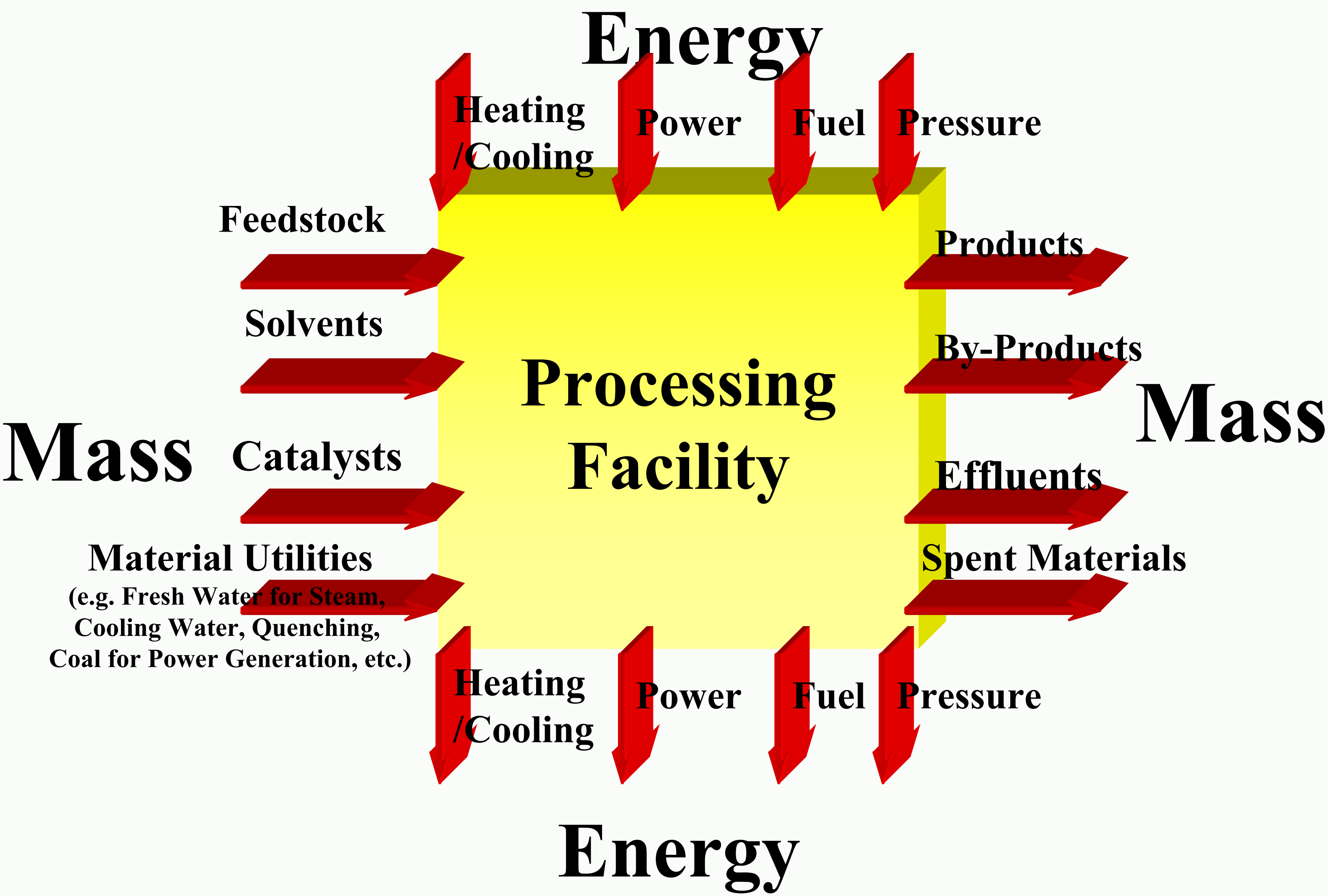
Process Synthesis + Process Analysis





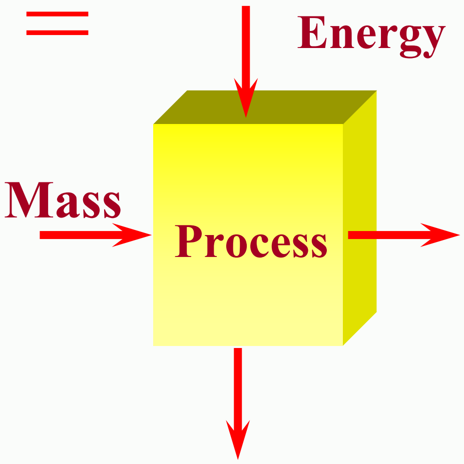
PROCESS INTEGRATION

A holistic approach to process design and operation that emphasizes the unity of the process and optimizes its design and operation



Mass-Energy Matrix of a Process

<u>PROCESS</u> INTEGRATION = <u>MASS</u> INTEGRATION + <u>ENERGY</u> INTEGRATION



Mass Integration

A systematic methodology that provides fundamental understanding of the global flow of mass within a process and employs this understanding in identifying performance targets and optimizing the generation and routing of species throughout the process.

Overall Philosophy

<u>BIG</u> PICTURE FIRST,
DETAILS LATER

FIRST, understand the global picture of the process and develop system insights

→

LATER, think equipment, detailed simulation, and process details.

TARGETING APPROACH OF PROCESS INTEGRATION

Identification of performance targets for the whole process <u>AHEAD</u> of detailed design!!!

Specific Performance Objectives

- **Profitability improvement**
- **Yield enhancement**
- **Resource (mass and energy) conservation**
- **Pollution prevention/waste minimization**
- **Safety improvement**

How?

ELEMENTS OF PROCESS INTEGRATION

- **Task Identification: Explicitly express the goal as an actionable task**

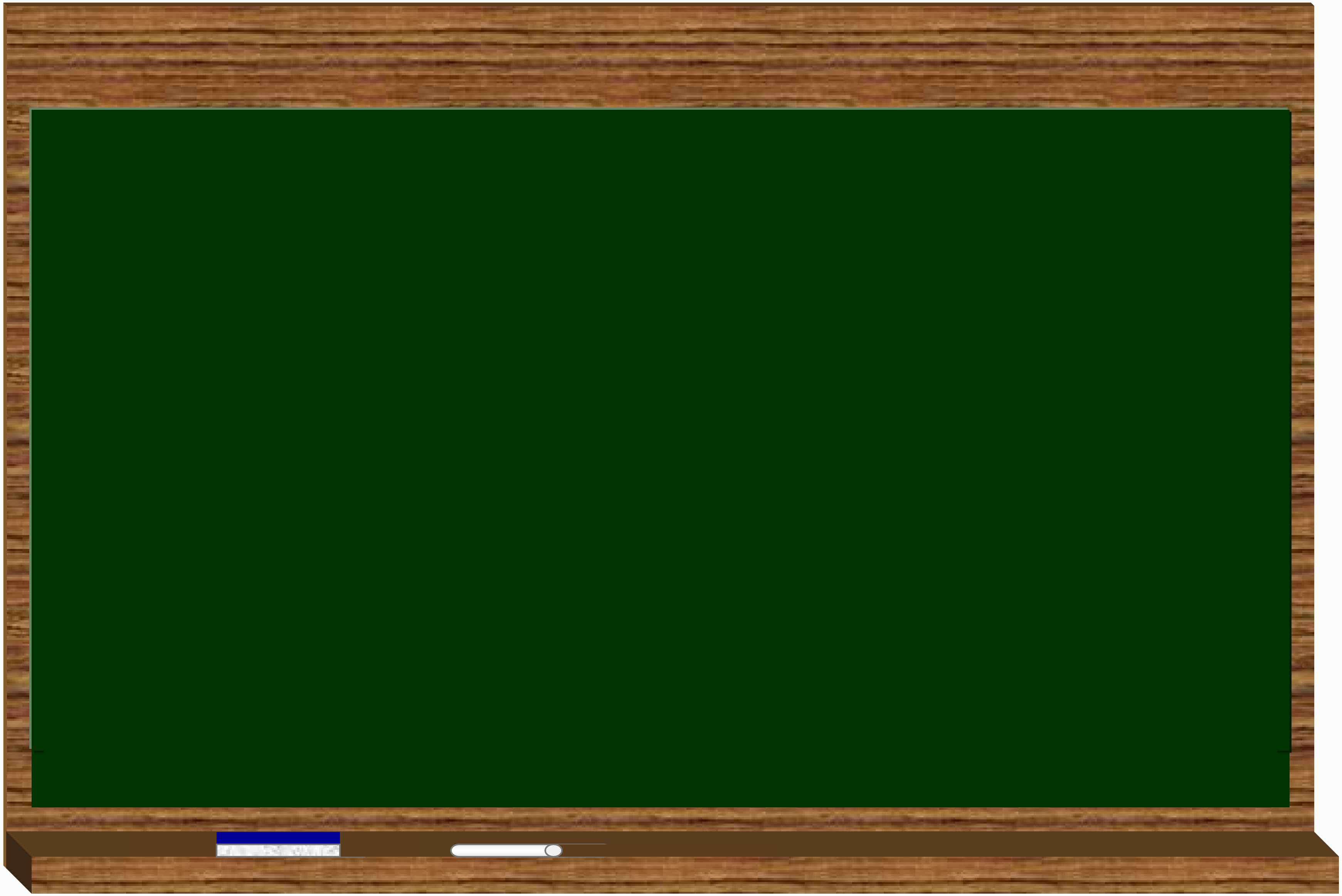
  Examples: - Pollution prevention = decrease flowrate of wastewater, pollutant loading, etc.

  - Debottlenecking = reduction in wastewater flowrate

- **Targeting: Benchmark performance ahead of detailed design**

- **Generation and selection of alternatives (synthesis)**

- **Evaluation of selected alternatives (analysis)**



We will learn:

⇒ How to identify best achievable pollution-prevention targets for a process WITHOUT detailed calculations.

⇒ How to systematically reach the target at minimum cost?

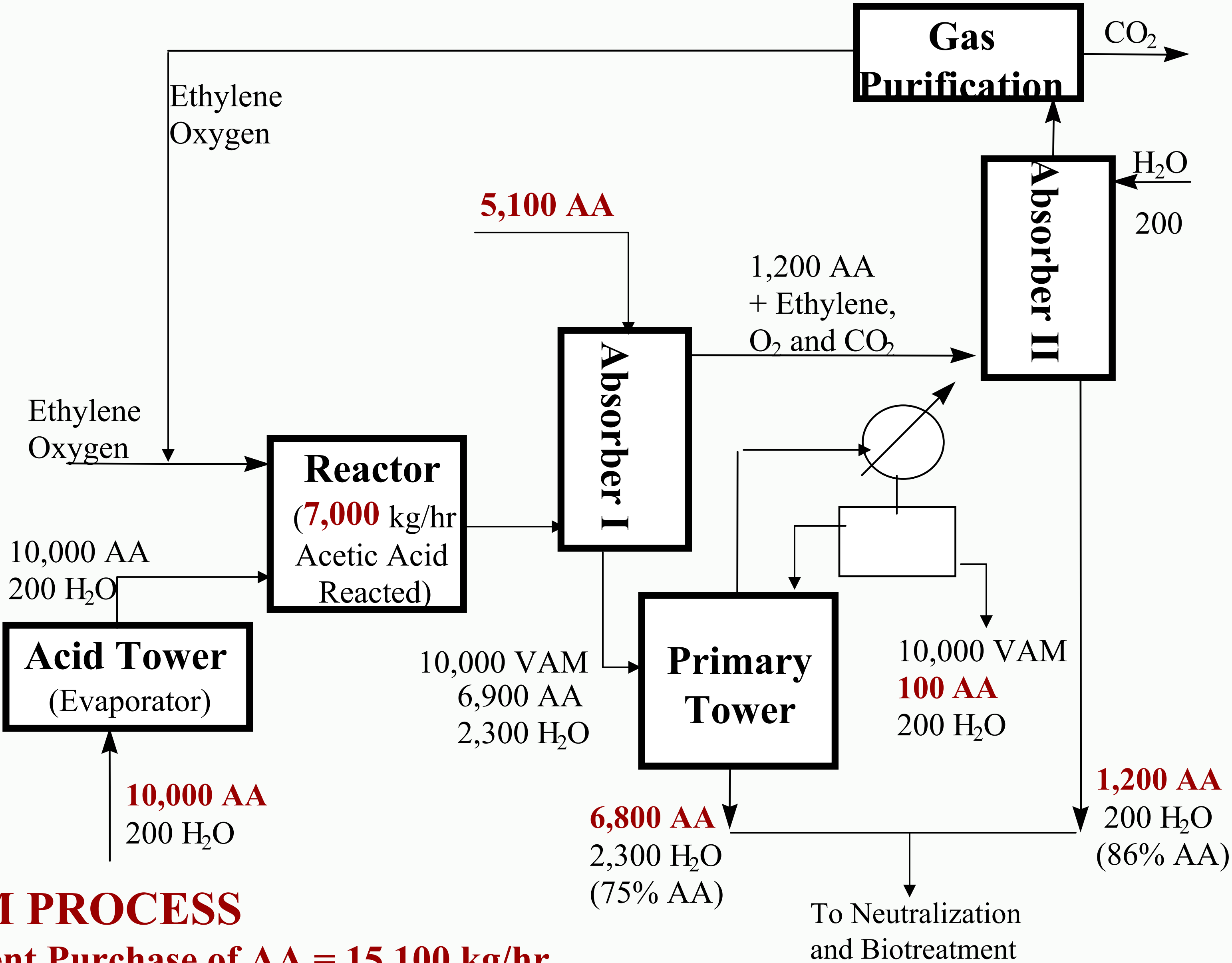
⇒ How to determine optimal stream rerouting?

⇒ How to place additional units and determine their performance?

⇒ How to understand the BIG picture of a process and use it to reduce waste from any plant?

OVERALL MASS TARGETING

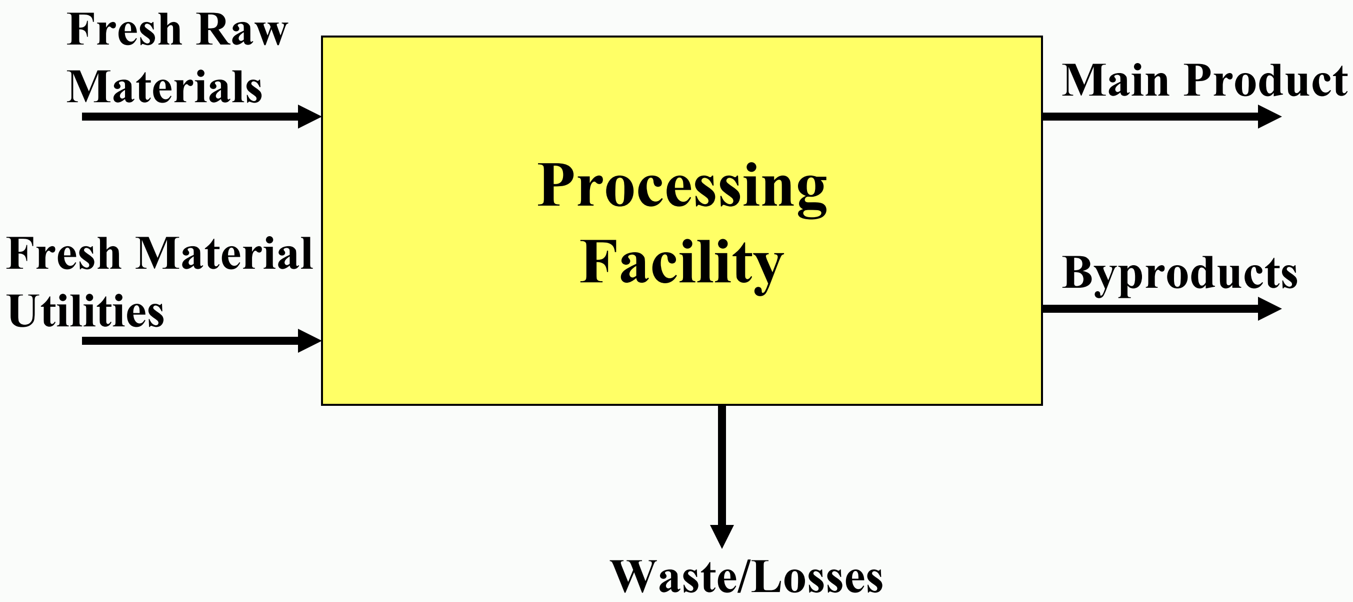
WHAT IS TARGET FOR MINIMUM AA FRESH PURCHASE?



VAM PROCESS

Current Purchase of AA = 15,100 kg/hr

OVERALL MASS TARGETING



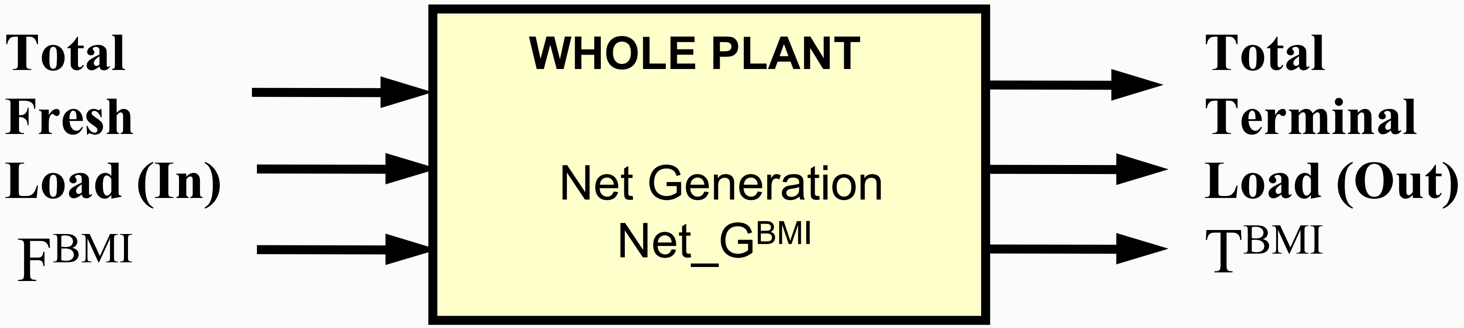
How to benchmark performance for mass objectives of the whole process ahead of detailed design?

- **Minimization of waste discharge/losses**
- **Minimization of purchase of fresh resources (raw materials, material utilities)**
- **Maximization of desired products/byproducts**

Need a holistic and generally applicable procedure

Example 1: Reduction of Terminal Losses or Discharge of Waste

- **Terminal Load (out) = Fresh Load (in) + Net Generation**



Overall Mass Balance Before Mass Integration (BMI)

$$T^{BMI} = F^{BMI} + Net\_G^{BMI}$$

For fixed generation:

Minimum terminal (out) corresponds to minimum fresh (in)

To minimize fresh:

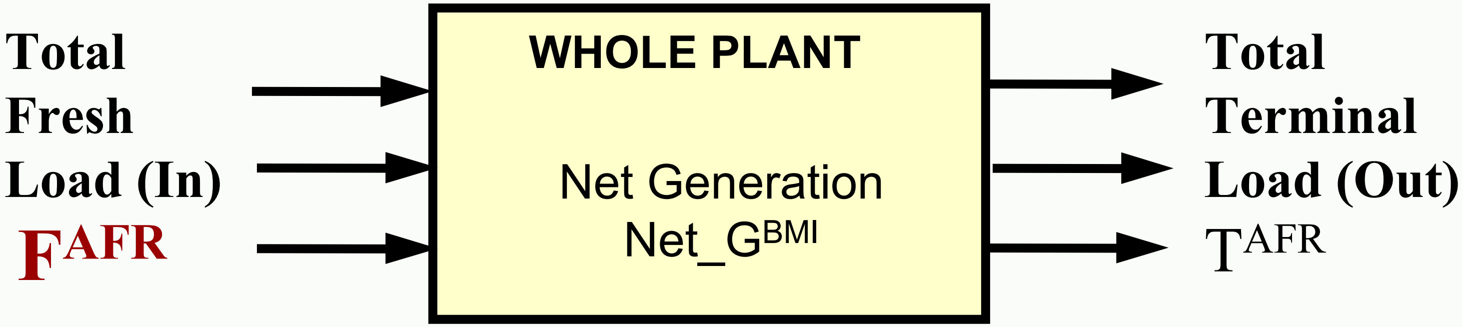
1. Adjust design and operating variables
2. Maximize recycle to replace fresh usage

1. Adjust Design and Operating Variables to Reduce Fresh

- **What are the design and operating variables in the process that influence fresh consumption?**
- **Which ones are allowed to be changed (manipulated variables)?**
- **How is fresh usage related to these design and operating variables?**

Fresh Usage = f (manipulated design variables, manipulated operating variables)

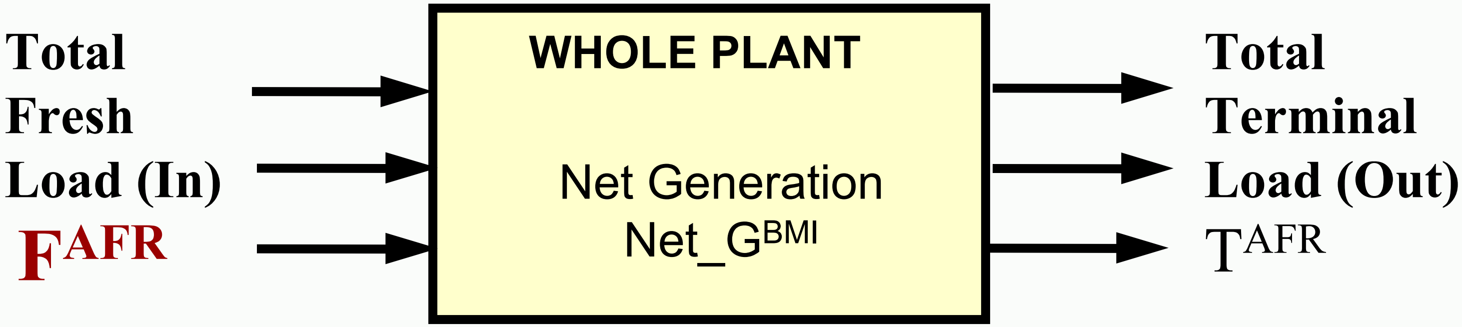
F^{AFR}= minimize f (manipulated design variables, manipulated operating variables)



Overall Mass Balance after Fresh Reduction

$$T^{AFR} = F^{AFR} + Net\_G^{BMI}$$

2. Maximize Recycle to Reduce Fresh Usage



Overall Mass Balance after Fresh Reduction

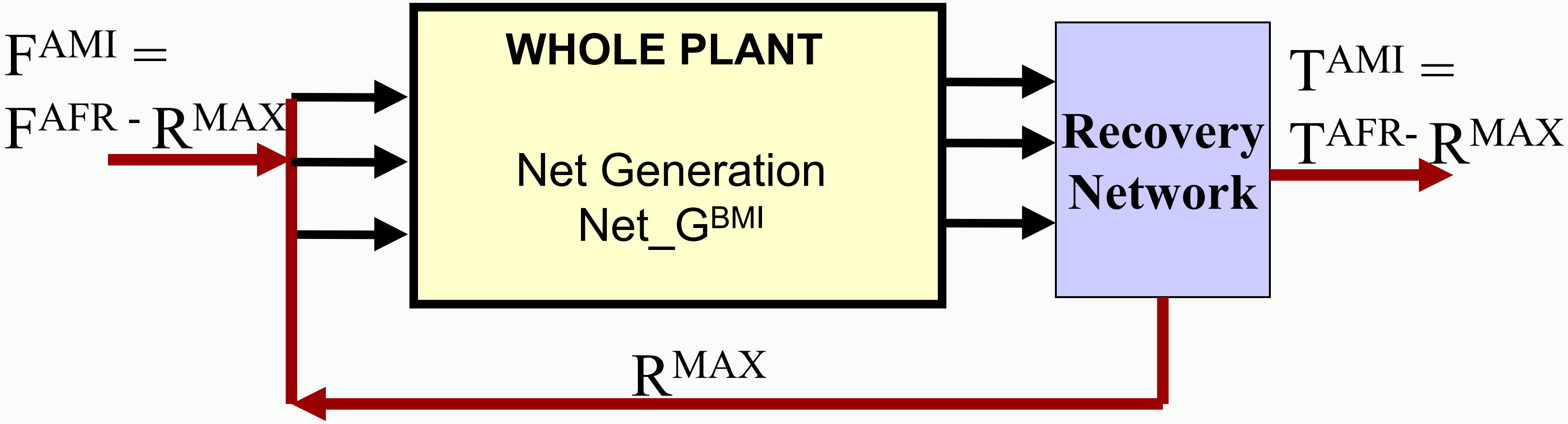
$$T^{AFR} = F^{AFR} + Net\_G^{BMI}$$

Need to replace maximum load of fresh load with recycled terminal load

What is maximum recyclable load?

Recycle Rules to Reduce Terminal Load (continued):

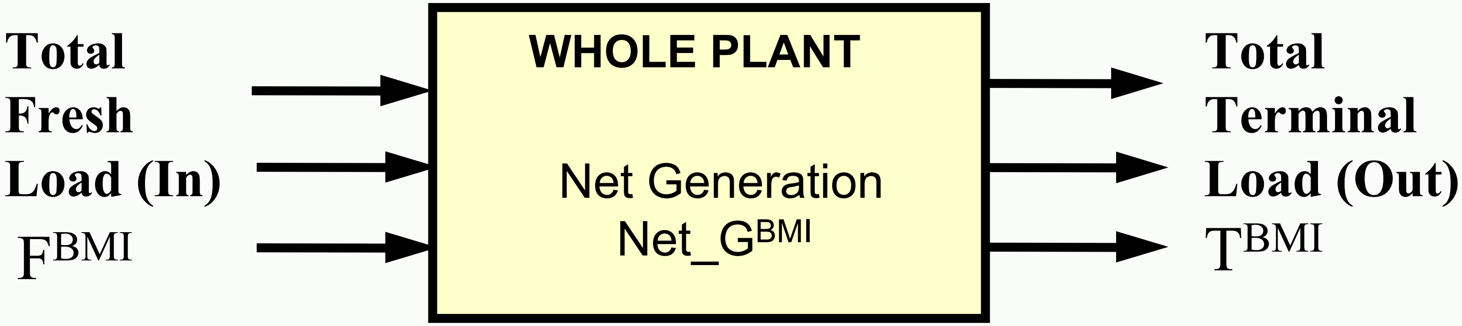
- **Recovery devices can recover (almost) all terminal load and render acceptable quality to replace fresh feed. During targeting, cost and details of recovery are not relevant (yet)**
- **Maximize recycle from outlet path to fresh inlets (can recycle the smaller of the two loads: total recovered terminal vs. total needed fresh). $R^{max} = \text{argmin}\{F^{AFR}, T^{AFR}\}$**



Target After Mass Integration (AMI)

Example 2: Reduction of Terminal Losses or Discharge of Waste for Variable Generation

- **Terminal Load (out) = Fresh Load (in) + Net Generation**



Overall Mass Balance Before Mass Integration (BMI)

$$T^{BMI} = F^{BMI} + Net\_G^{BMI}$$

Minimize generation of waste (or targeted species)

Minimize fresh:

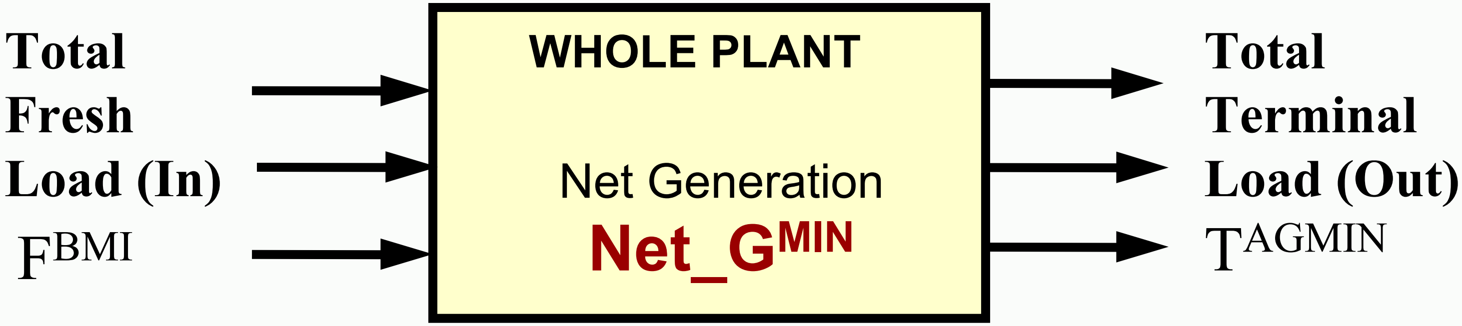
1. Adjust design and operating variables
2. Maximize recycle to replace fresh usage

When generation and fresh cannot be decoupled, see *Noureldin, M. B. and M. M. El-Halwagi, 1999, "Interval-Based Targeting for Pollution Prevention via Mass Integration", Comp. Chem. Eng., 23, 1527-1543.*

Minimizing Generation of Waste

Minimize generation (or maximize depletion) of targeted species (e.g., Describe generation quantitatively then identify values of design and operating conditions of reactors to minimize generation)

Terminal Load (out) = Fresh Load (in) + Generation (- Depletion)

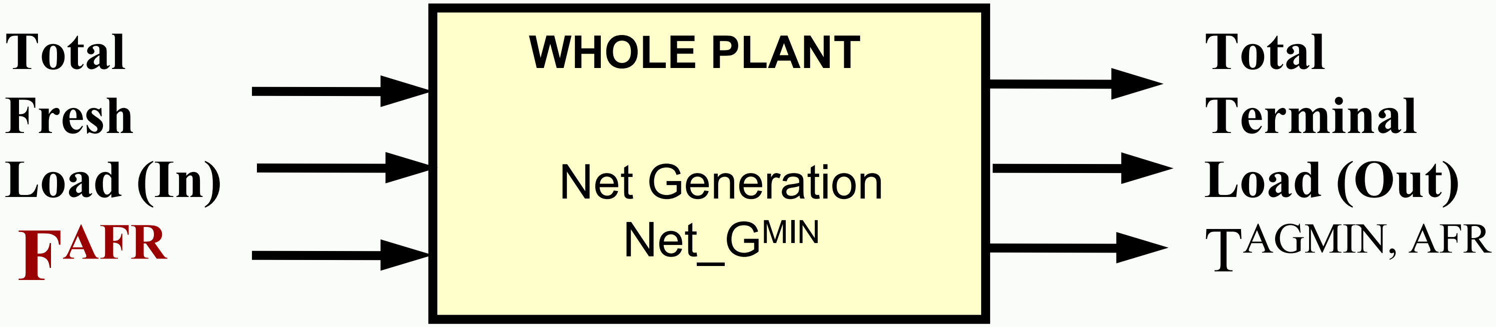


Overall Mass Balance after Minimization of Generation

$$T^{AGMIN} = F^{BMI} + Net\_G^{MIN}$$

Adjust Design and Operating Variables to Reduce Fresh

Terminal Load (out) = Fresh Load (in) + Generation (- Depletion)

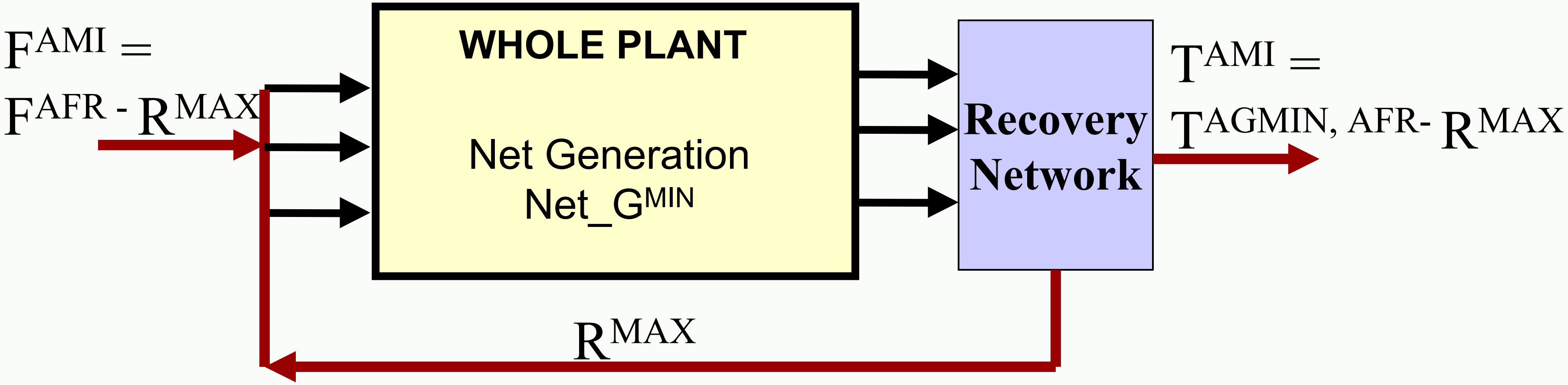


Overall Mass Balance after Fresh Reduction and Minimization of Generation

$$T^{AGMIN,\ AFR} = F^{AFR} + Net\_G^{MIN}$$

Recycle Rules to Reduce Terminal Load (continued):

- **Recovery devices can recover (almost) all terminal load and render acceptable quality to replace fresh feed. During targeting, cost and details of recovery are not relevant (yet)**
- **Maximize recycle from outlet path to fresh inlets (can recycle the smaller of the two loads: total recovered terminal vs. total needed fresh). $R^{max} = \text{argmin}\ \{F^{AFR}, T^{AGMIN, AFR}\}$**



Target After Mass Integration (AMI)

TARGETING PROCEDURE TO MINIMIZE TERMINAL LOSS OR WASTE DISCHARGE

Generation/Depletion Model/Data
(e.g., chemical reaction, fugitive emissions, etc.)

↓

Minimize generation of targeted species

↓ Minimum generation

Stream Data
(fresh and terminal loads of targeted species)

↓

Adjust design and operating variables to minimize fresh load, then carry out overall material balance on targeted species

↓ Revised data for fresh and terminal loads of targeted species

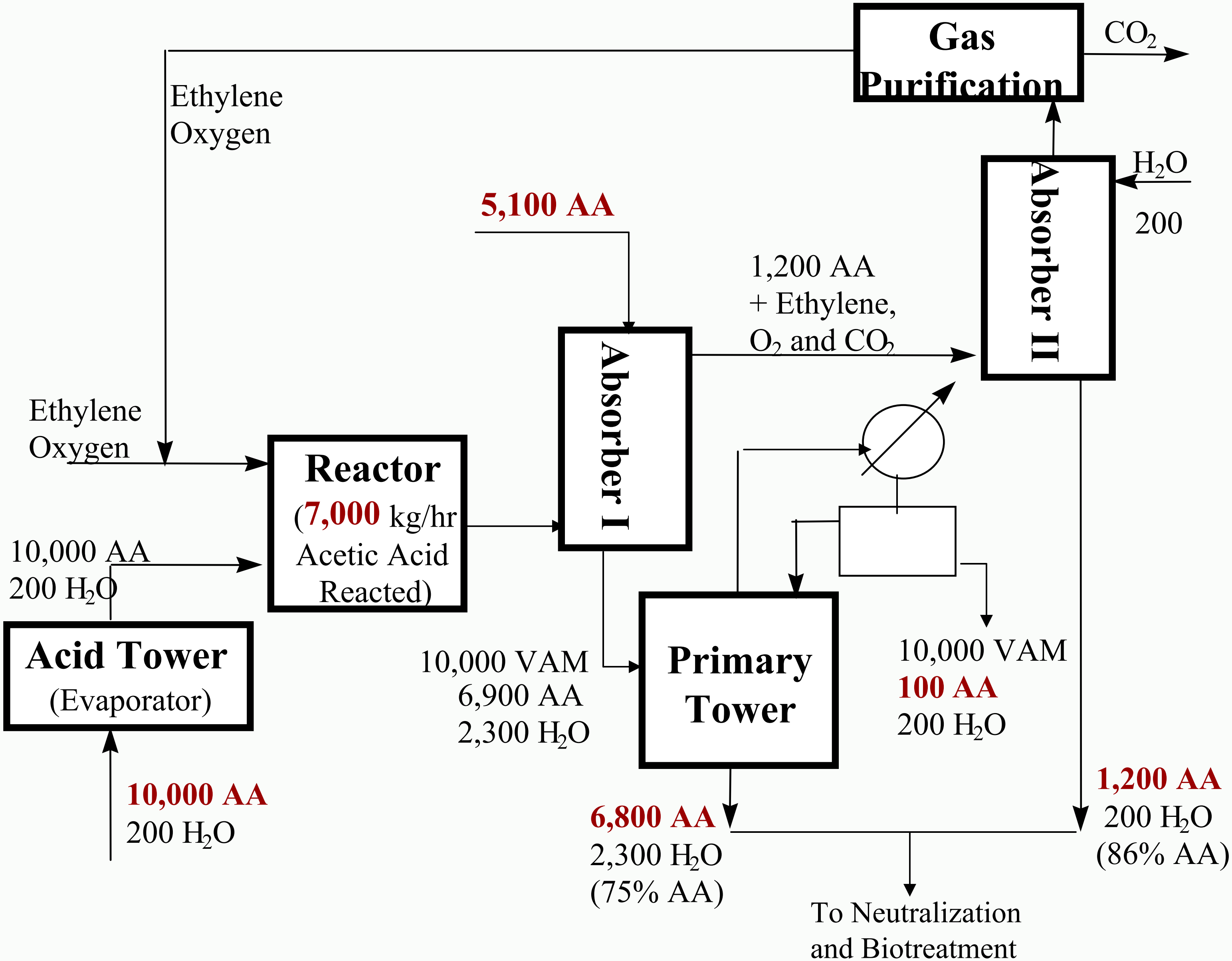
Maximize recycle (to minimize fresh load)
Maximum recycle = argmin {fresh load, recoverable terminal load}

↓ Maximum total recycle

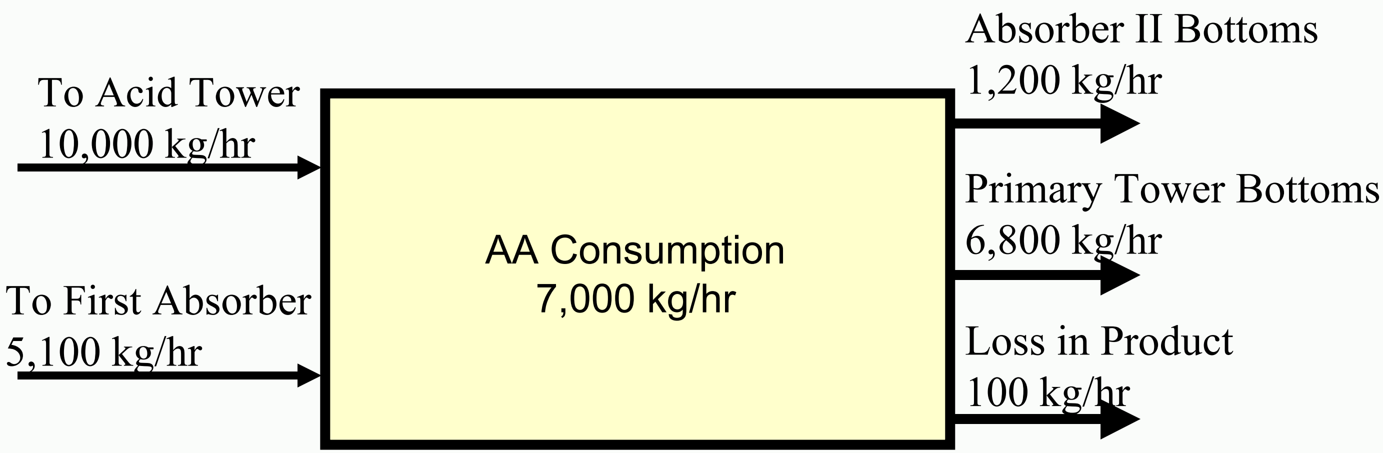
Revise overall material balance on targeted species

↓ **Target of minimum terminal load**

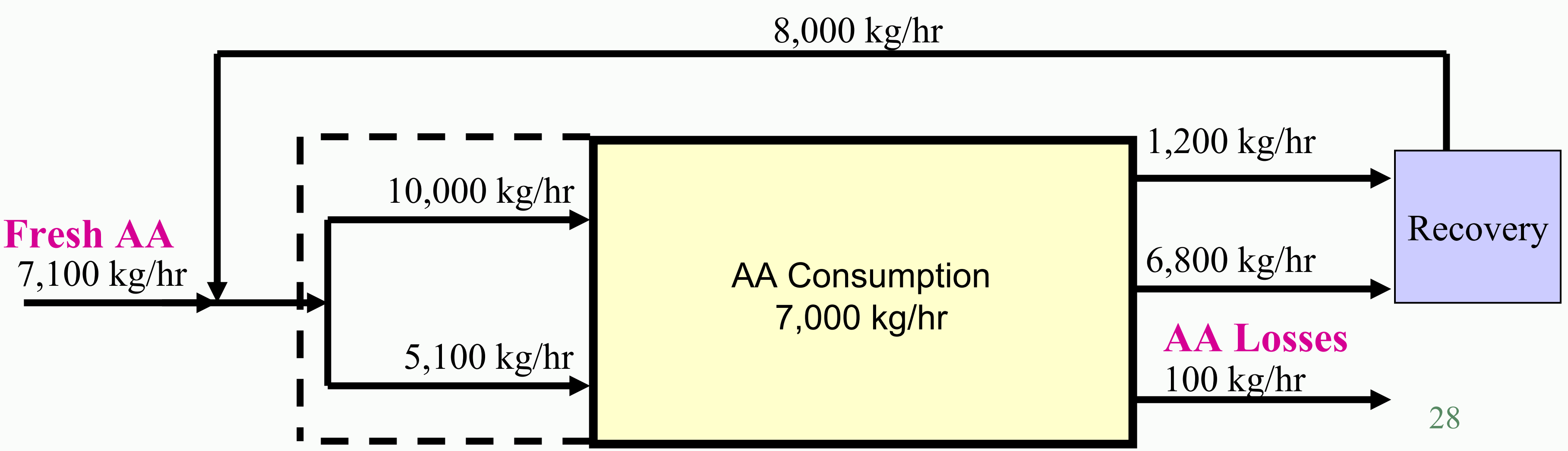
CASE STUDY I: MINIMIZE AA FRESH PURCHASE IN VAM PROCESS



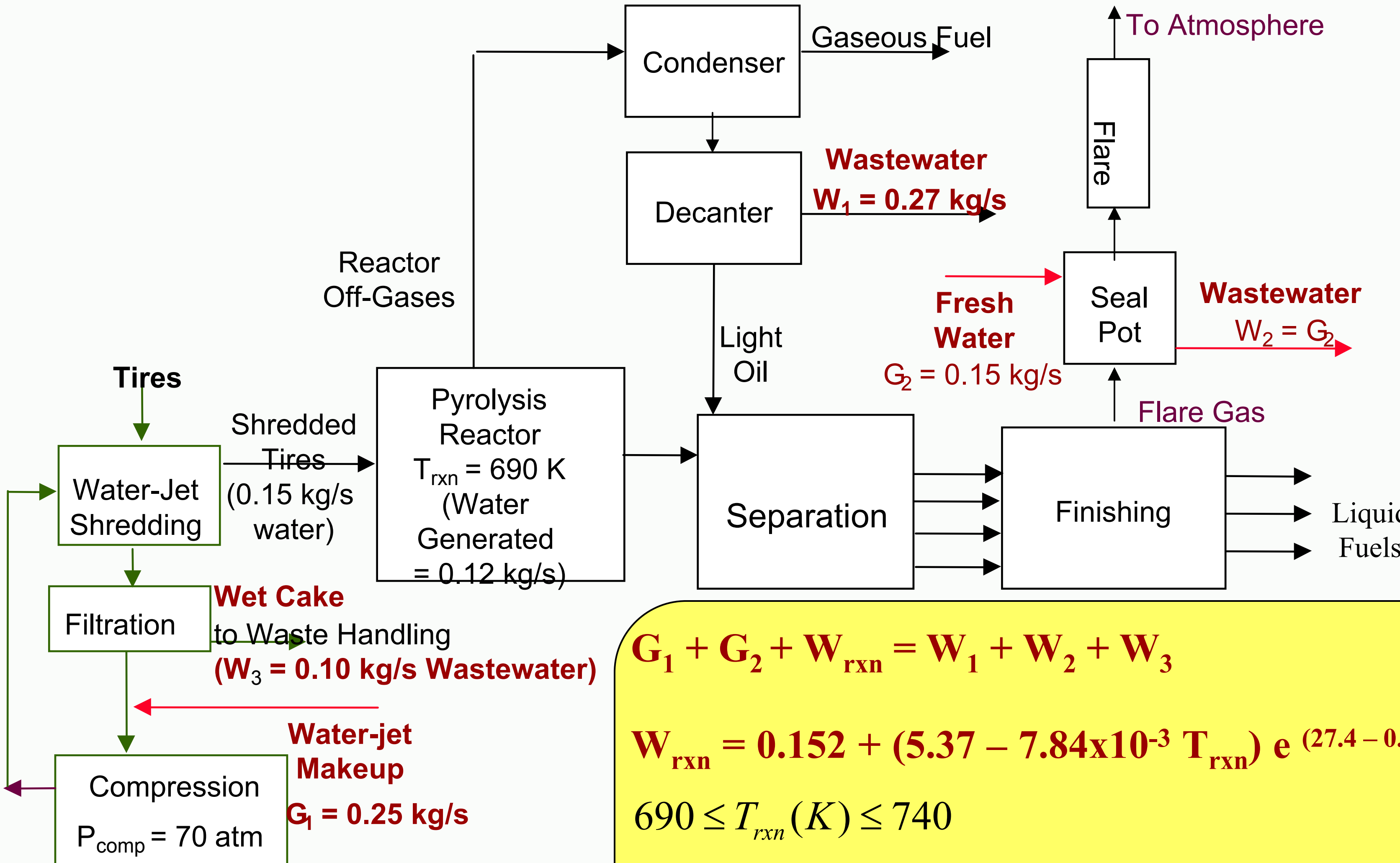
Overall AA Balance Before Mass Integration



Targeting for Minimum Purchase of Fresh AA



EXAMPLE II: MINIMIZE WATER DISCHARGE IN TIRE-TO-FUEL PROCESS



$$G_1 + G_2 + W_{rxn} = W_1 + W_2 + W_3$$

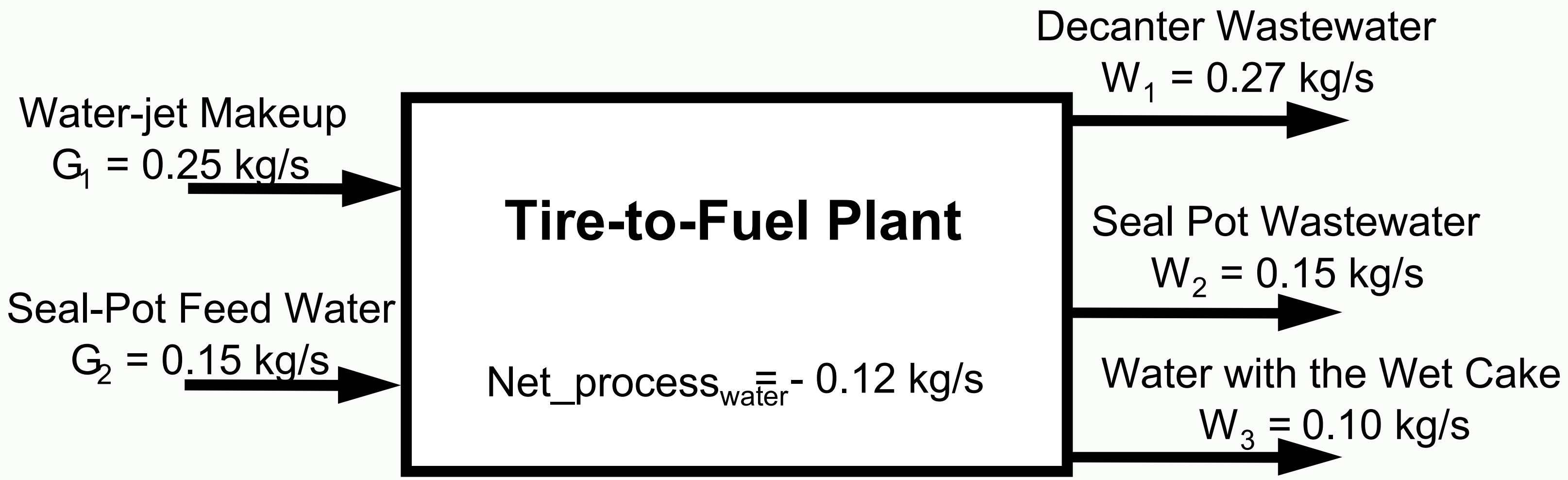
$$W_{rxn} = 0.152 + (5.37 - 7.84\text{x}10^{-3}\, T_{rxn})\, e^{(27.4 - 0.04 T_{rxn})}$$

$$690 \le T_{rxn}(K) \le 740$$

$$G_1 = 0.47\, e^{-0.009\, P_{comp}} \qquad 70 \le P_{comp}(atm) \le 90$$

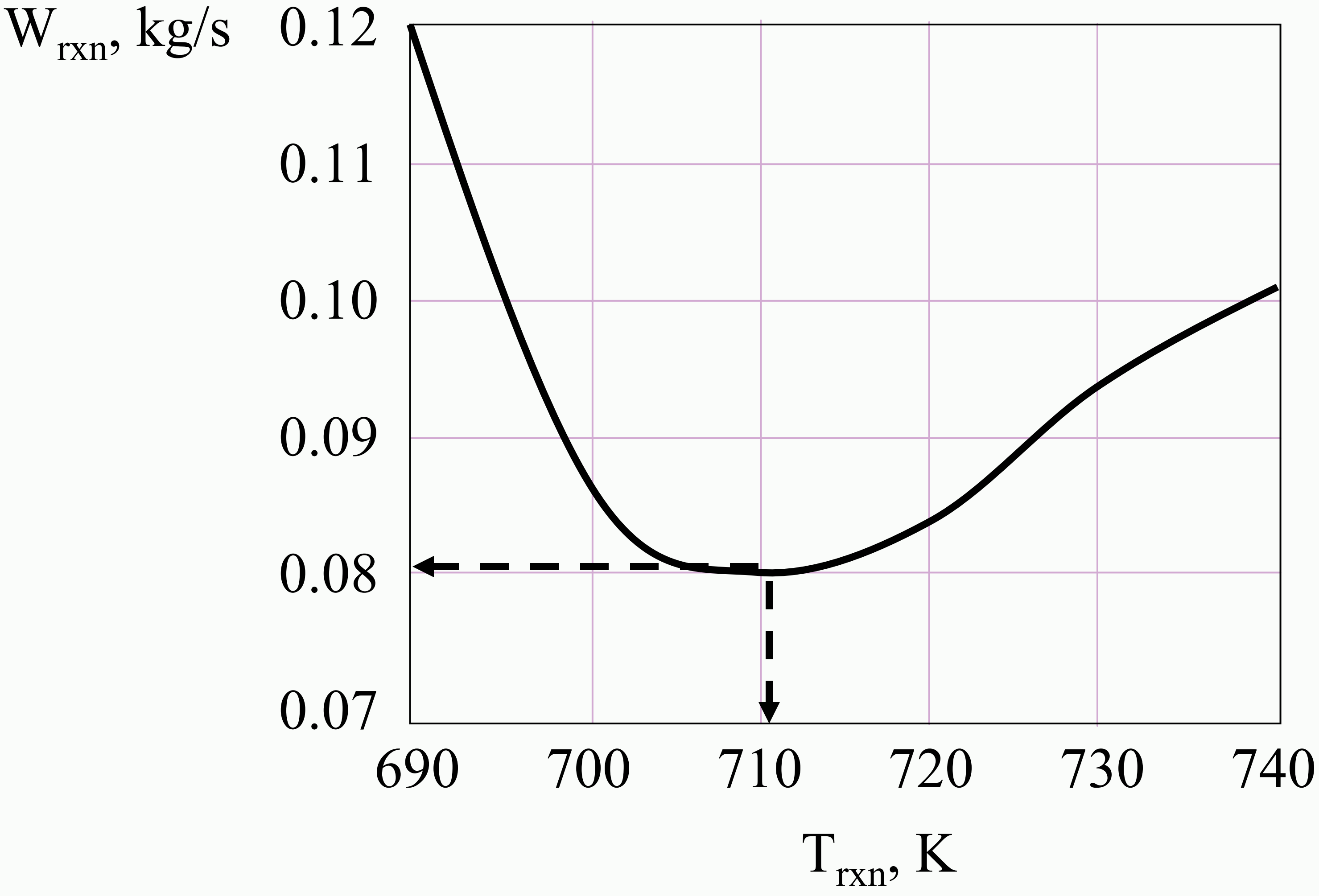
$$G_2 = 0.15 \qquad W_2 = G_2 \qquad W_3 = 0.4\, G_1$$

OVERALL WATER BALANCE BEFORE MASS INTEGRATION



Minimize generation of targeted species

$$W_{rxn} = 0.152 + (5.37 - 7.84x10^{-3}\ T_{rxn})\ e^{(27.4 - 0.04T_{rxn})}$$



Adjust design and operating variables to minimize fresh load, then carry out overall material balance on targeted species

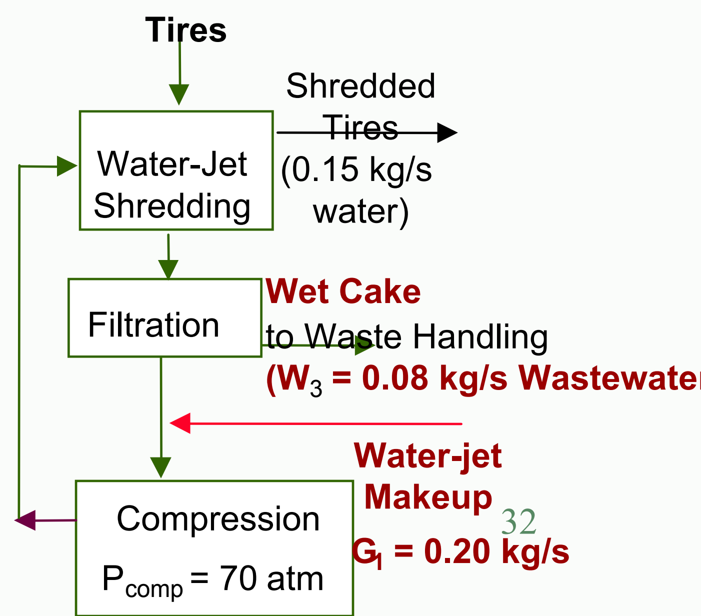
$$G_1 = 0.47\ e^{-0.009Pcomp}$$

$$70 \le P_{comp}\,(atm) \le 90$$

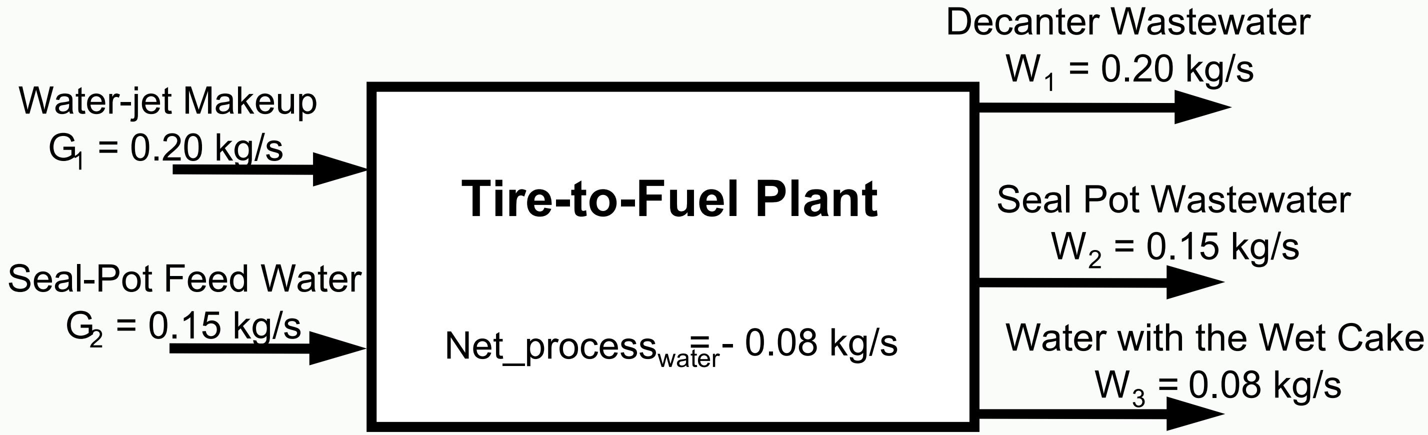
➔ **Set P_{comp} = 90 atm** $G_1 = 0.47\ e^{-0.009*90} = 0.2$

➔ **Minimum water for shredding G_1 = 0.2 kg/s**

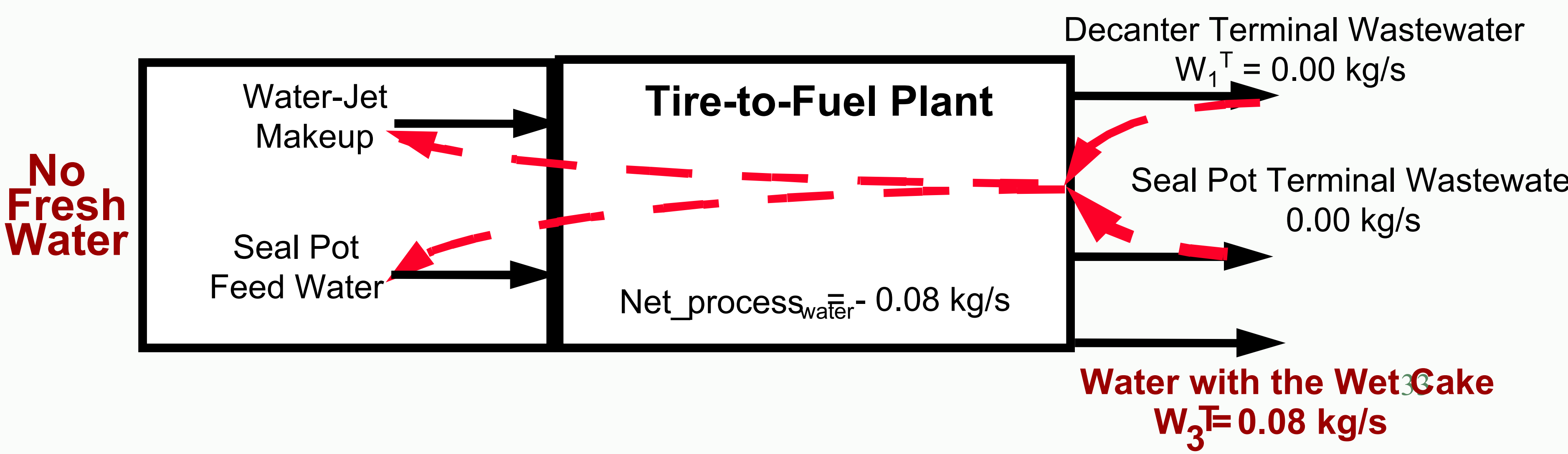
$W_3 = 0.4\ G_1 = 0.08$ kg/s



OVERALL WATER BALANCE AFTER MASS INTEGRATION

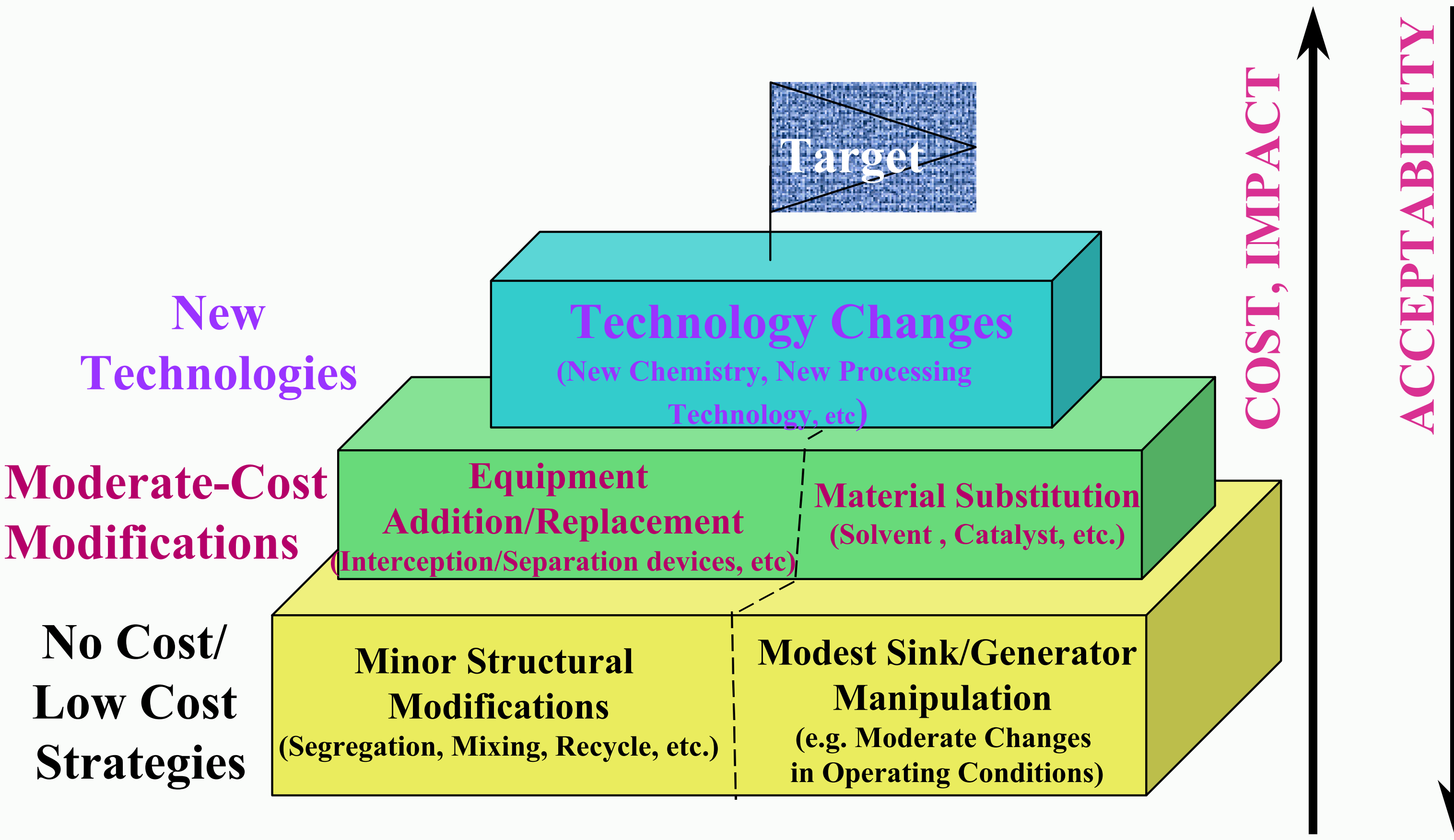


WATER TARGETING



ACHIEVING THE TARGET

Mass Integration Strategies



PRACTICE EXERCISE

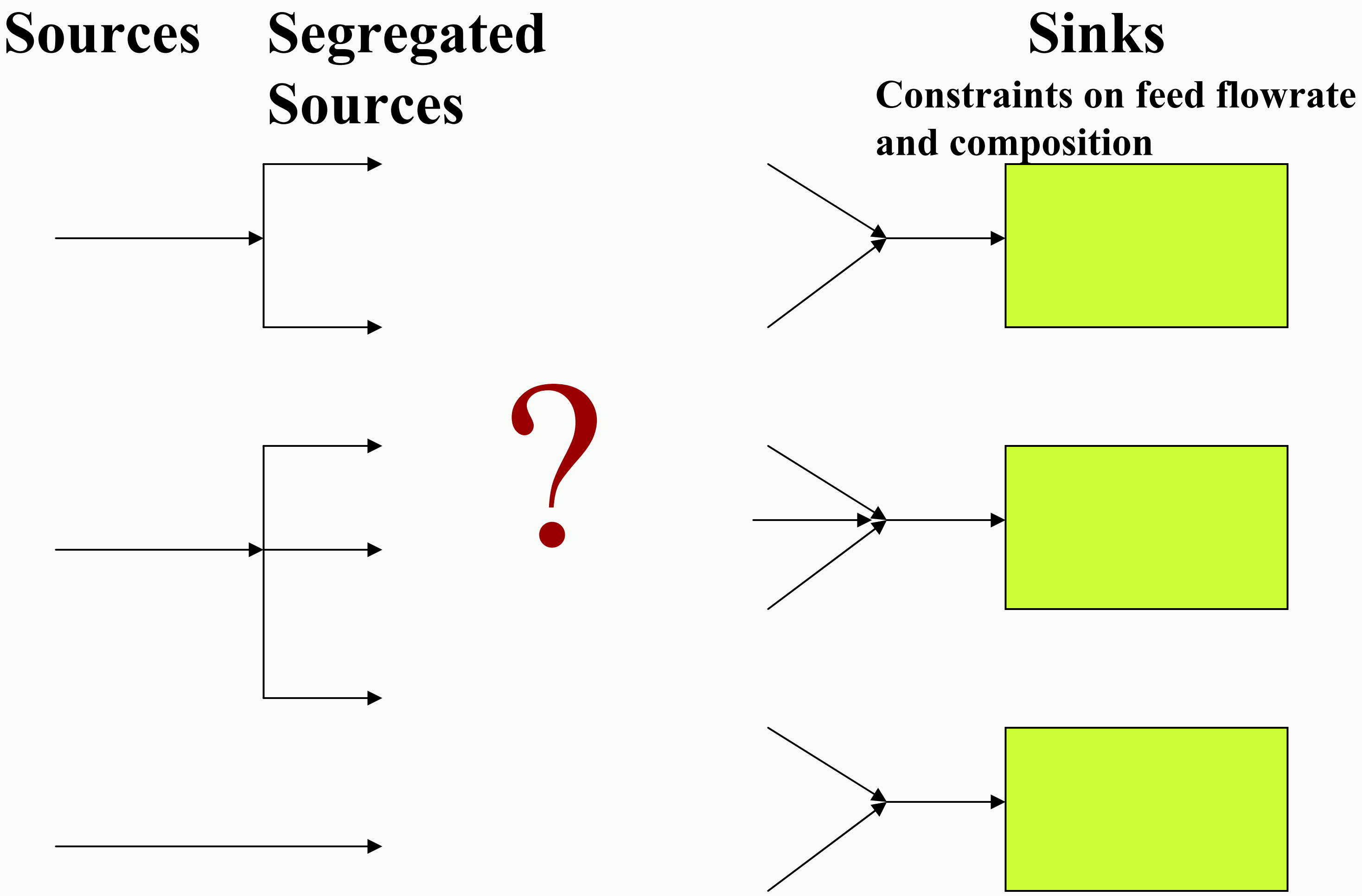
Consider the VAM process described earlier. A new reaction pathway has been developed and will to be used for the production of VAM. This new reaction does not involve acetic acid. The rest of the process remains virtually unchanged and the AA losses with the product are 100 kh/hr. What are the targets for minimum fresh usage and discharge/losses of AA?

DIRECT RECYCLE STRATEGIES

Objective: to develop a graphical procedure that determines the target and implementation for minimum usage of the fresh resource, maximum material reuse, and minimum discharge to waste as a result of direct recycle.

Direct Recycle: rerouting of streams without the addition of new units. It involves segregation, mixing, and allocation.

DIRECT RECYCLE REPRESENTATION



Source: A stream which contains the targeted species

Sink: An existing process unit/equipment that can accept a source

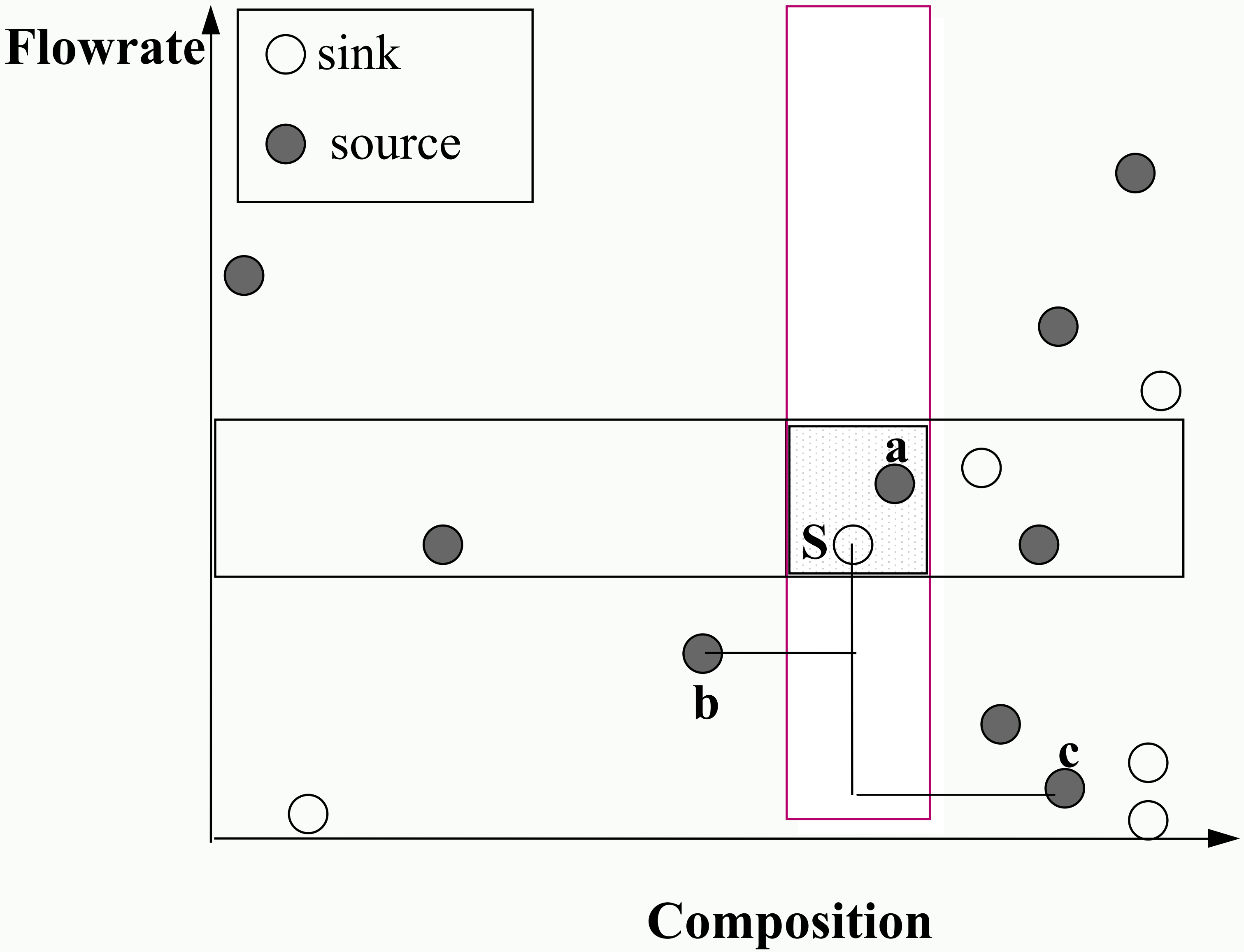
PROBLEM STATEMENT

Consider a process with a number of process sources (e.g., process streams, wastes) that can be considered for possible recycle and replacement of the fresh material and/or reduction of waste discharge. Each source, i, has a given flow rate, W_i, and a given composition of a targeted species, y_i. Available for service is a fresh (external) resource that can be purchased to supplement the use of process sources in sinks. The sinks are process units such as reactors, separators, etc. Each sink, j, requires a feed whose flow rate, G_j , and an inlet composition of a targeted species, z_j, must satisfy certain bounds on their values.

DESIGN CHALLENGES

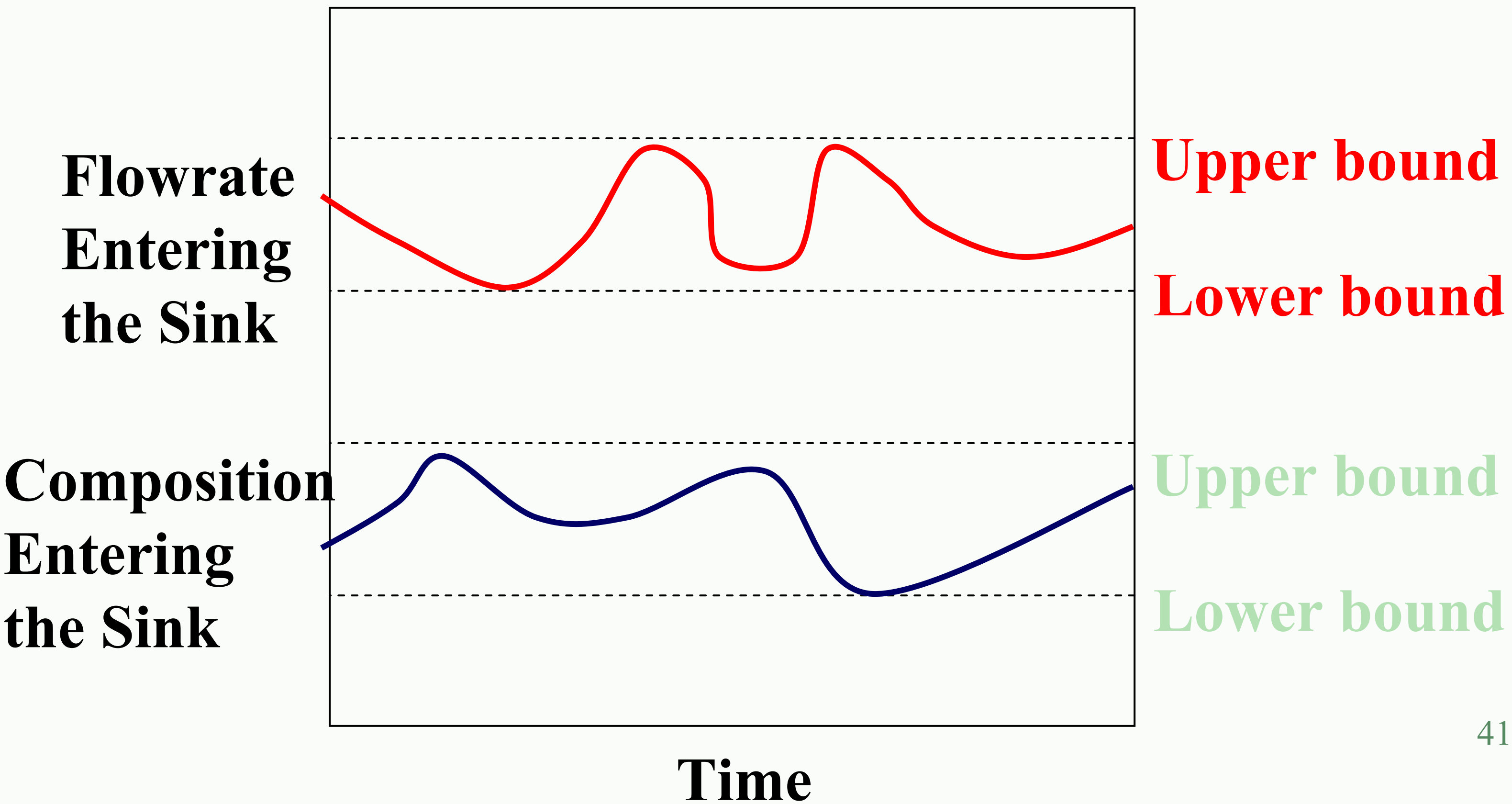
- Should a stream (source) be segregated and split? To how many fractions? What should be the flowrate of each split?
- Should streams or splits of streams be mixed? To what extent?
- What should be the optimum feed entering each sink? What should be its composition?
- What is the minimum amount of fresh resource to be used?
- What is the minimum discharge of unused process sources?

SOURCE-SINK MAPPING DIAGRAM



How to Identify Bounds on Sinks?

1. **From physical limitations** (e.g., flooding flowrate, weeping flowrate, channeling flowrate, saturation composition)
2. **From manufacturer's design data**
3. **From technical constraints** (e.g., to avoid scaling, corrosion, explosion, buildup, etc.)
4. **From historical data**



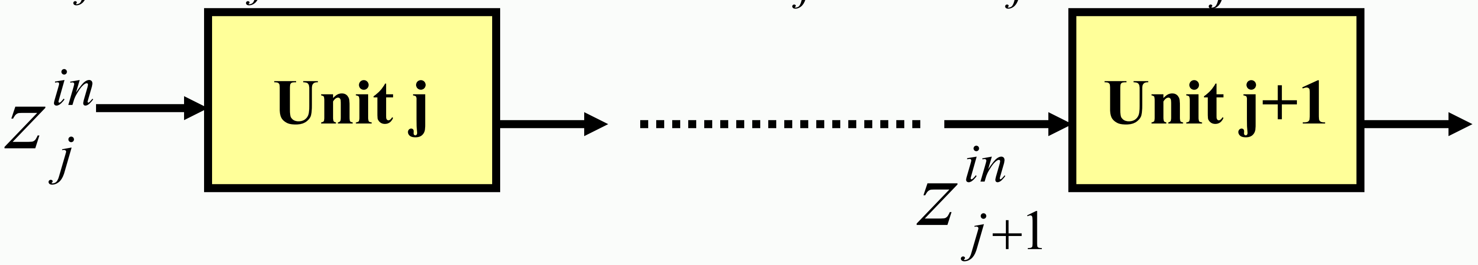
5. By constraint propagation

Unknown Constraints

$$z_j^{\min} \le z_j^{in} \le z_j^{\max}$$

Known Constraints

$$z_{j+1}^{\min} \le z_{j+1}^{in} \le z_{j+1}^{\max}$$

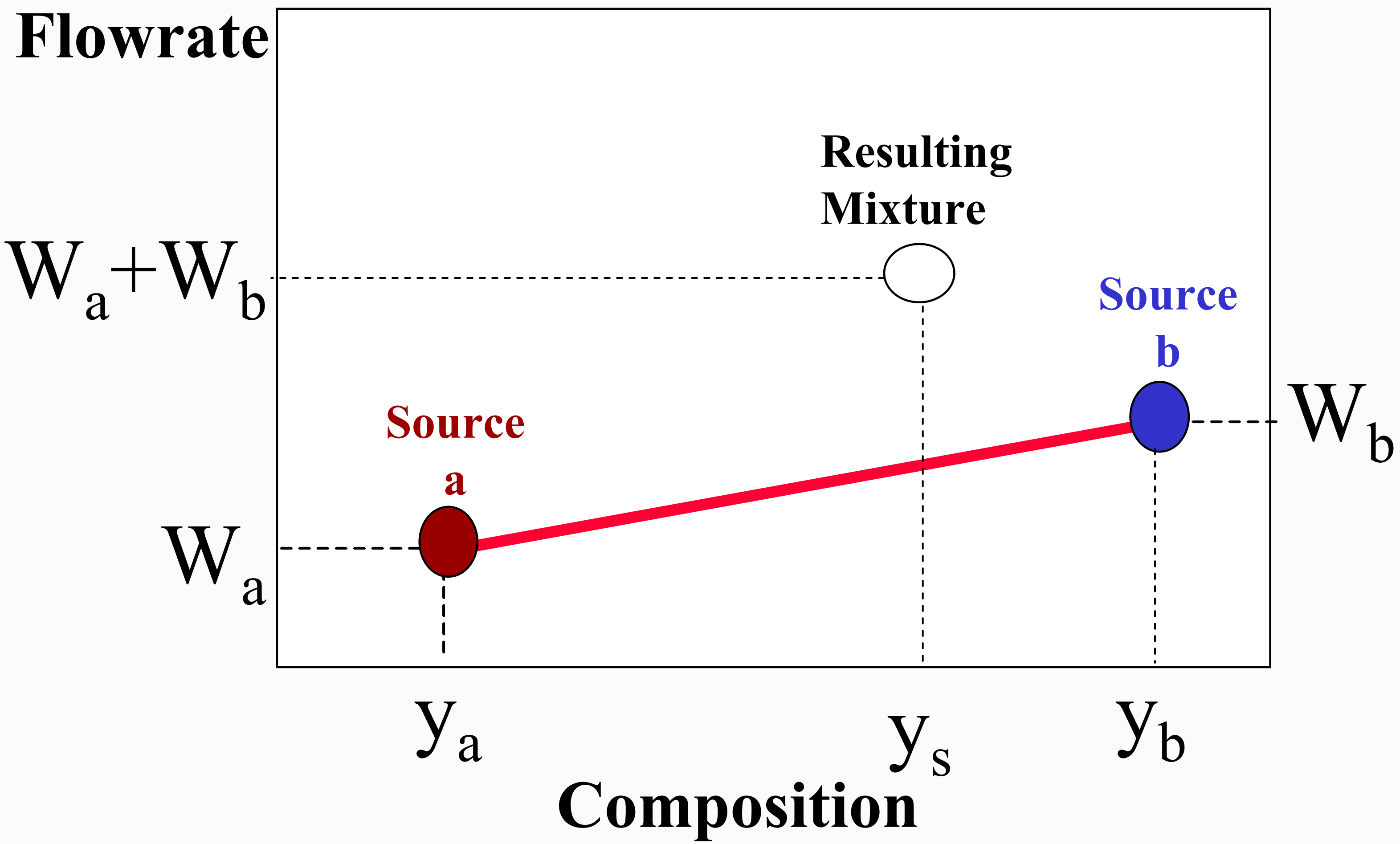


From process model: $z_{j+1}^{in} = 2\, z_j^{in}$

$$0.03 \le z_j^{in} \le 0.04 \quad \longleftarrow \quad 0.06 \le z_{j+1}^{in} \le 0.08$$

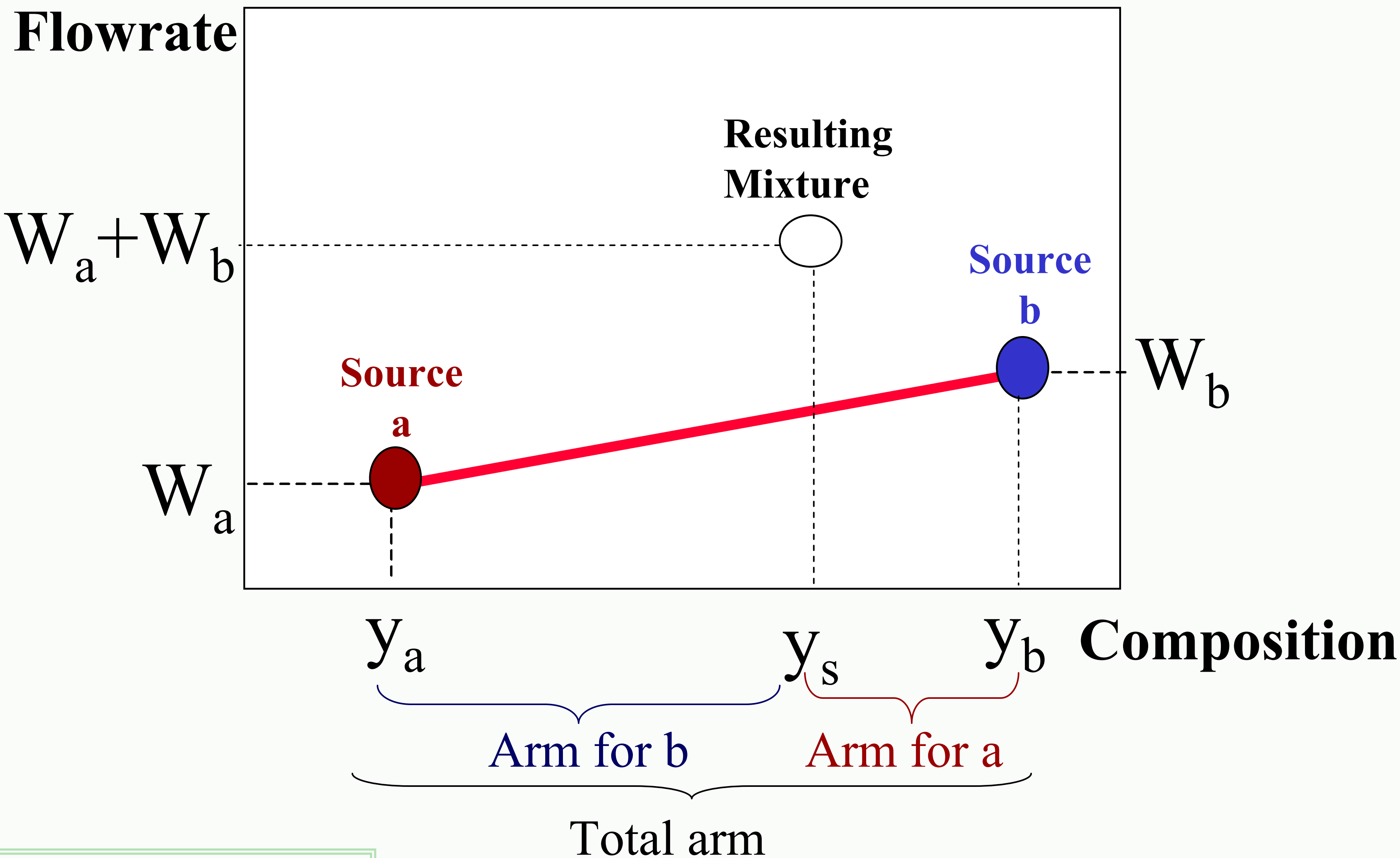
6. Tolerate a certain deviation from nominal case (e.g., allow +/- certain %ages from nominal flowrate and compositions)

LEVER-ARM RULES



$$y_s(W_a + W_b) = y_a W_a + y_b W_b \Rightarrow \frac{W_a}{W_b} = \frac{y_b - y_s}{y_s - y_a}$$

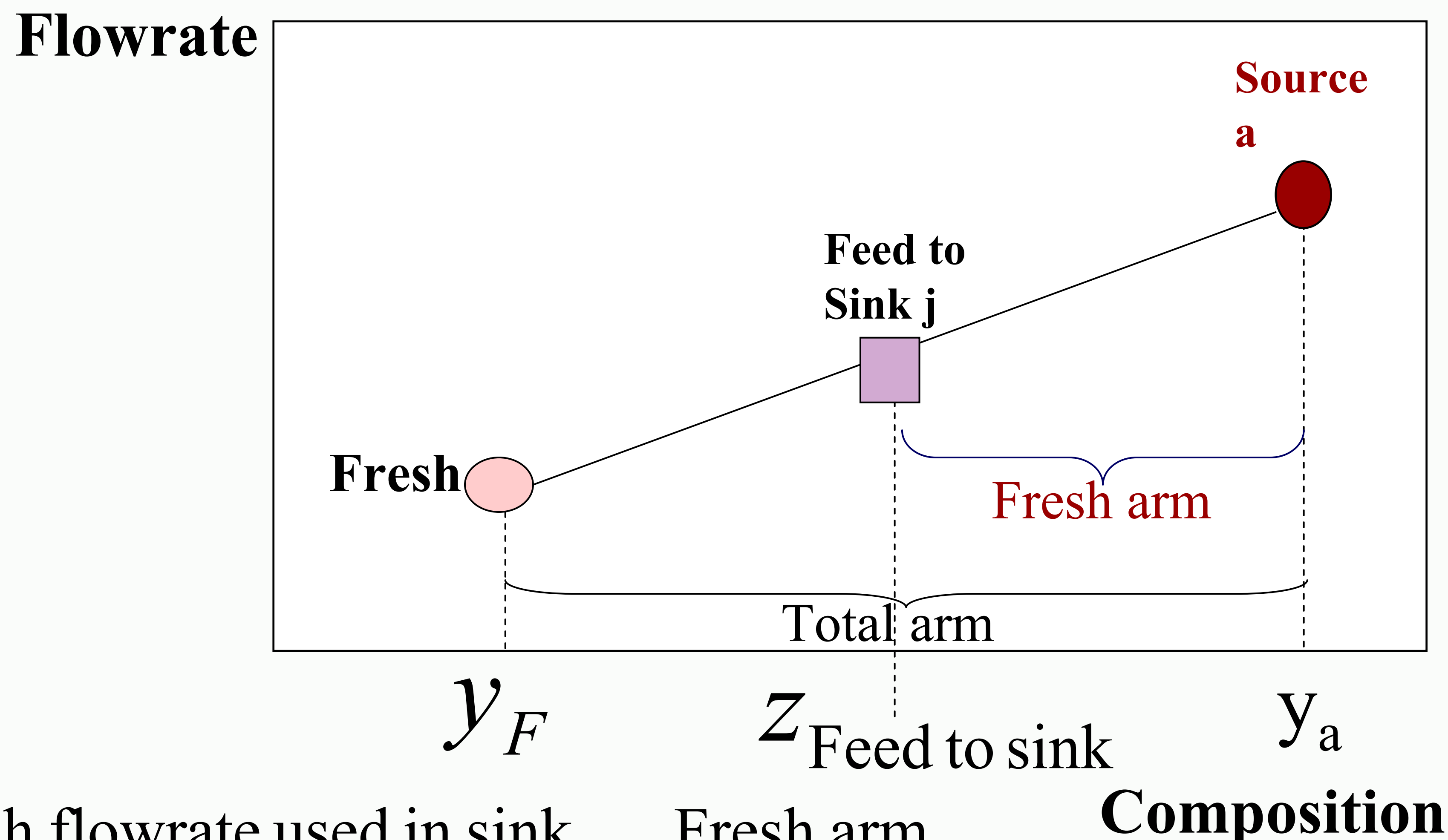
LEVER-ARM RULES



$$\frac{W_a}{W_b} = \frac{Arm\ for\ a}{Arm\ for\ b}$$

$$\frac{W_a}{W_a + W_b} = \frac{Arm\ for\ a}{Total\ arm}$$

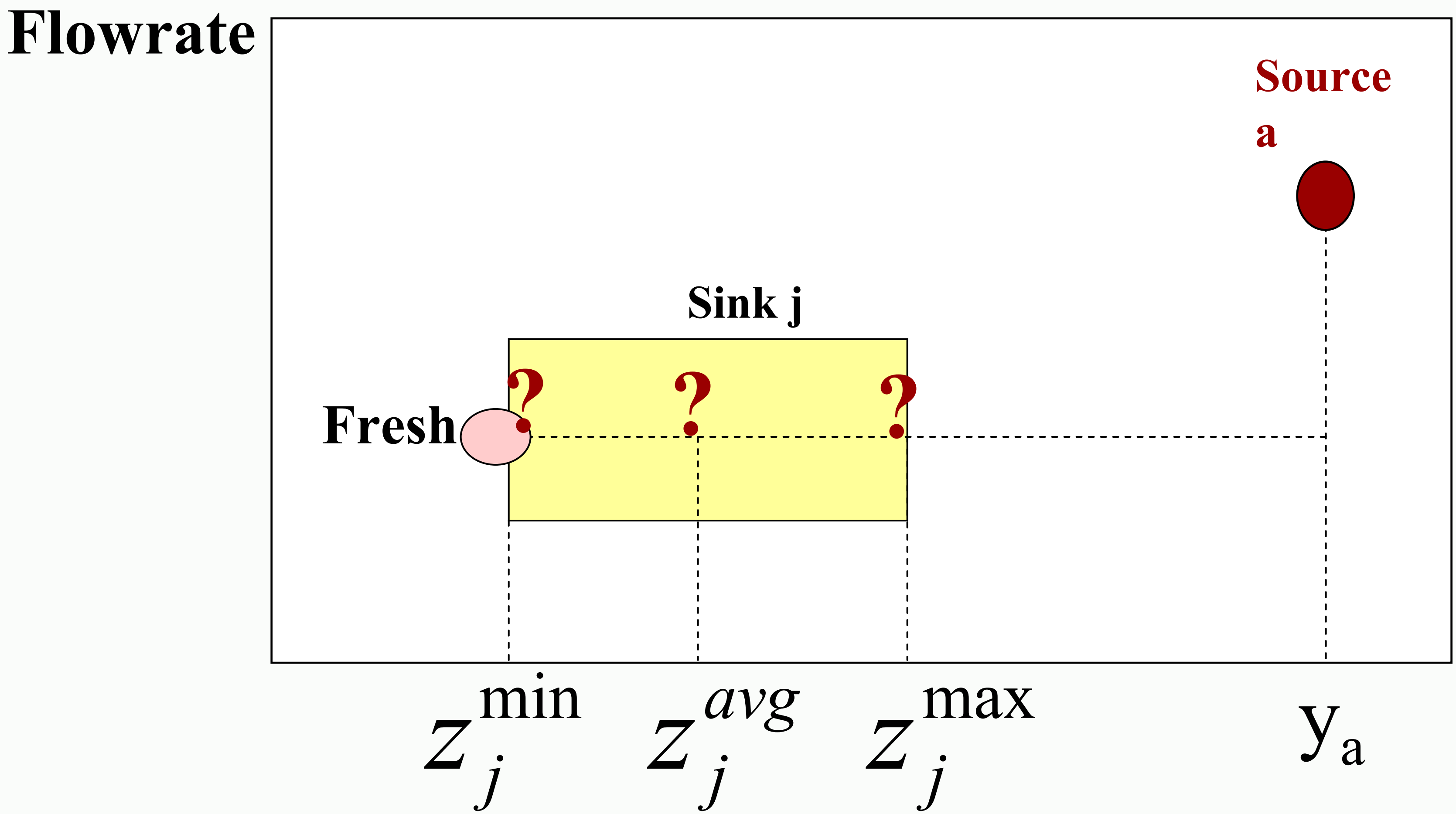
LEVER-ARM RULES FOR FRESH USAGE



$$\frac{\text{Fresh flowrate used in sink}}{\text{Total flowrate fed to sink}} = \frac{\text{Fresh arm}}{\text{Total arm}}$$

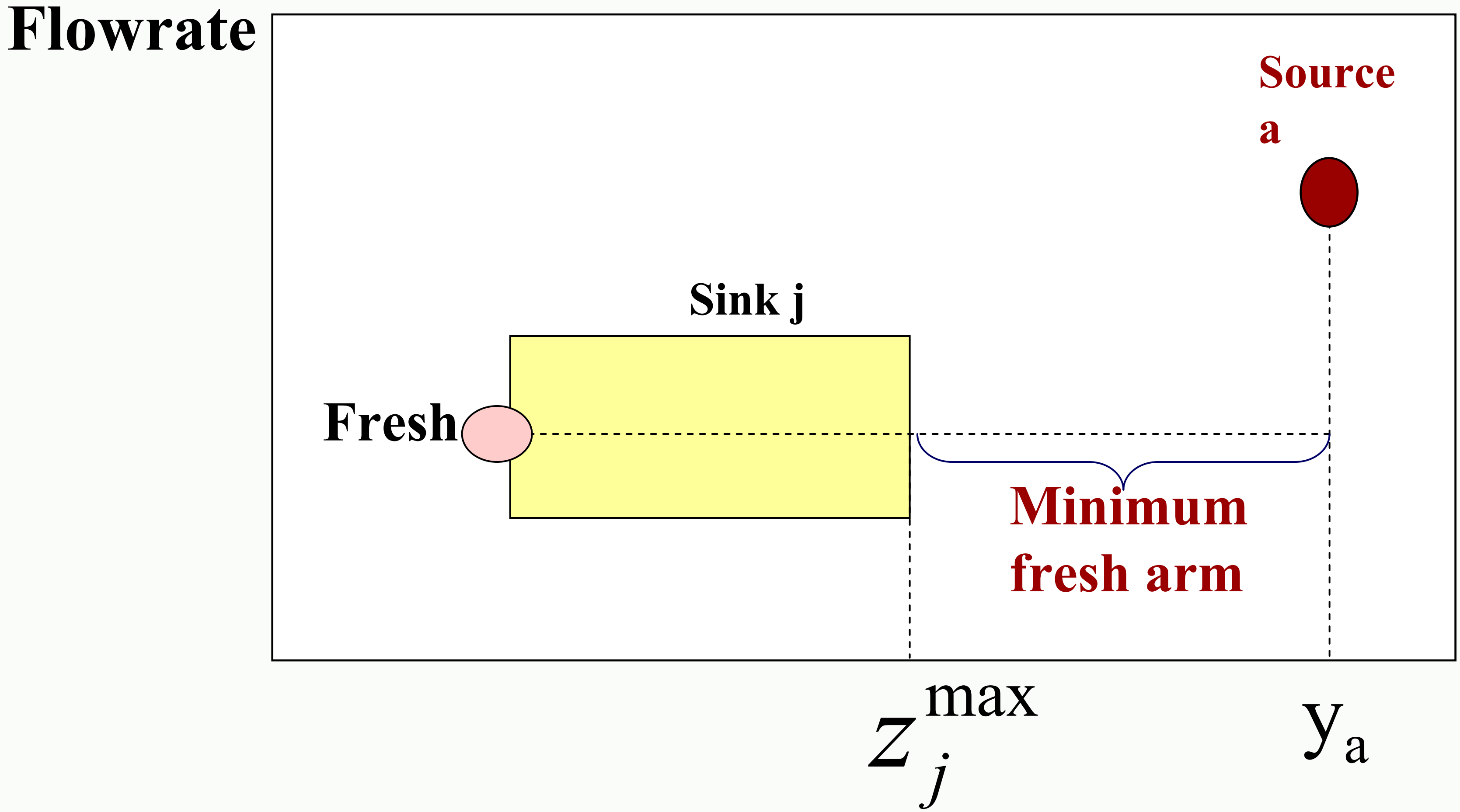
$$\Rightarrow \quad \frac{\text{Fresh flowrate used in sink}}{\text{Total flowrate fed to sink}} = \frac{y_a - z_{\text{Feed to sink}}}{y_a - y_F}$$

SINK COMPOSITION RULE



What should be feed composition to sink to minimize fresh usage?

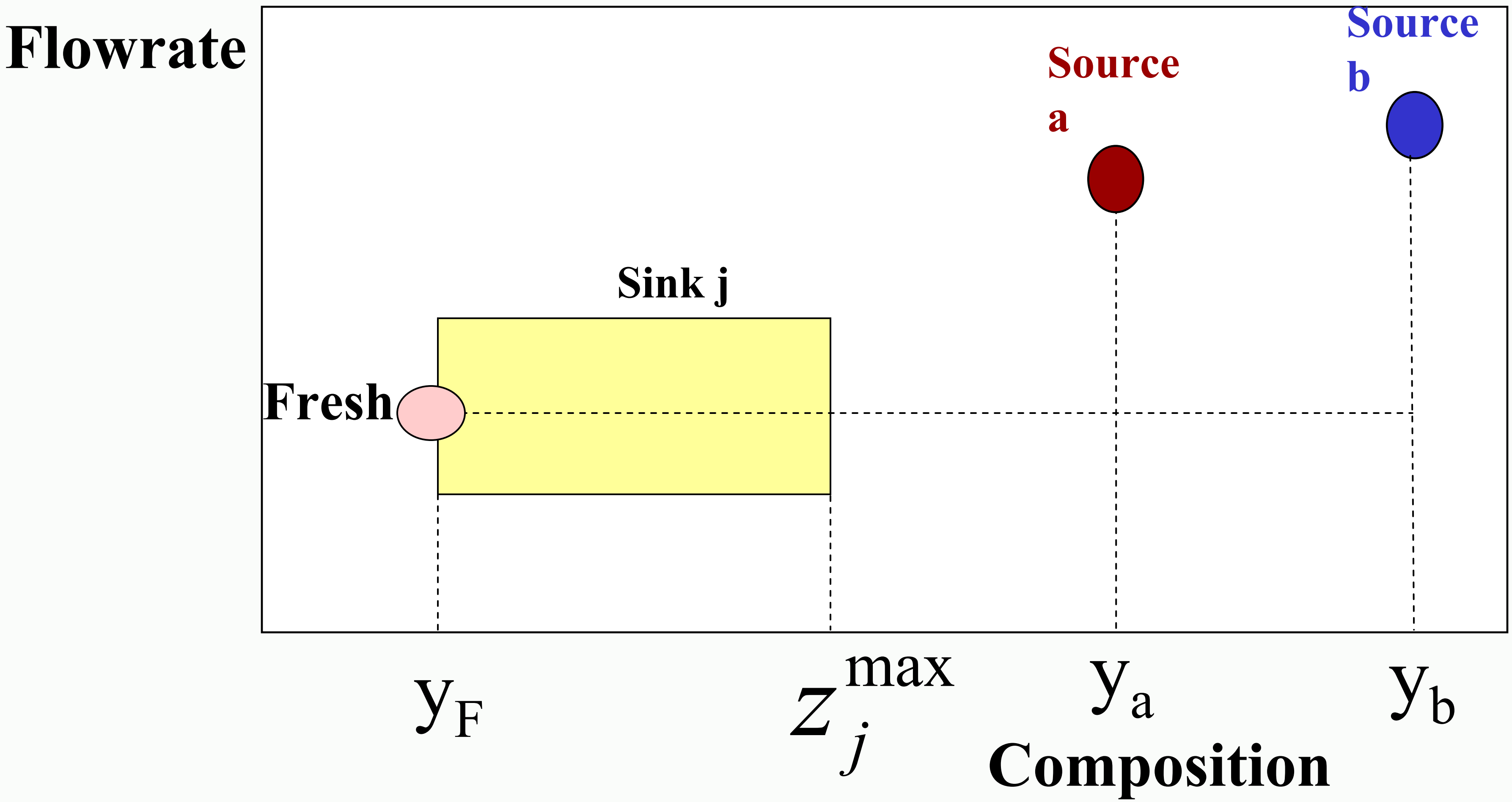
SINK COMPOSITION RULE



What should be feed composition to sink to minimize fresh usage?

Sink Composition Rule: When a fresh resource is mixed with process source(s), the composition of the mixture entering the sink should be set to a value that minimizes the fresh arm. For instance, when the pure fresh, the composition of the mixture should be set to the maximum admissible value.

SOURCE PRIORITIZATION RULE

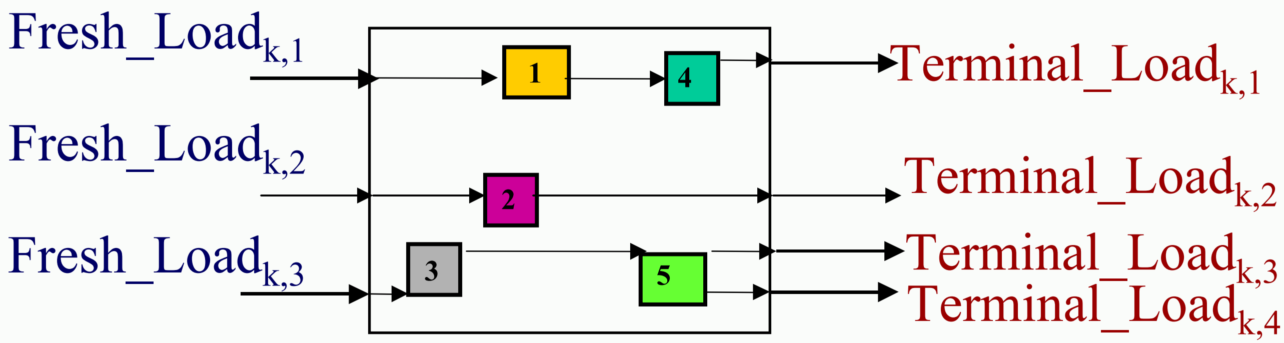


Which source (a or b) should be used to minimize fresh usage?

<u>Source Prioritization Rule:</u> To minimize the usage of the fresh resource, recycle of the process sources should be prioritized in order of their fresh arms starting with the source having the shortest fresh arm.

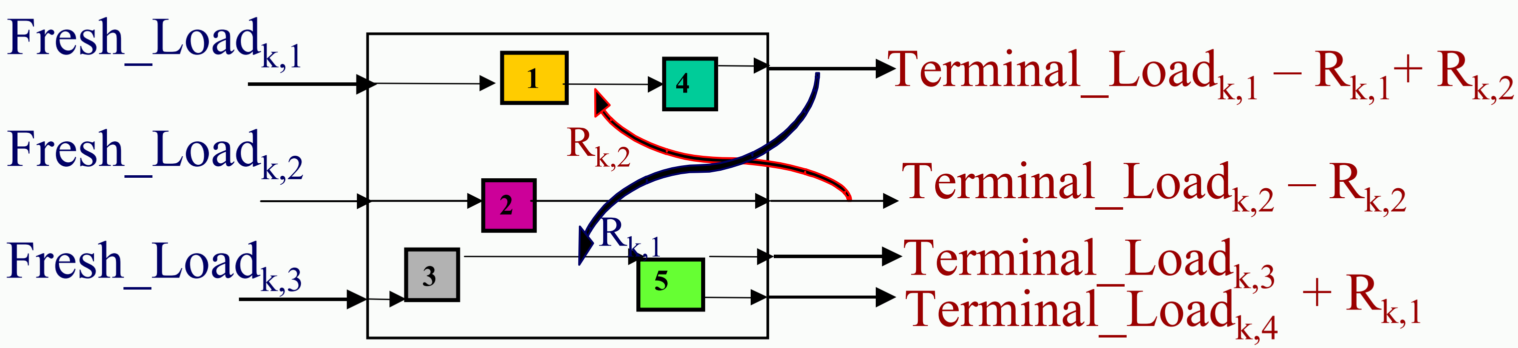
Targeting Rules

Recycle Strategies



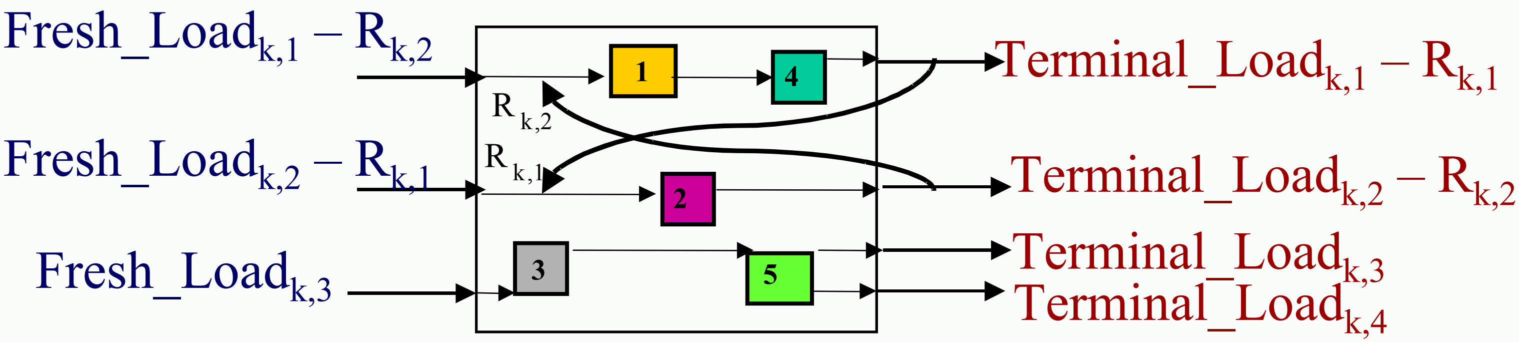
Process Before Recycle

Recycle Alternatives to Reduce Terminal Load

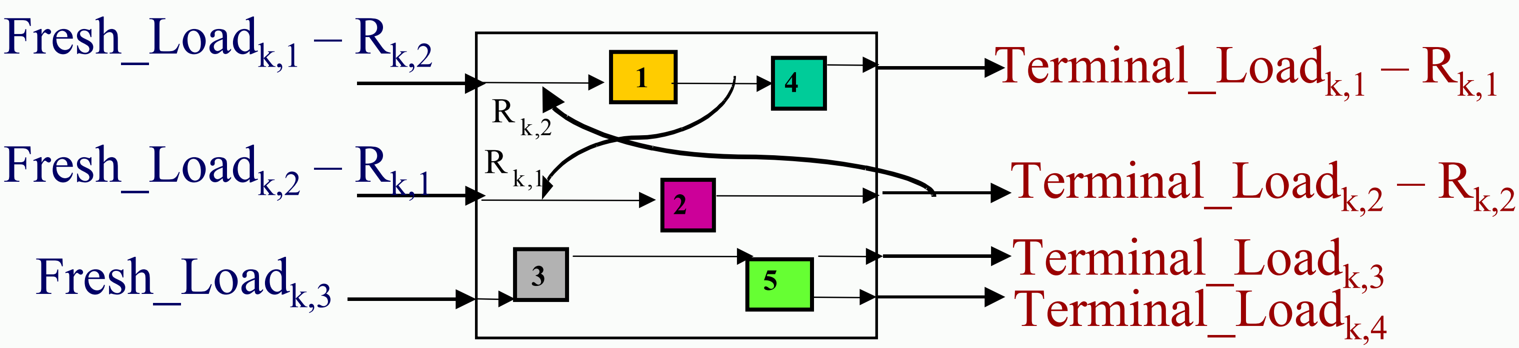


Net terminal load unchanged

Poor Recycle



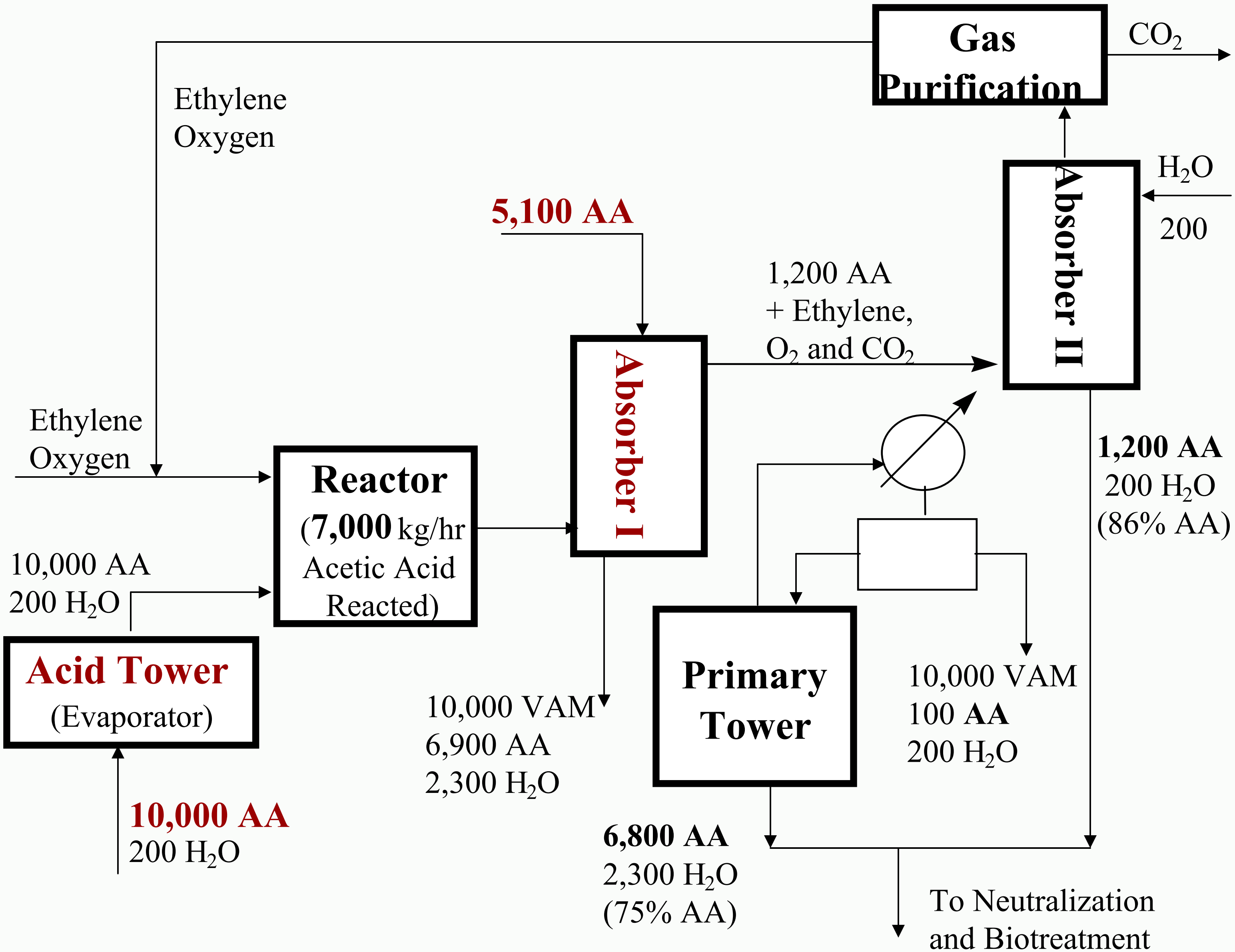
Effective Recycle From Terminal



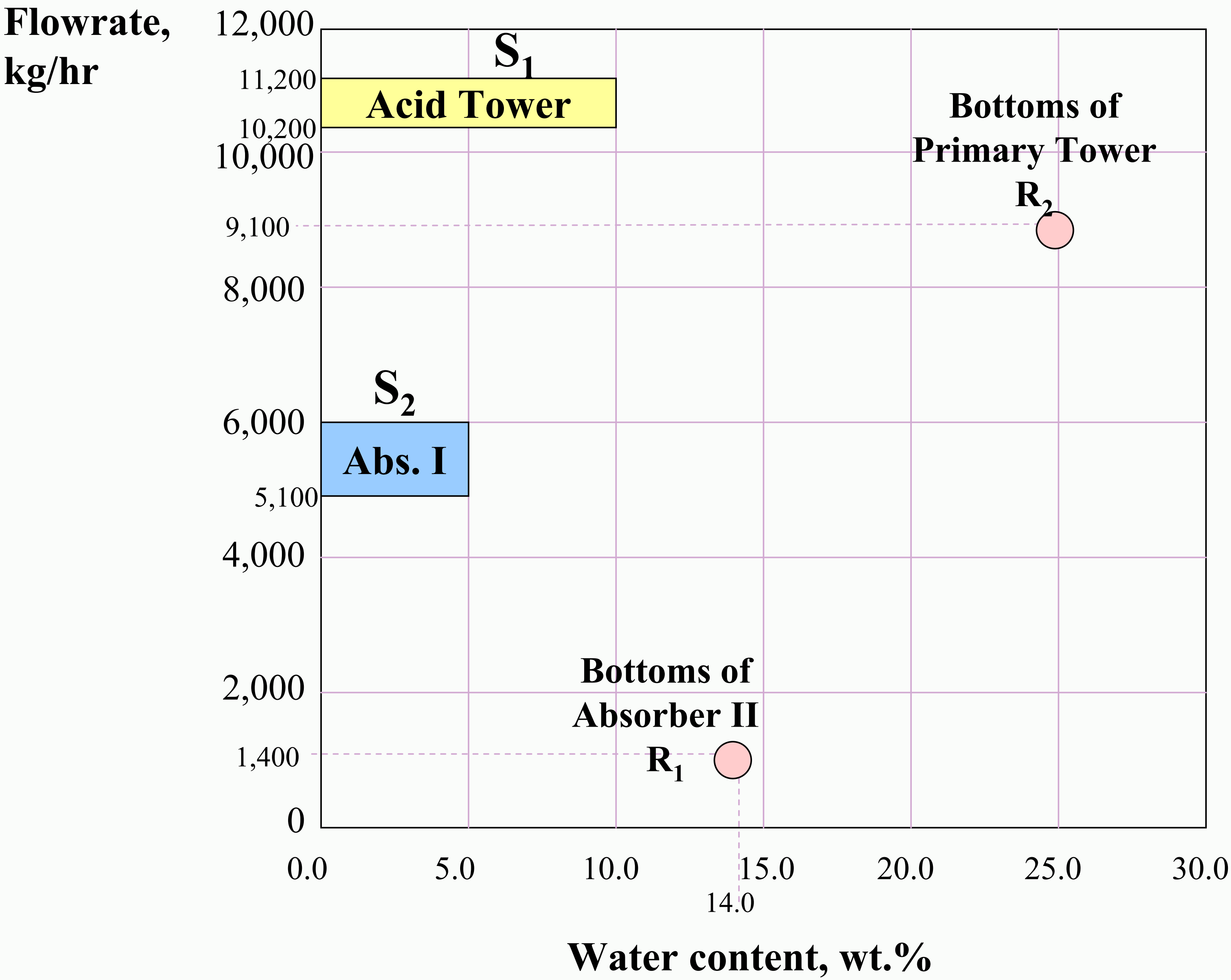
Effective Recycle From Terminal and Intermediate

Noureldin and El-Halwagi, 1999

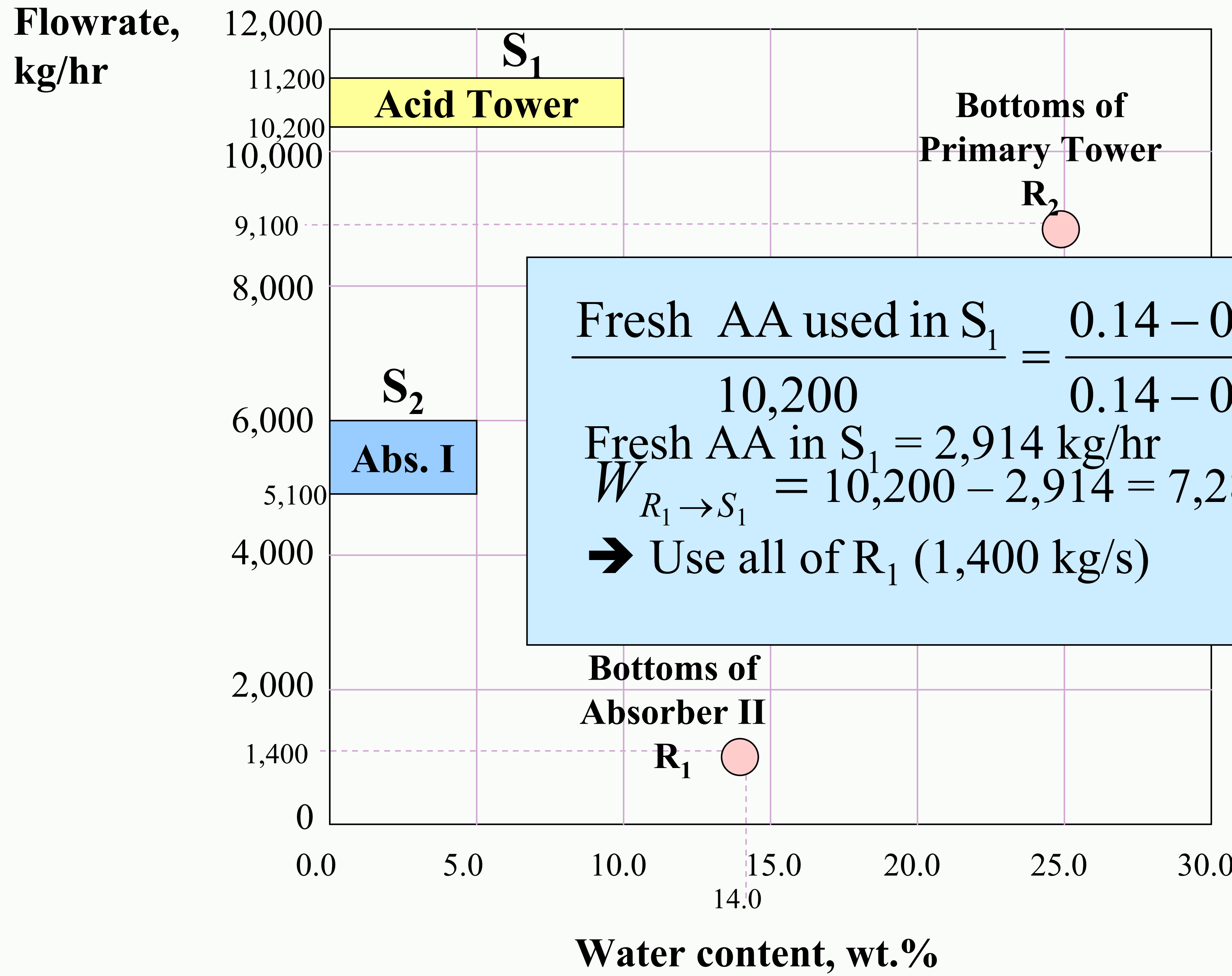
Example: Minimization of AA Usage in VAM Process by Direct Recycle



Source-Sink Mapping Diagram for AA Example



For S_1, R_1 has shortest AA arm



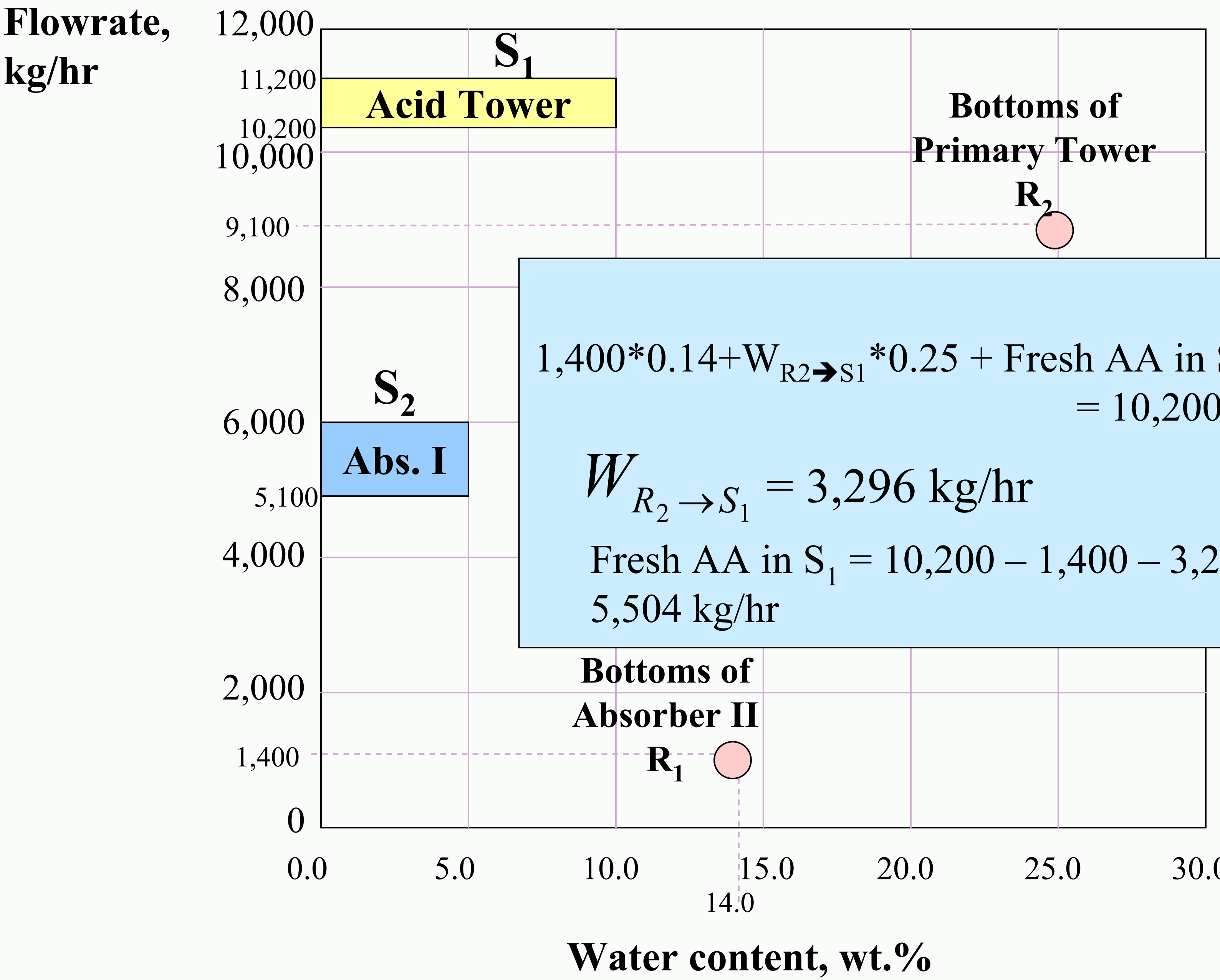
$$\frac{\text{Fresh AA used in } S_1}{10{,}200} = \frac{0.14 - 0.10}{0.14 - 0.00}$$

Fresh AA in S_1 = 2,914 kg/hr

$$W_{R_1 \rightarrow S_1} = 10{,}200 - 2{,}914 = 7{,}286 \text{ kg/s}$$

➔ Use all of R_1 (1,400 kg/s)

Acid Tower Continued

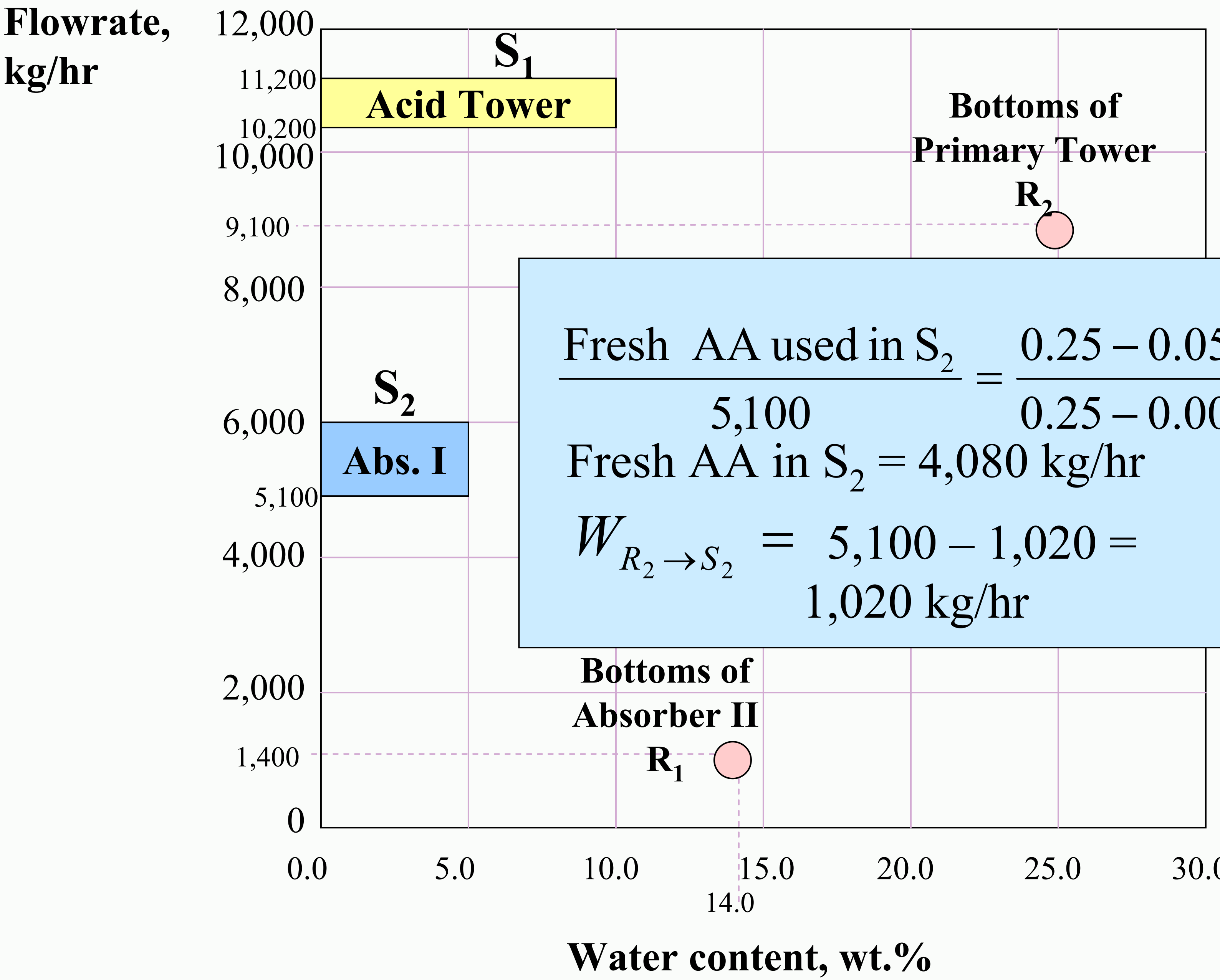


$1{,}400*0.14+W_{R2\rightarrow S1}*0.25$ + Fresh AA in $S_1*0.0$
$= 10{,}200*0.10$

$$W_{R_2\rightarrow S_1} = 3{,}296 \text{ kg/hr}$$

Fresh AA in $S_1 = 10{,}200 - 1{,}400 - 3{,}296 =$ 5,504 kg/hr

Absorber I Calculations

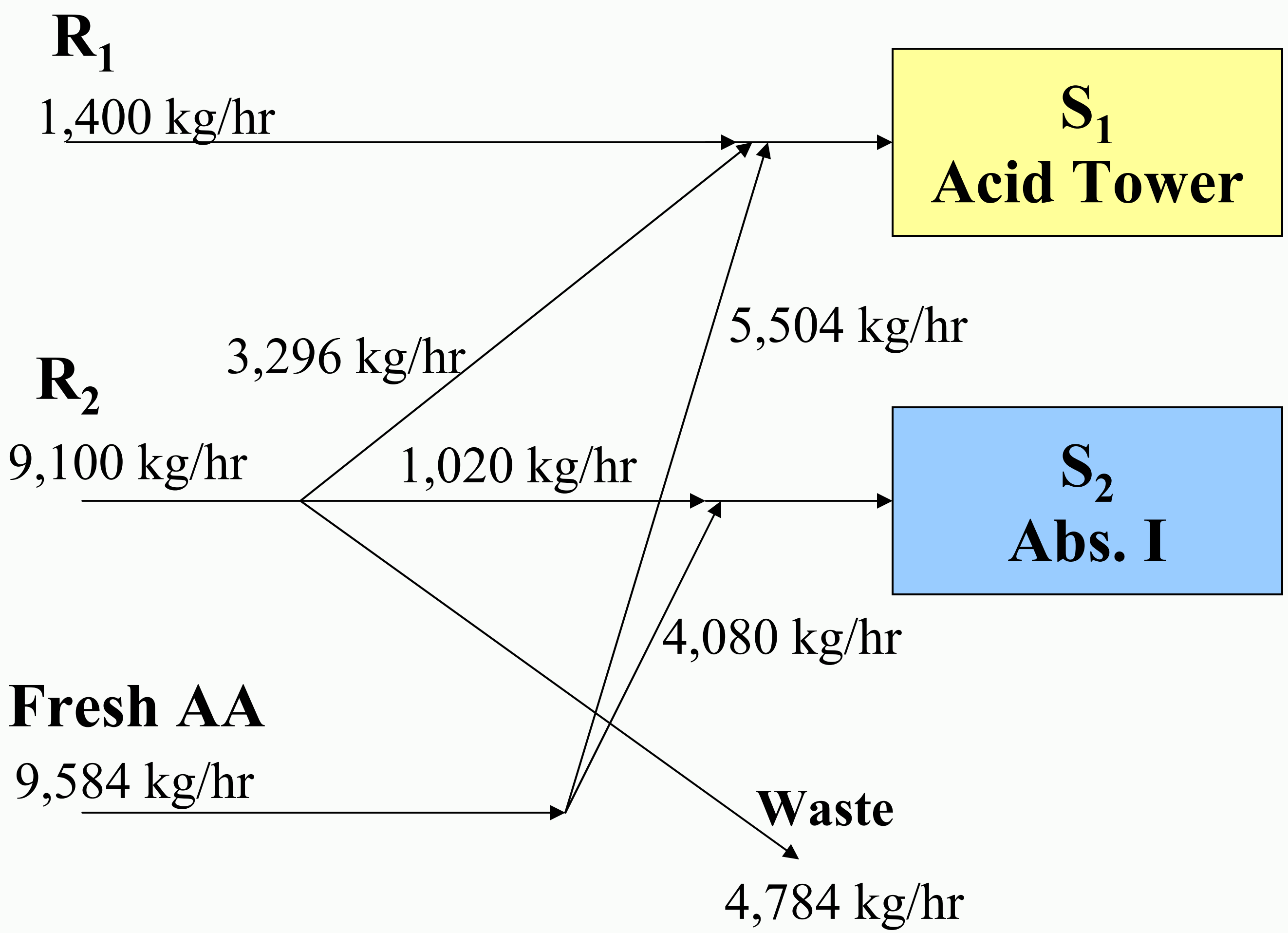


$$\frac{\text{Fresh AA used in } S_2}{5{,}100} = \frac{0.25 - 0.05}{0.25 - 0.00}$$

$$\text{Fresh AA in } S_2 = 4{,}080 \text{ kg/hr}$$

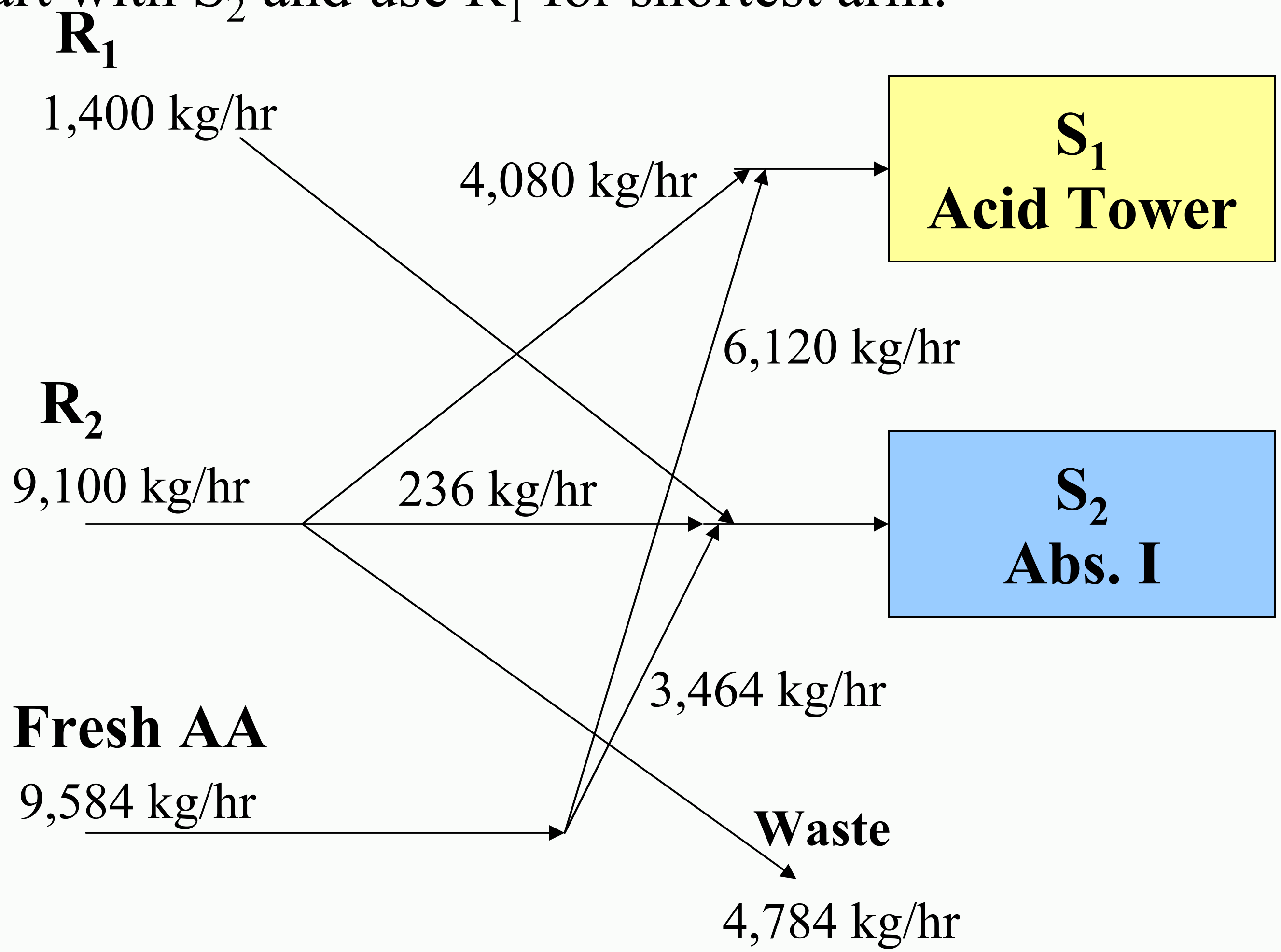
$$W_{R_2 \rightarrow S_2} = 5{,}100 - 1{,}020 = 1{,}020 \text{ kg/hr}$$

SOLUTION TO AA MINIMIZATION PROBLEM



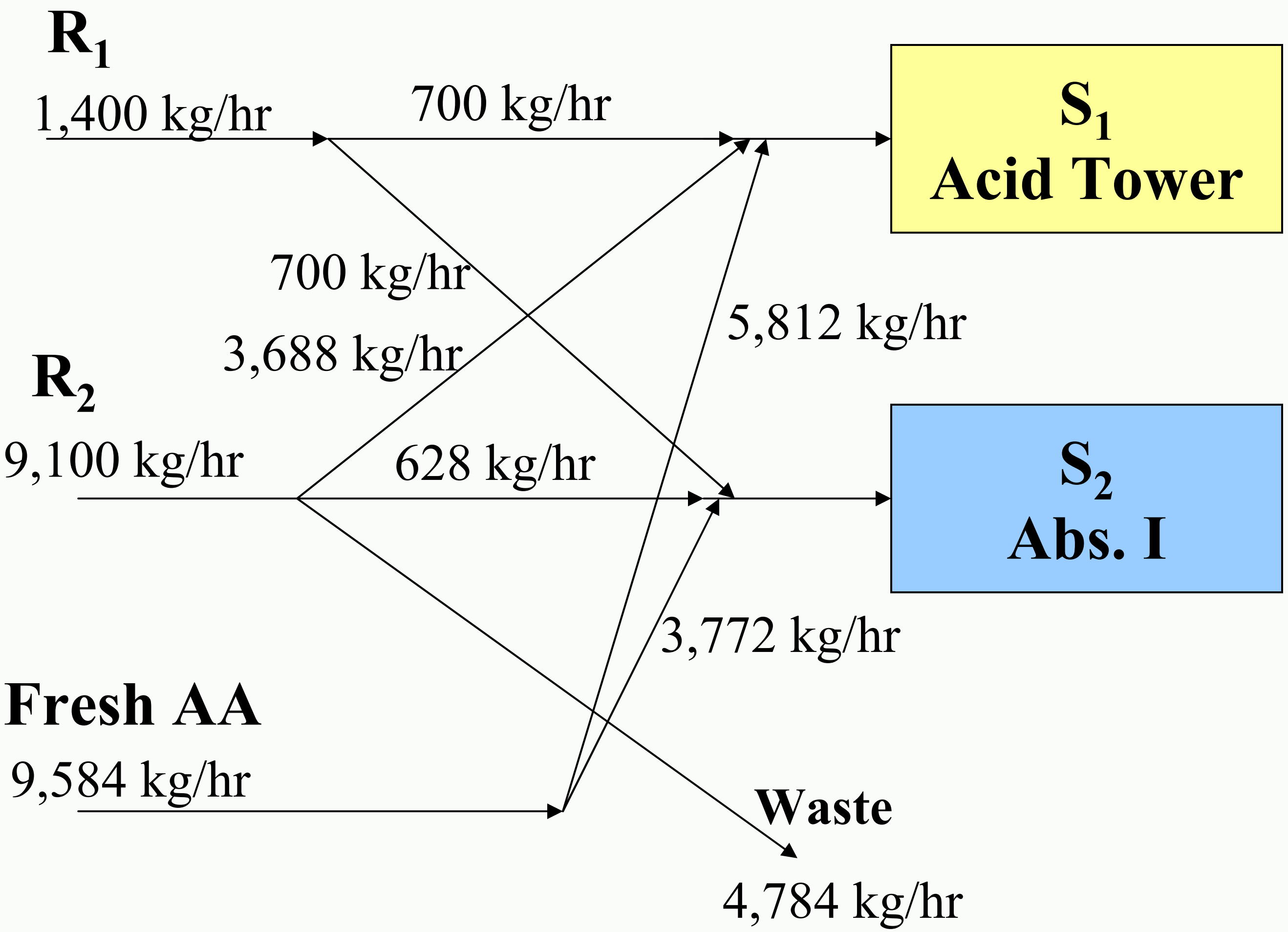
ALTERNATE SOLUTION TO AA MINIMIZATION PROBLEM

Start with S_2 and use R_1 for shortest arm.



ALTERNATE SOLUTION TO AA MINIMIZATION PROBLEM

Split R_1 between two sinks.

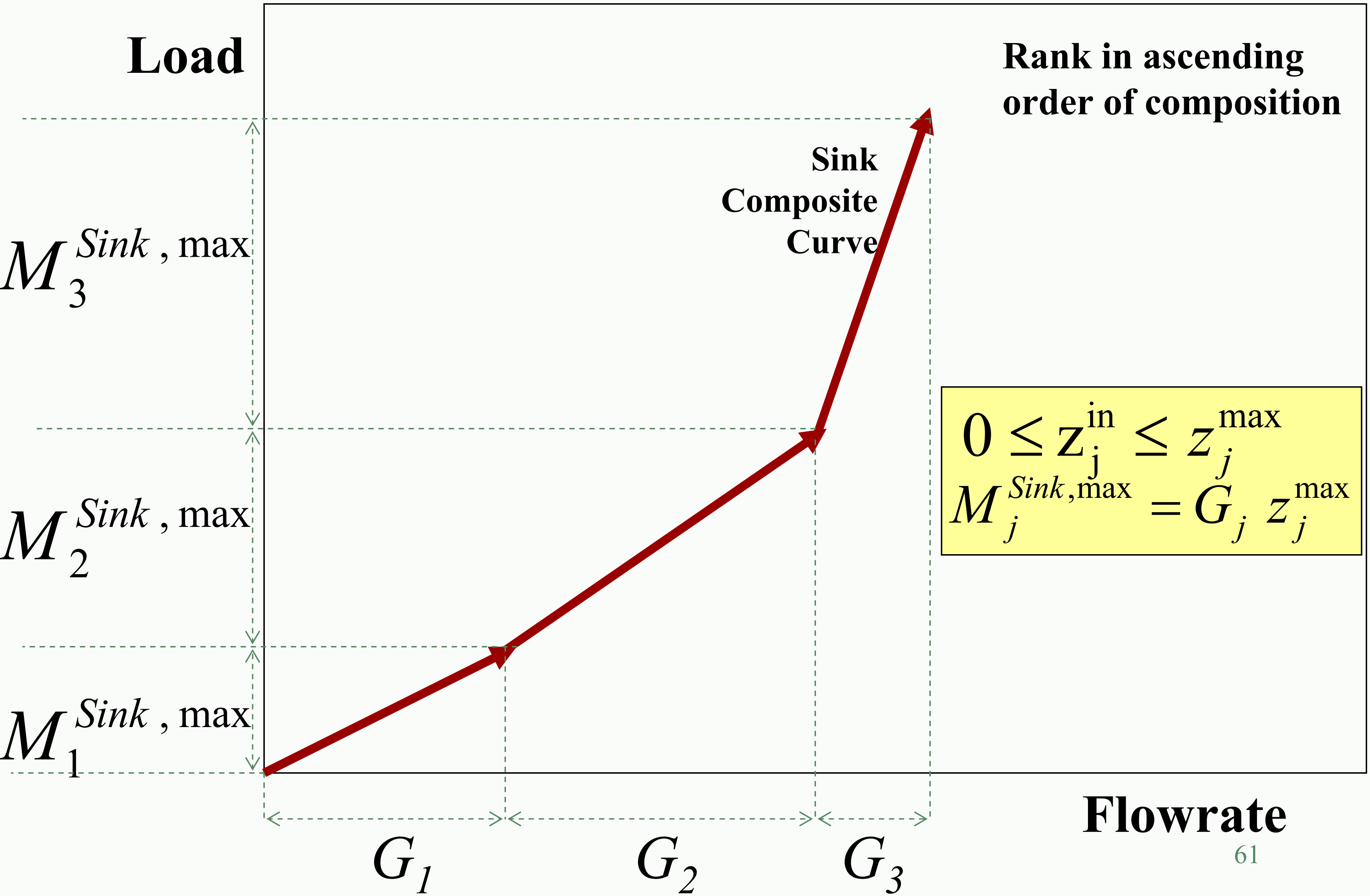


Same target, infinite implementations.

Need a targeting procedure before detailed implementation

MATERIAL RECYCLE PINCH DIAGRAM

Sink Composite Diagram

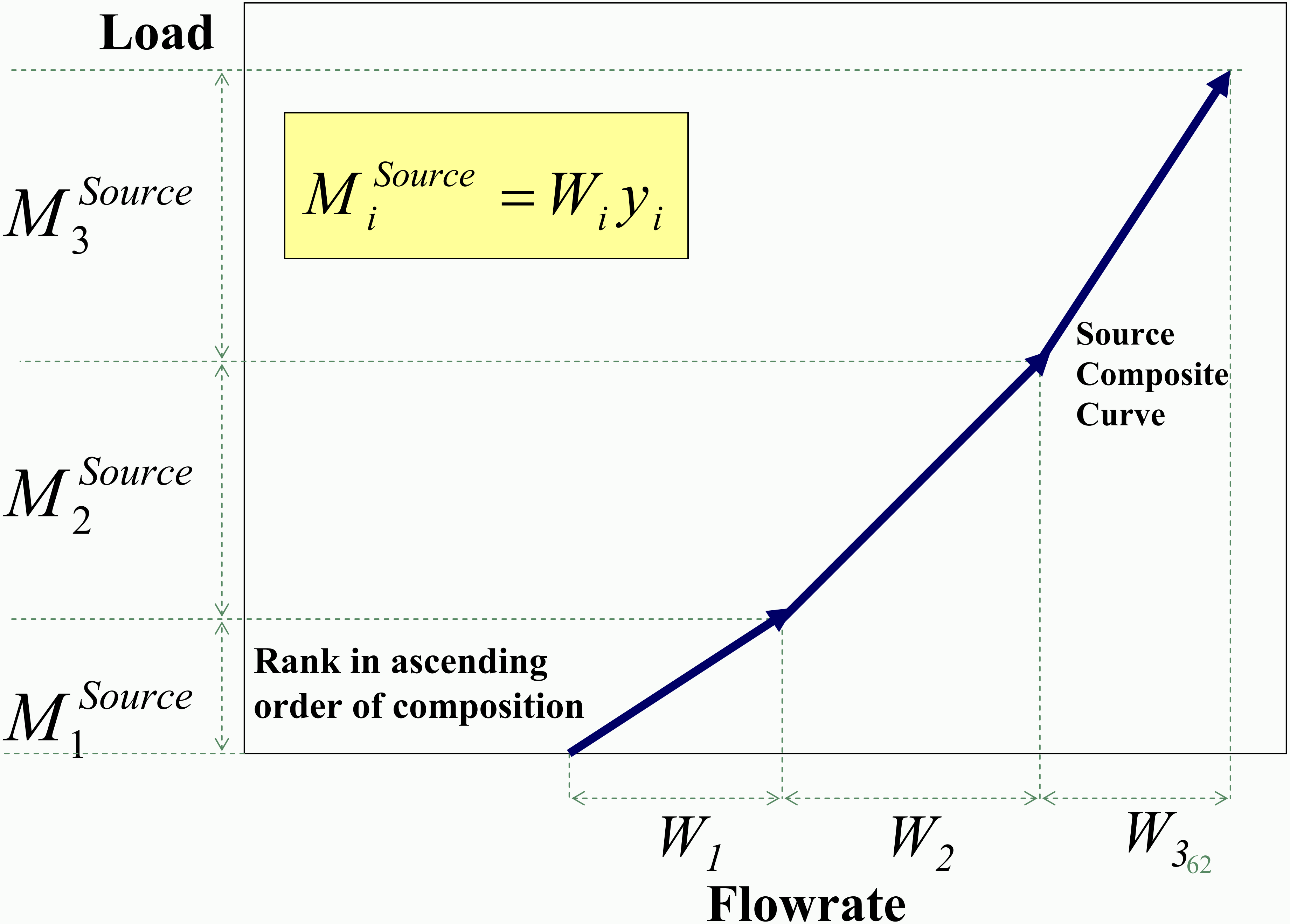


$$0 \le z_j^{in} \le z_j^{\max}$$

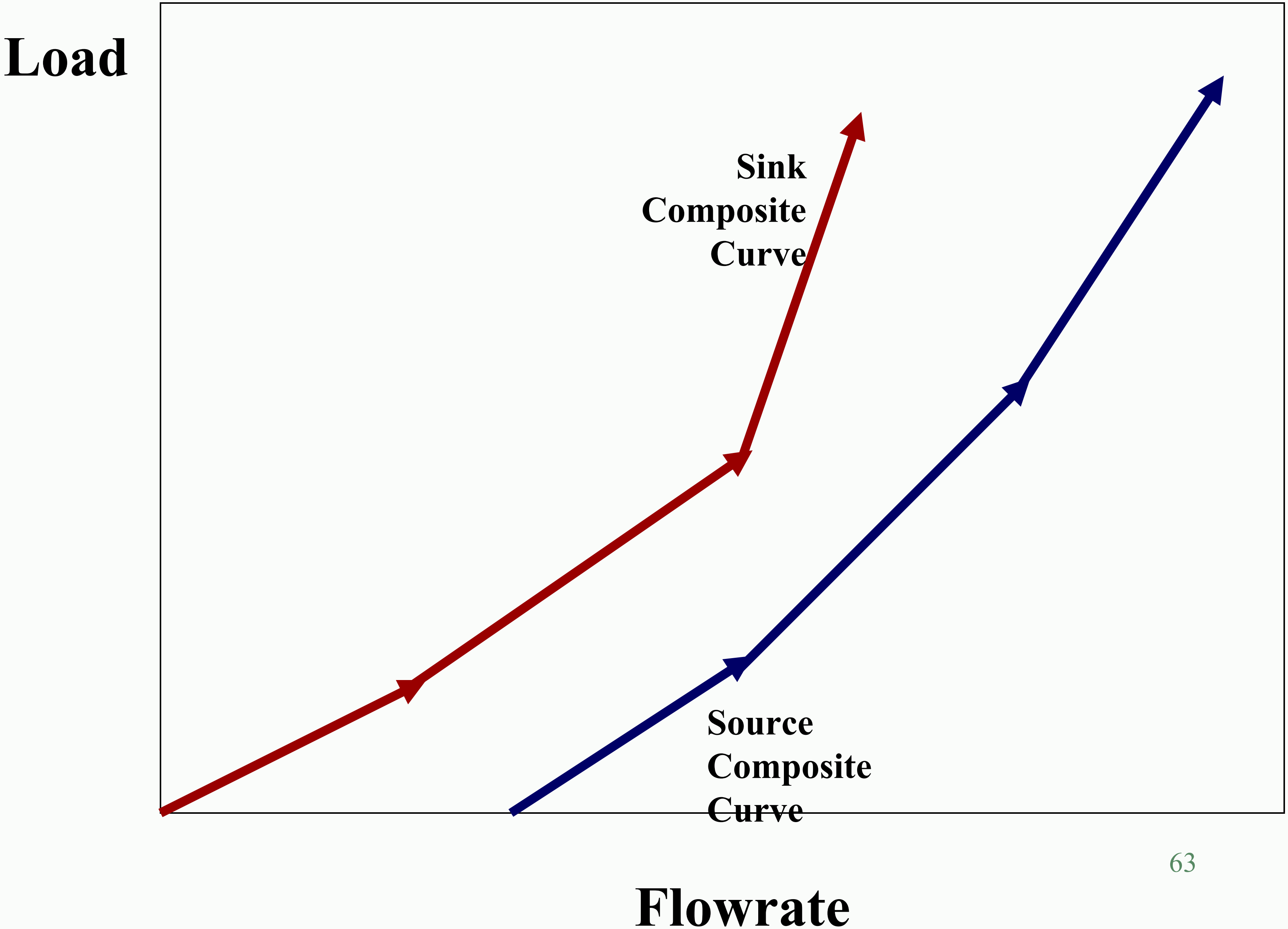
$$M_j^{Sink,\max} = G_j \, z_j^{\max}$$

Source Composite Diagram

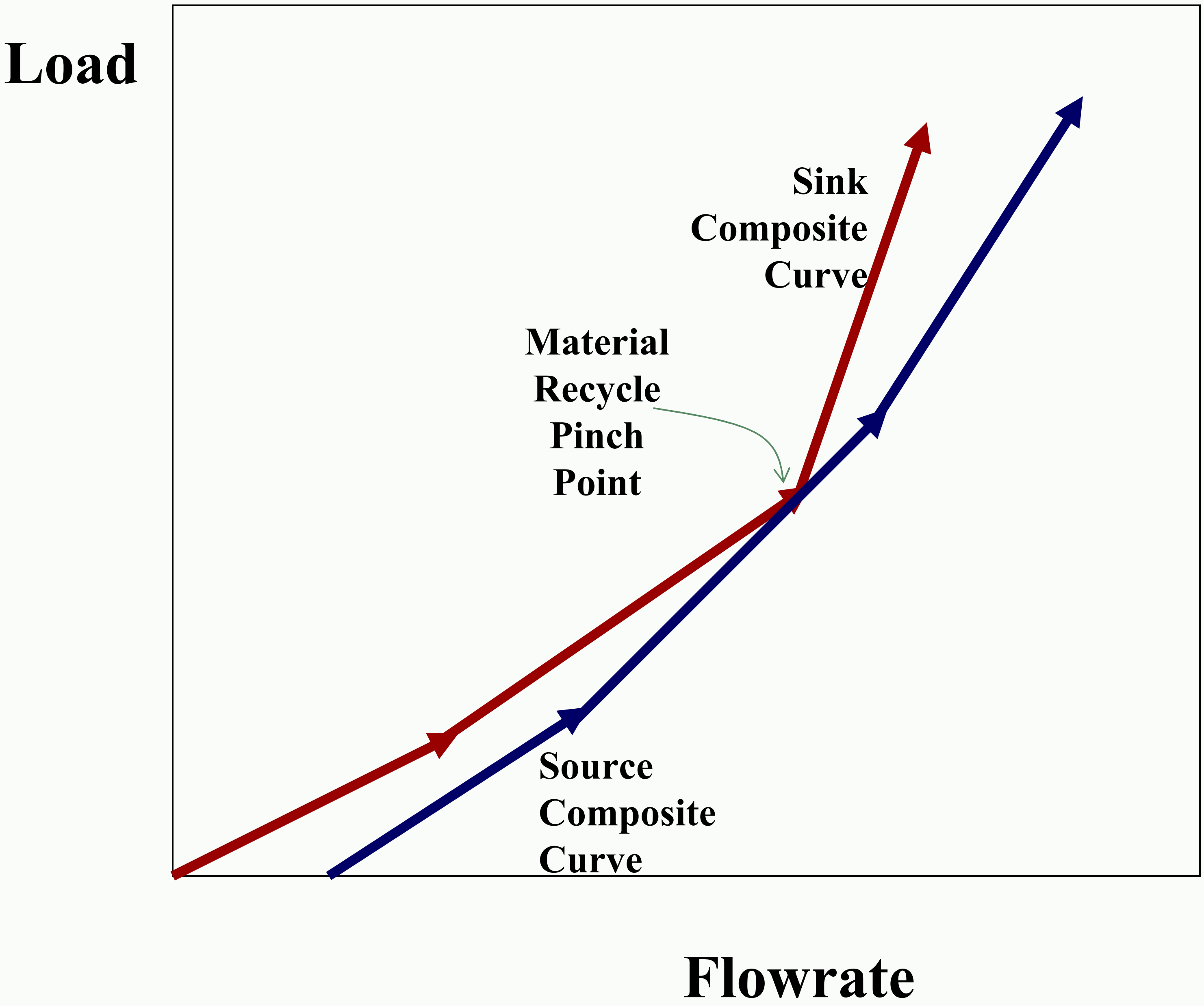
$$M_i^{Source} = W_i y_i$$



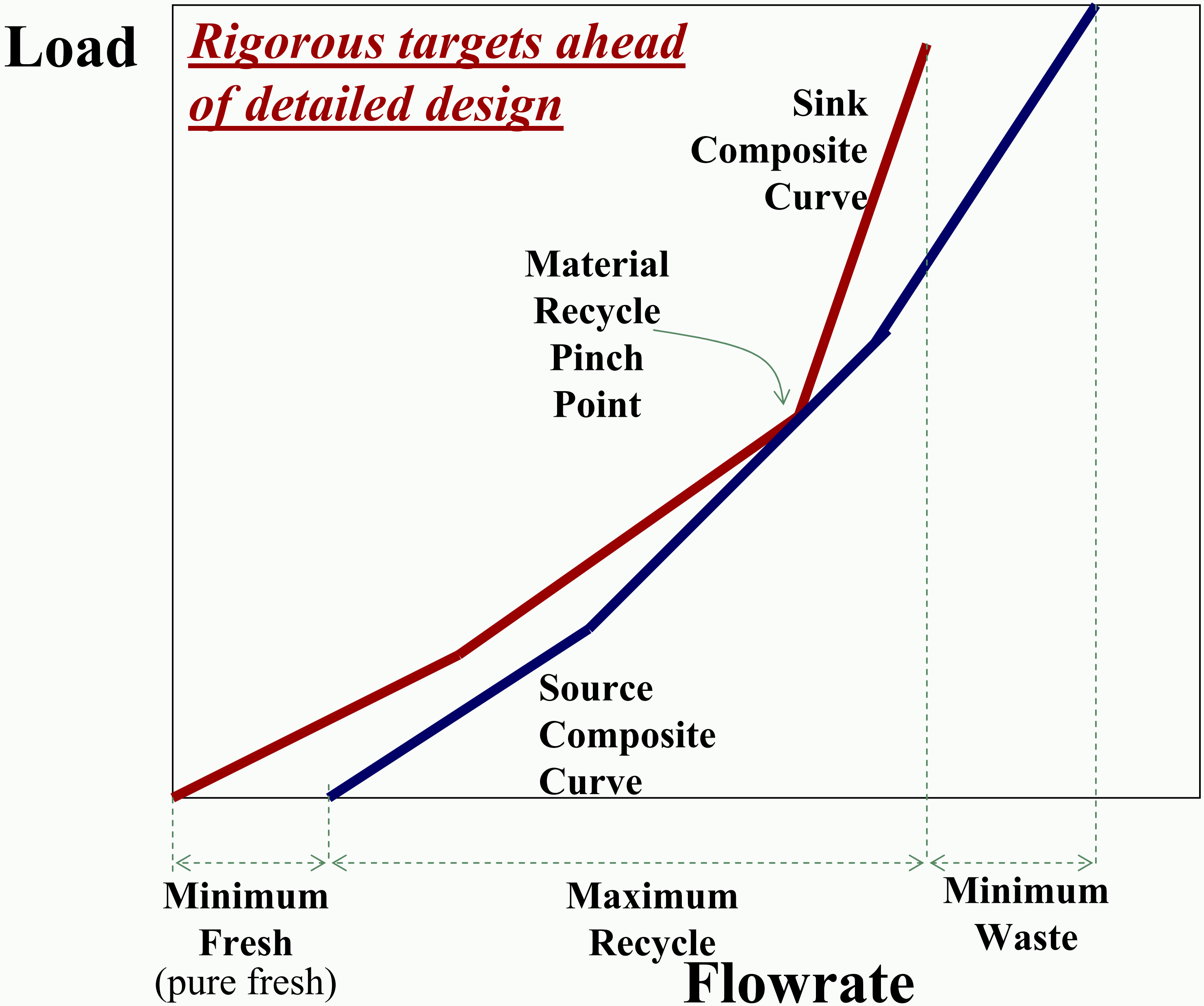
Sink Composite Must Lie Above Source Composite



Integrating Source and Sink Composites

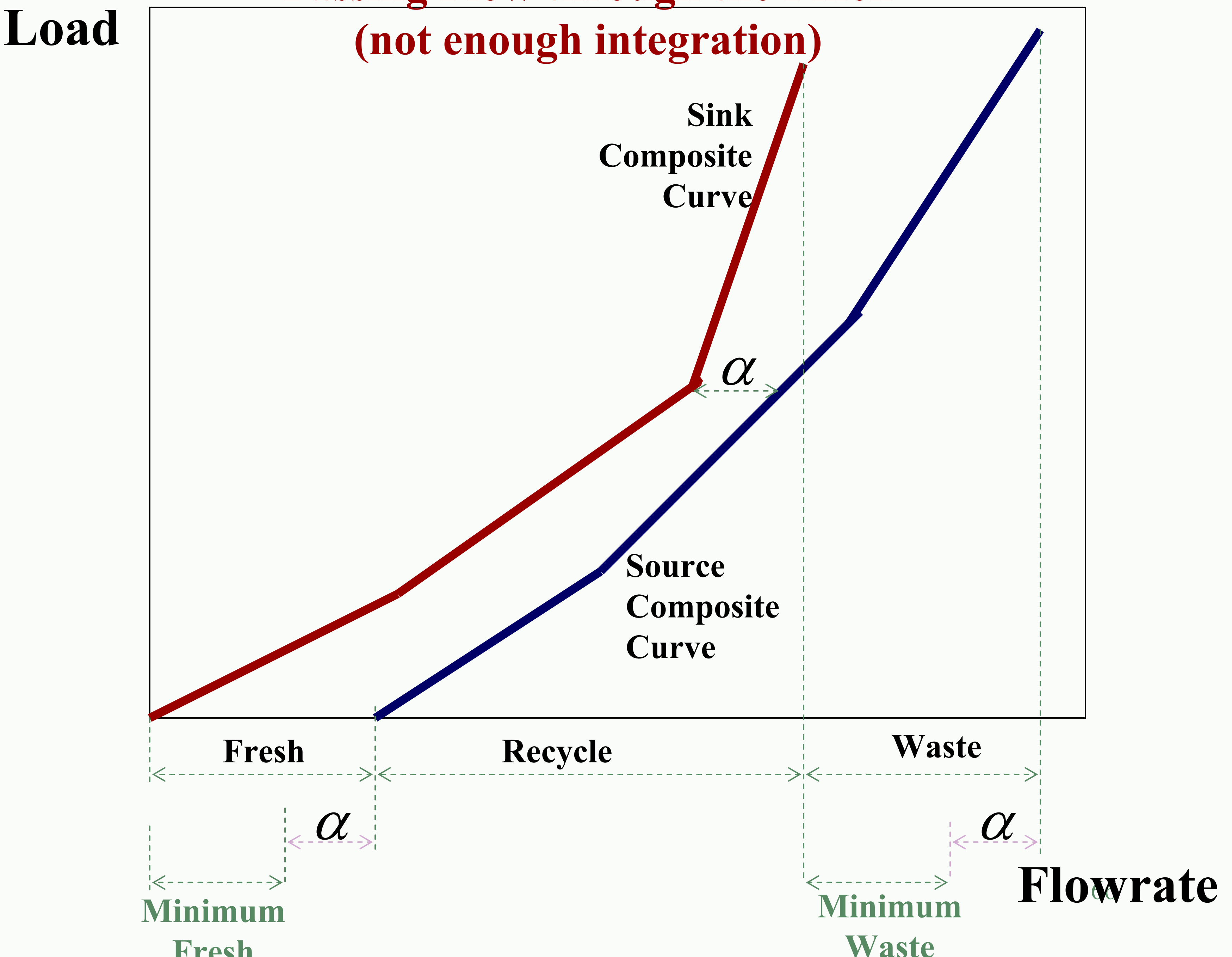


Material Recycle Pinch Diagram

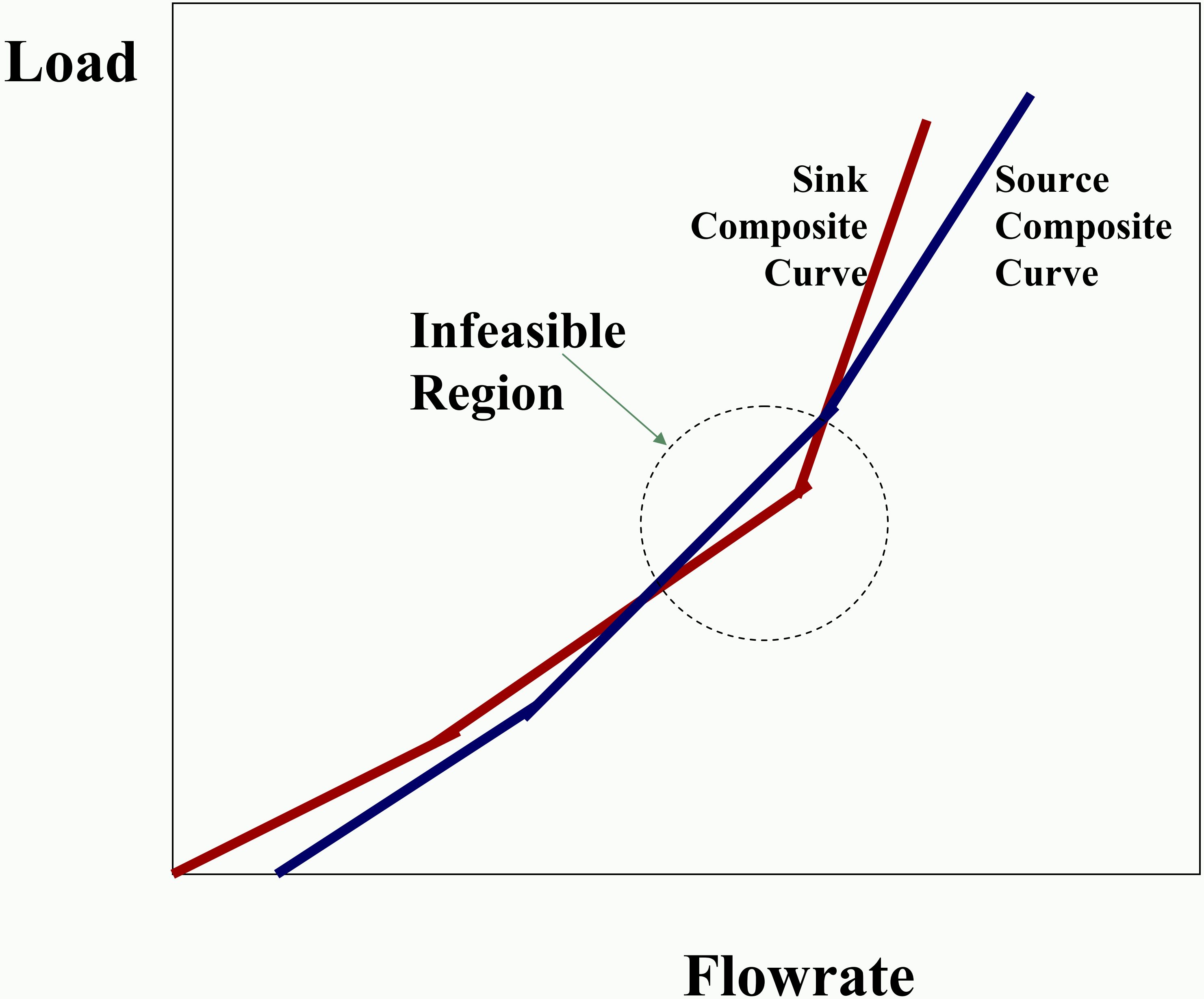


[1]*Ref.*: *El-Halwagi, M. M., F. Gabriel, and D. Harell, "Rigorous Graphical Targeting for Resource Conservation via Material Recycle/Reuse Networks", Ind. Eng. Chem. Res., 42, 4319-4328 (2003)*

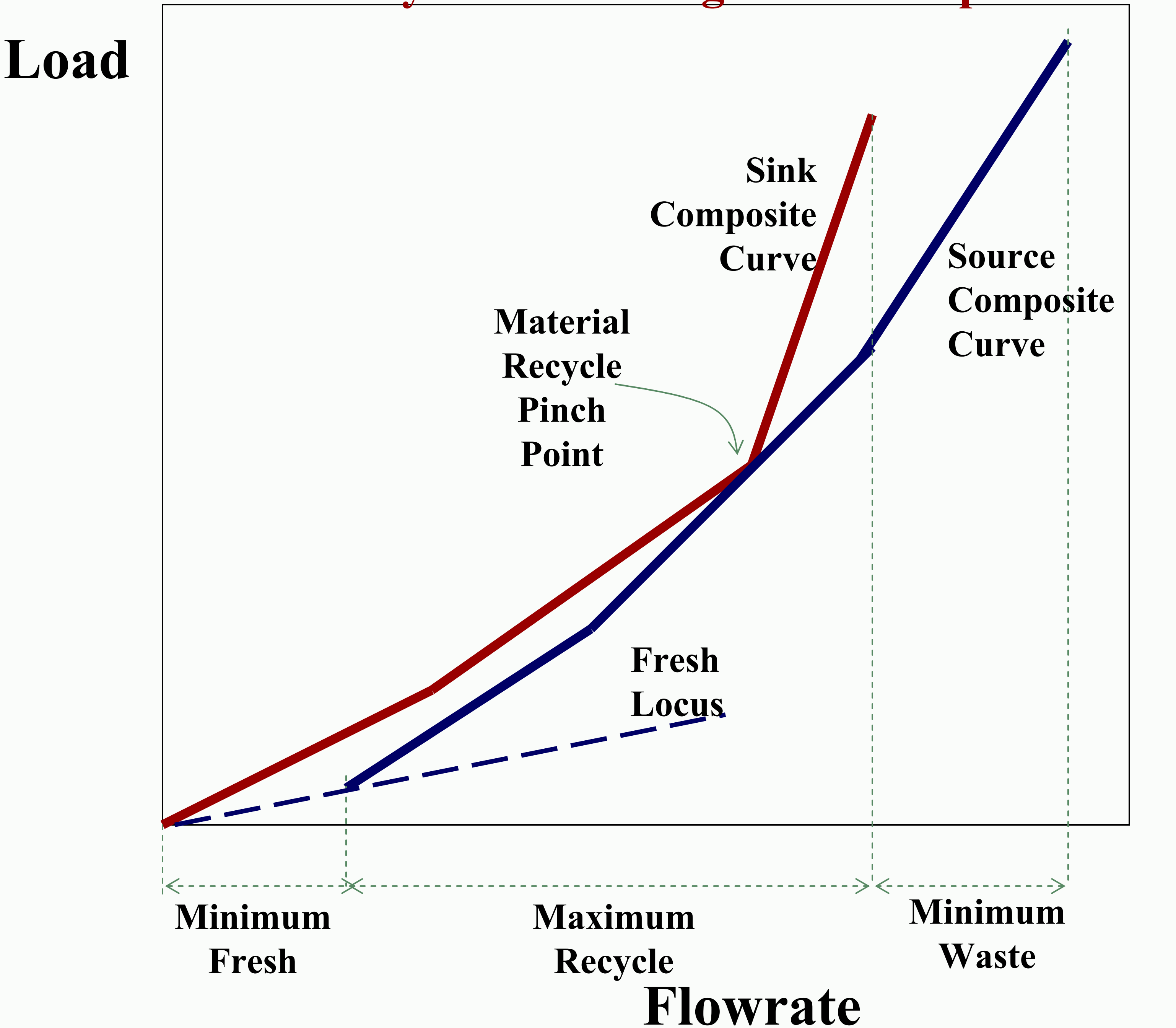
Passing Flow through the Pinch
(not enough integration)



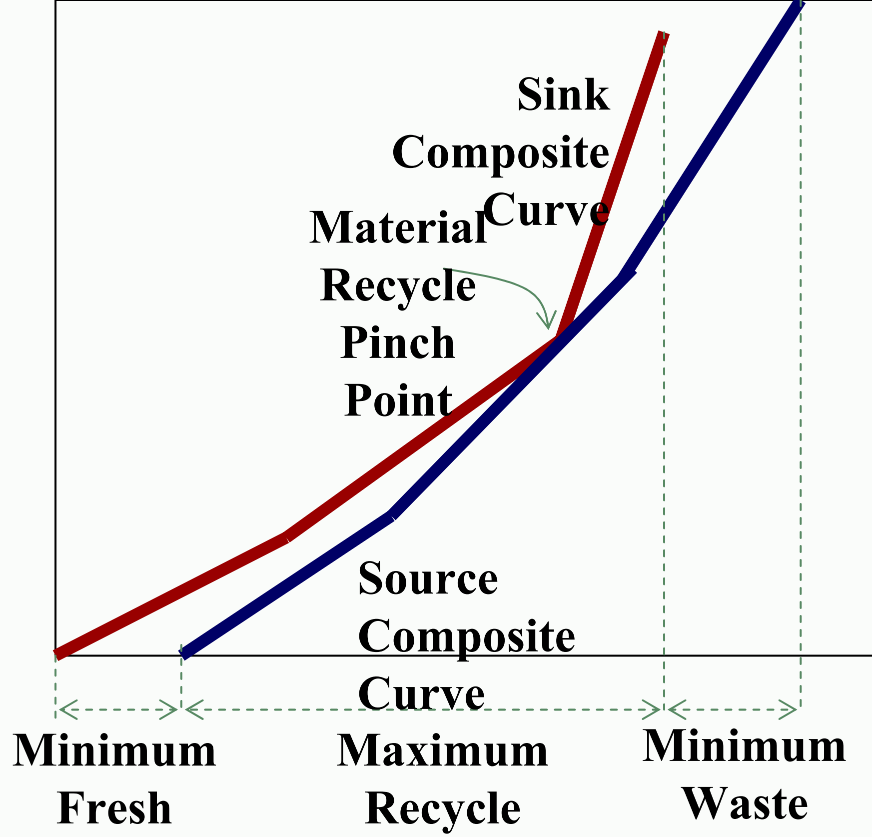
Infeasible Recycle
(too much integration)



Material Recycle Pinch Diagram for Impure Fresh

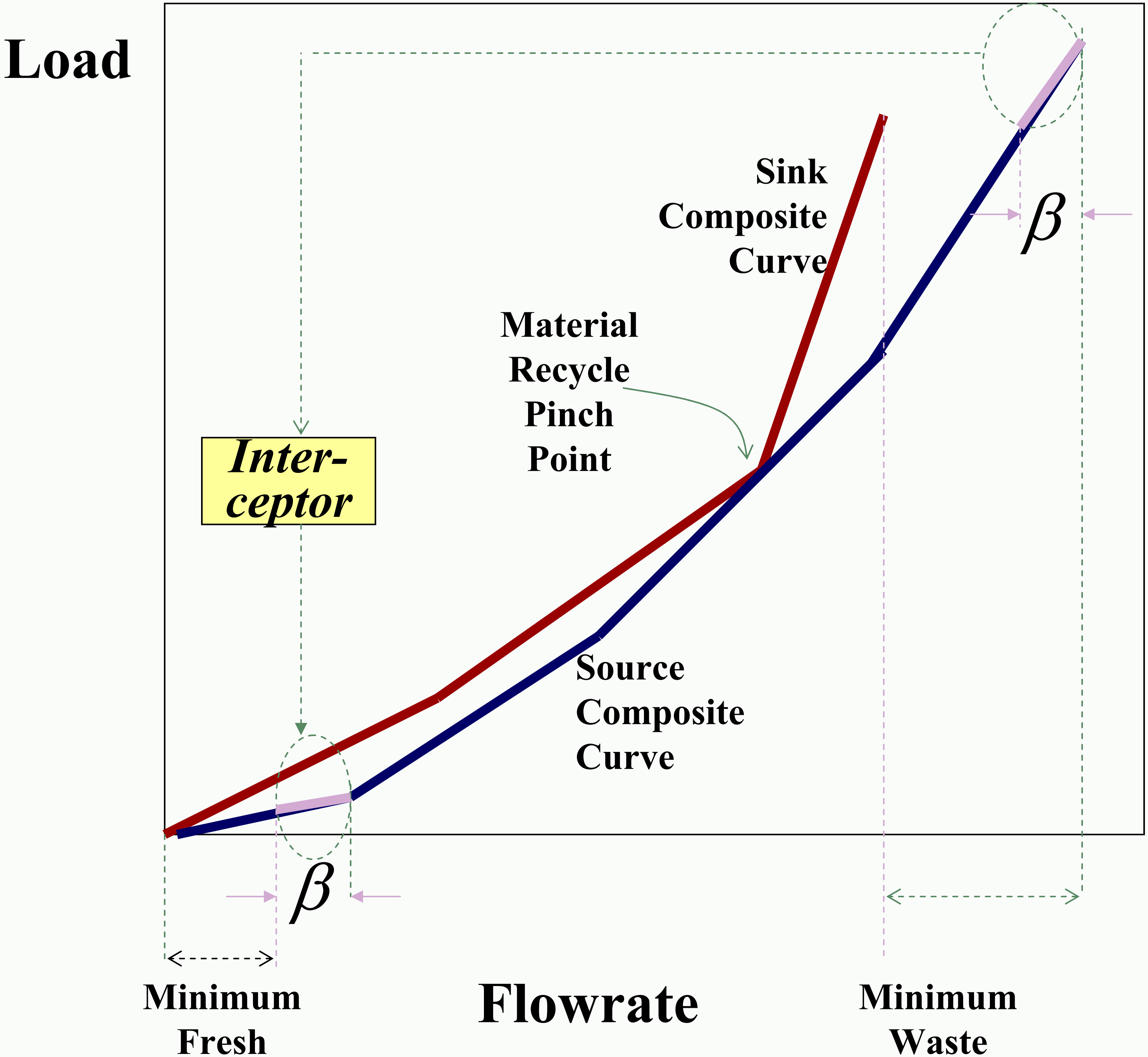


Useful Design Rules For Material Recycle Pinch Diagram

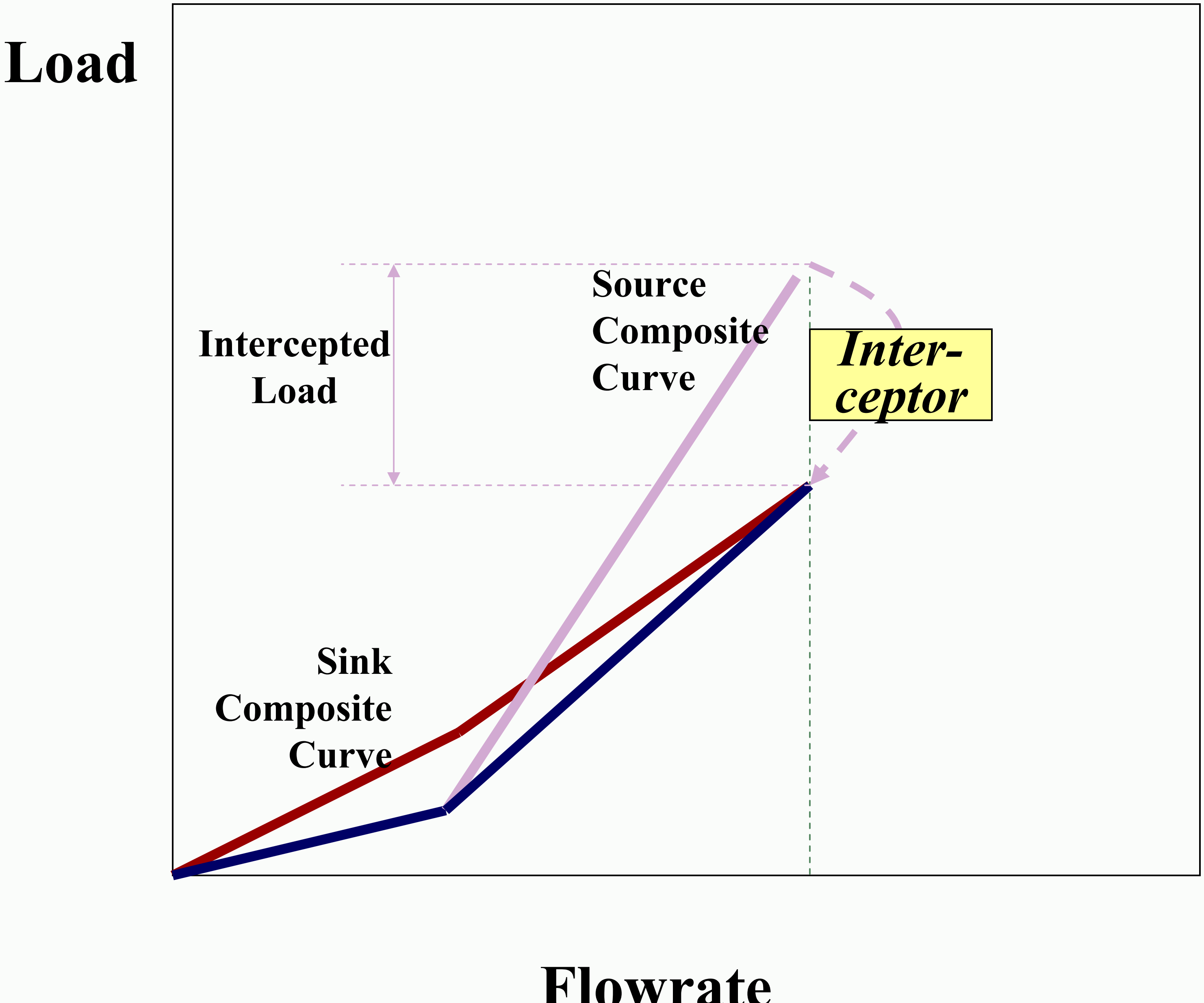


- ***No flowrate should be passed through the pinch (i.e. the two composites must touch)***
- ***No waste should be discharged from sources below the pinch***
- ***No fresh should be used in any sink above the pinch***

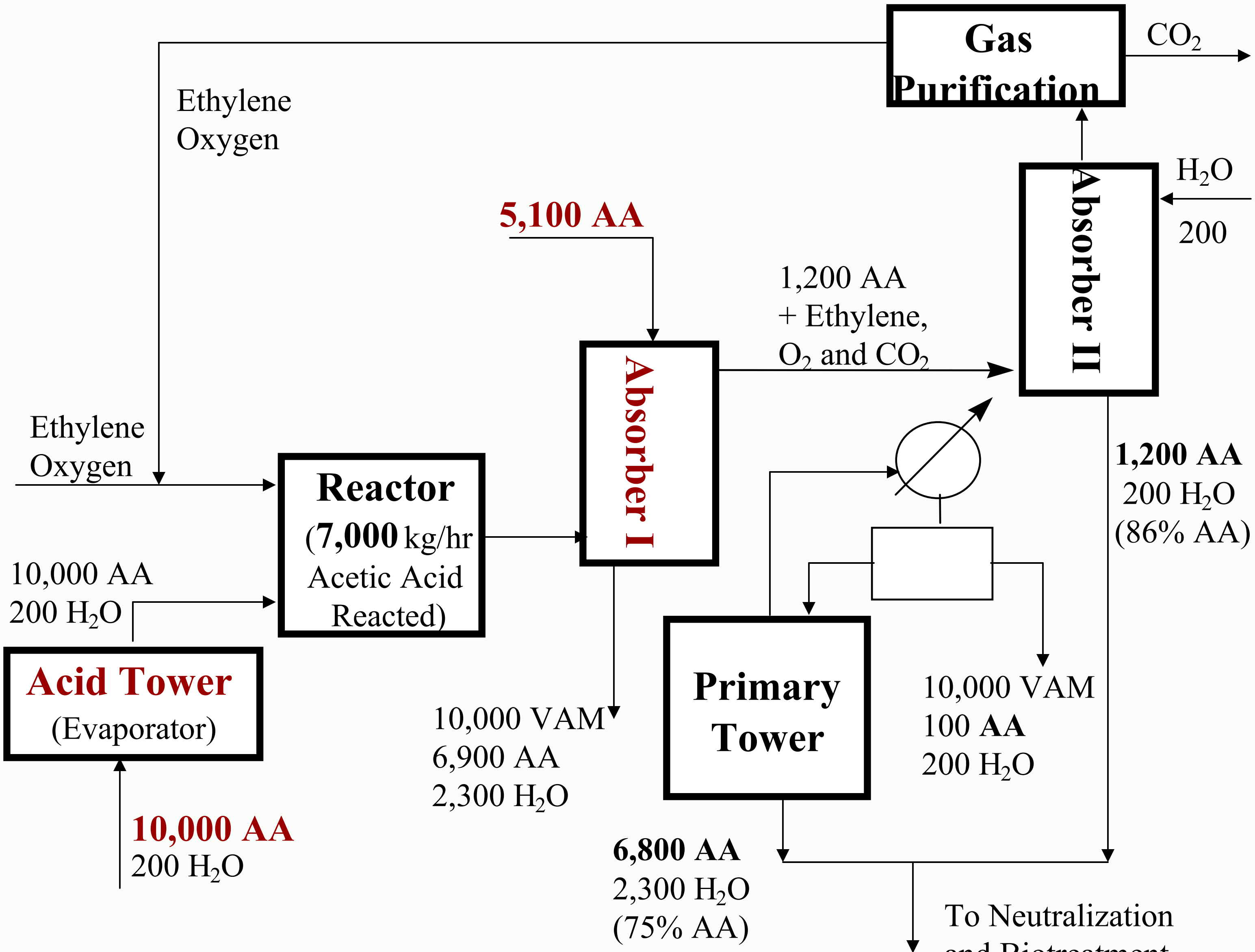
Effect of Interception



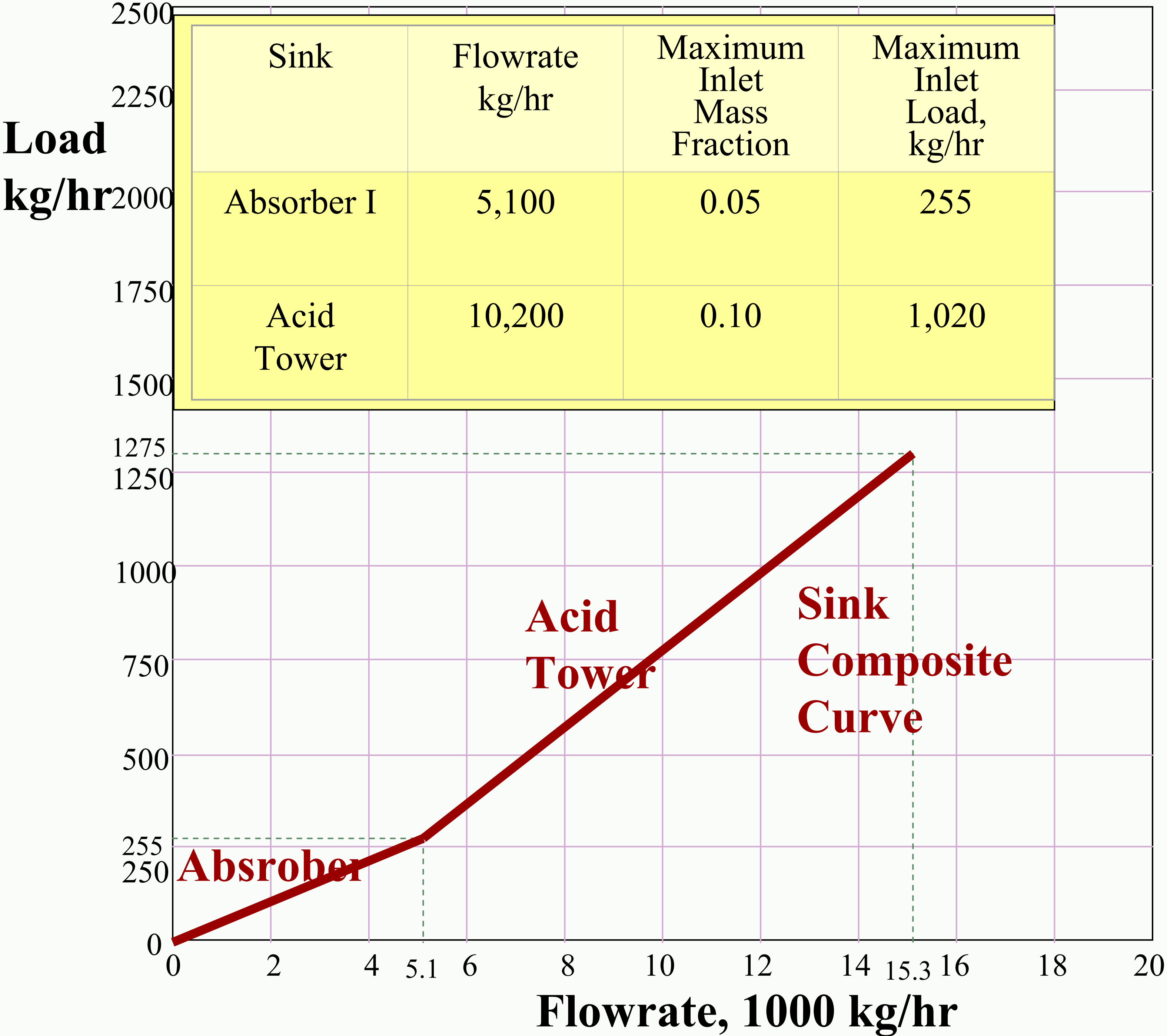
Effect of Interception

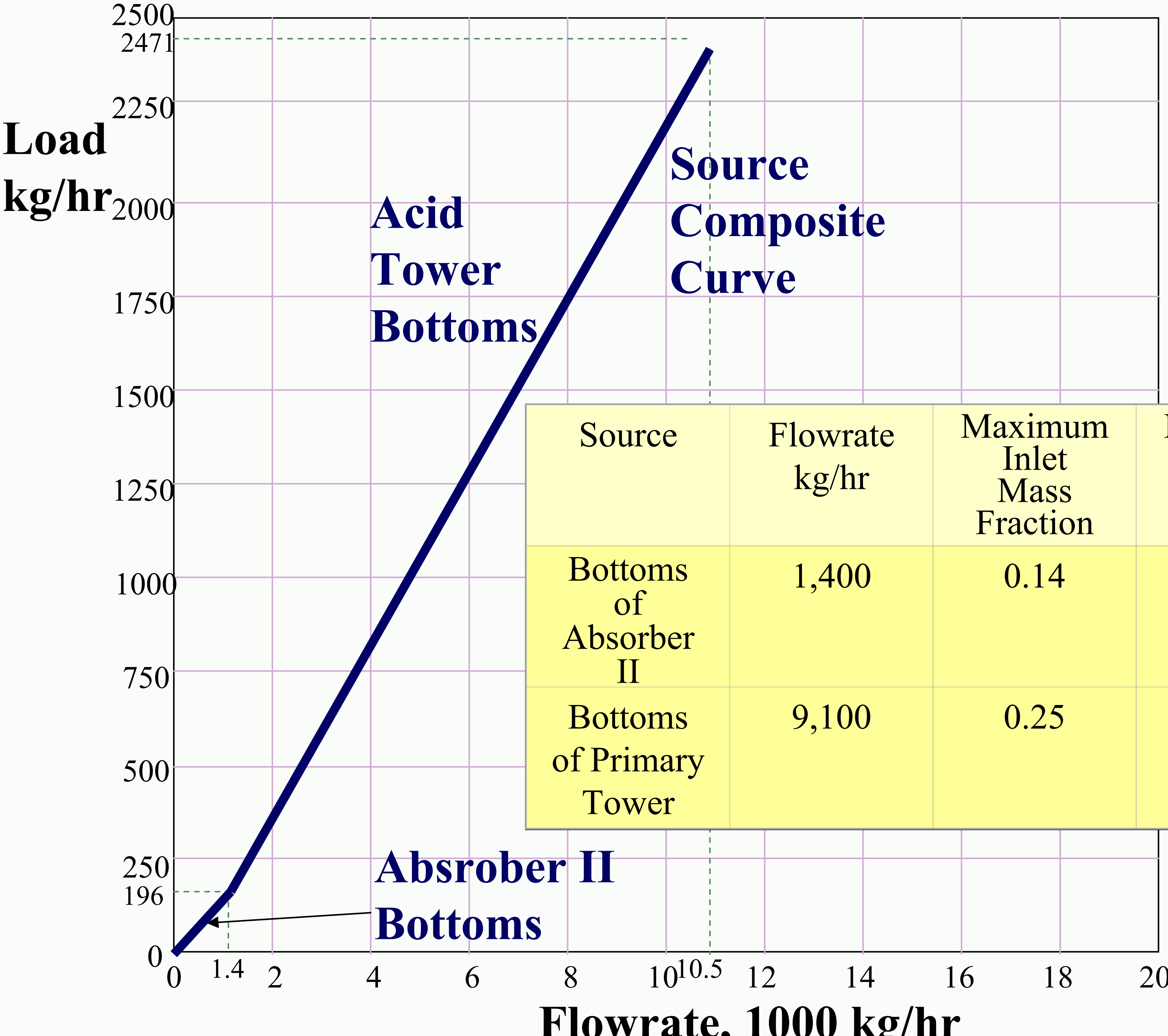


Example Revisited: Minimization of AA Usage in VAM Process

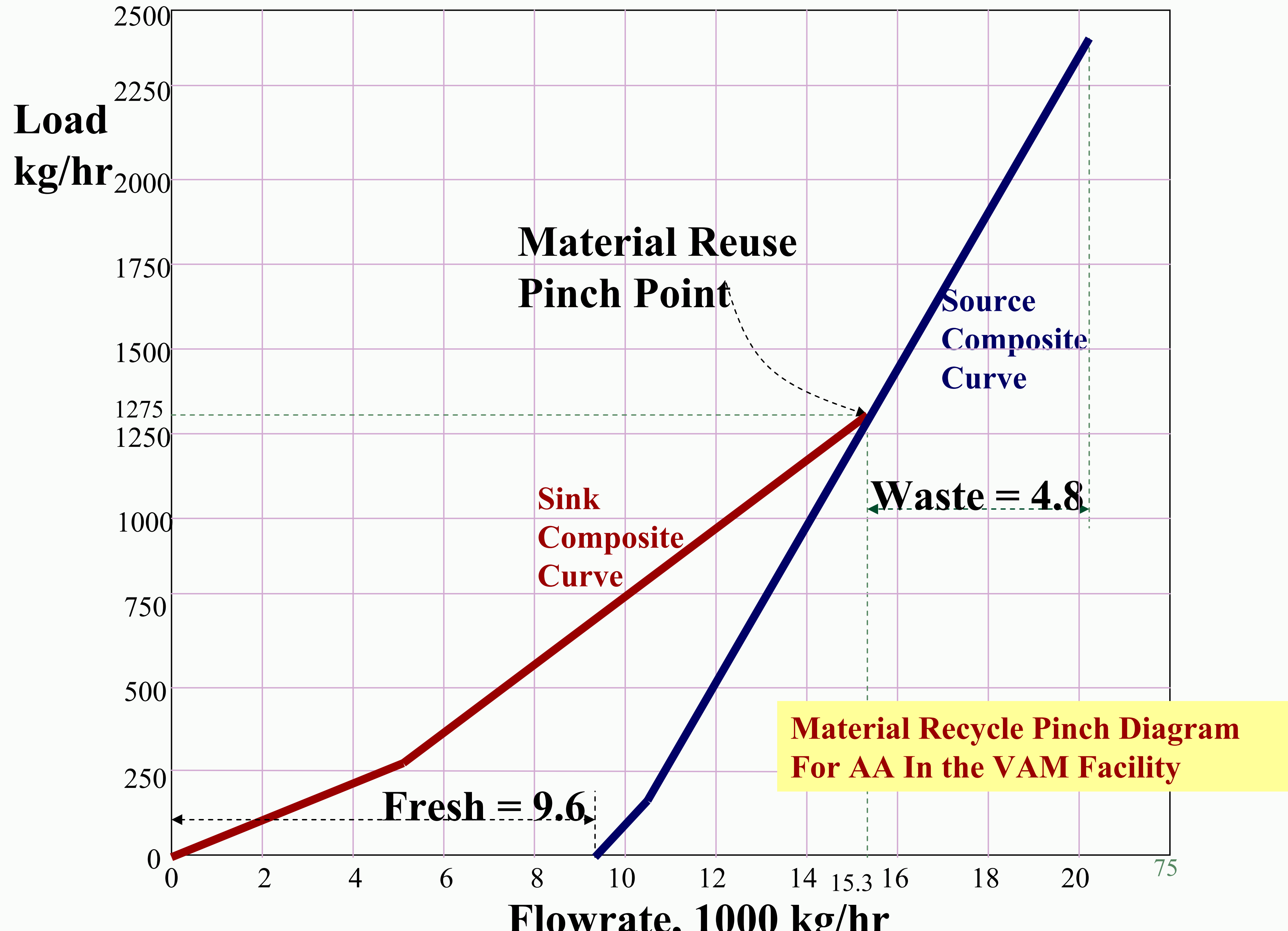


Sink	Flowrate kg/hr	Maximum Inlet Mass Fraction	Maximum Inlet Load, kg/hr
Absorber I	5,100	0.05	255
Acid Tower	10,200	0.10	1,020

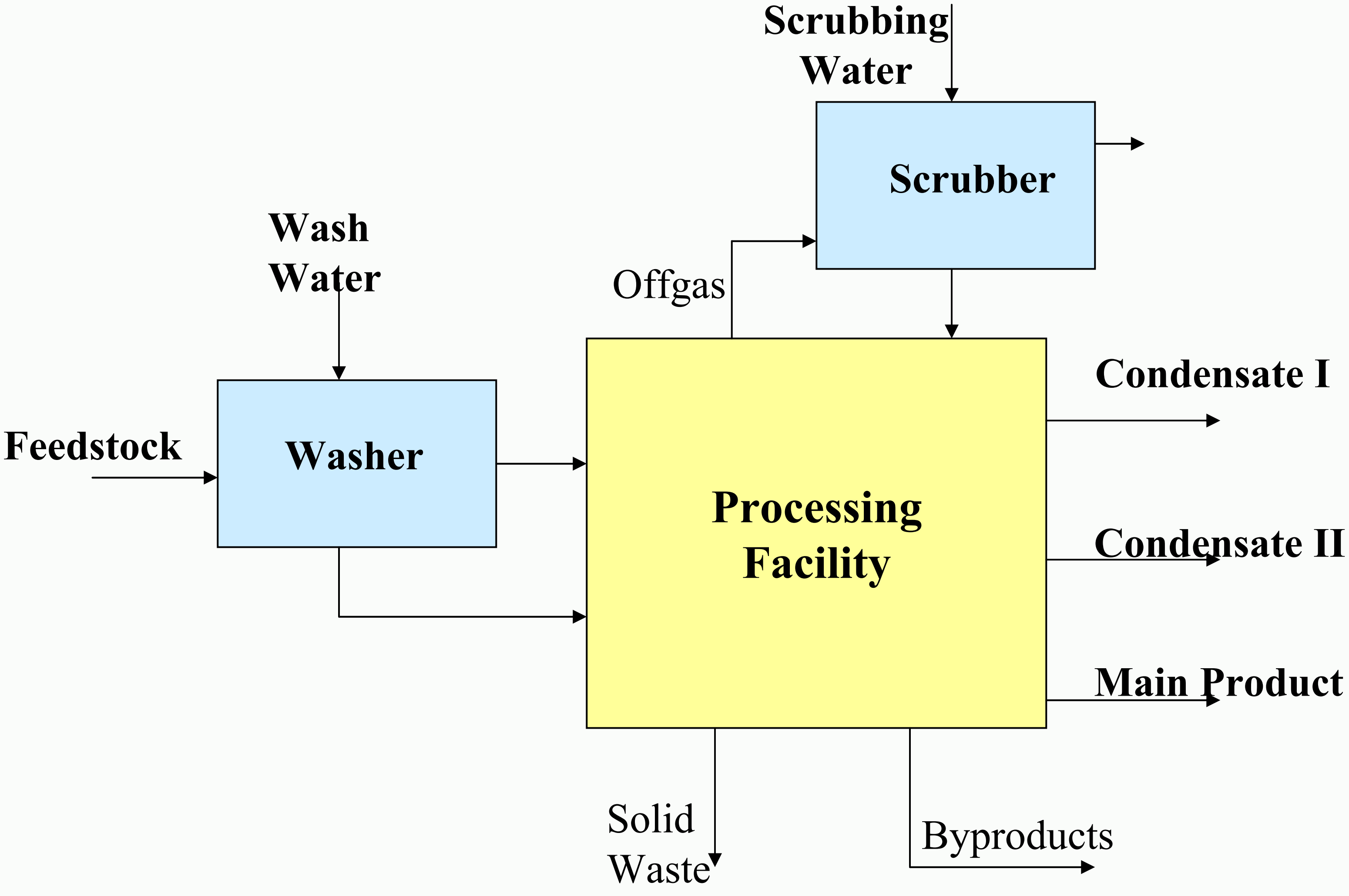




Source	Flowrate kg/hr	Maximum Inlet Mass Fraction	Maximum Inlet Load, kg/hr
Bottoms of Absorber II	1,400	0.14	196
Bottoms of Primary Tower	9,100	0.25	2,275


Load
kg/hr
2500
2250
2000
1750
1500
1275
1250
1000
750
500
250
0
Material Reuse
Pinch Point
Source
Composite
Curve
Sink
Composite
Curve
Waste = 4.8
Fresh = 9.6
Material Recycle Pinch Diagram
For AA In the VAM Facility
0
2
4
6
8
10
12
14
15.3
16
18
20
Flowrate, 1000 kg/hr

PRACTICE EXERCISE II: FOOD PROCESSING FACILITY



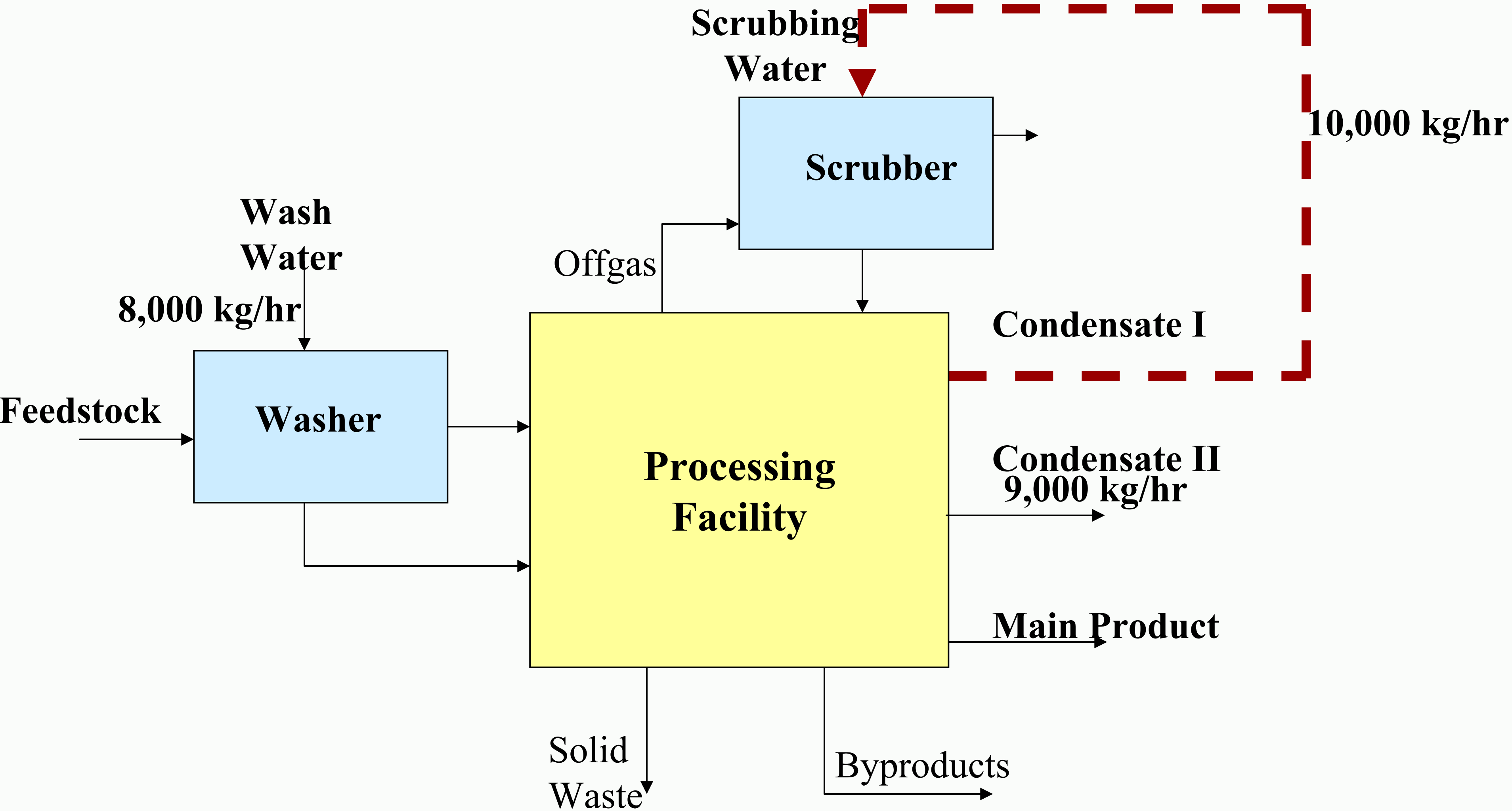
Two source (Condensate I and II), Two Sinks (Washer and Scrubber)

Sink Data for the Food Processing Example

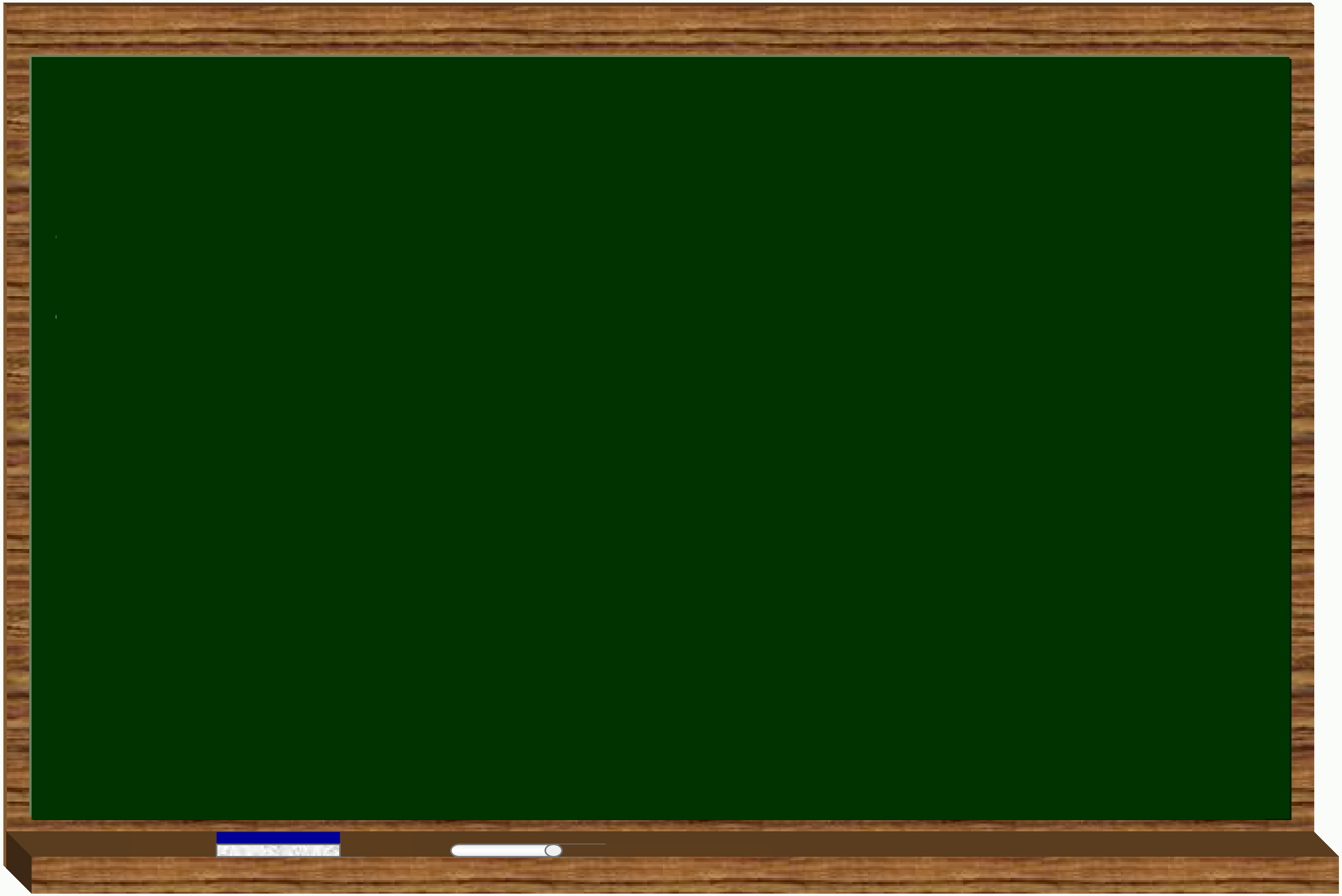
Sink	Flowrate kg/hr	Maximum Inlet Mass Fraction	Maximum Inlet Load, kg/hr
Washer	8,000	0.03	240
Scrubber	10,000	0.05	500

Source Data for the Food Processing Example

Source	Flowrate kg/hr	Maximum Inlet Mass Fraction	Maximum Inlet Load, kg/hr
Condensate I	10,000	0.02	200
Condensate II	9,000	0.09	810

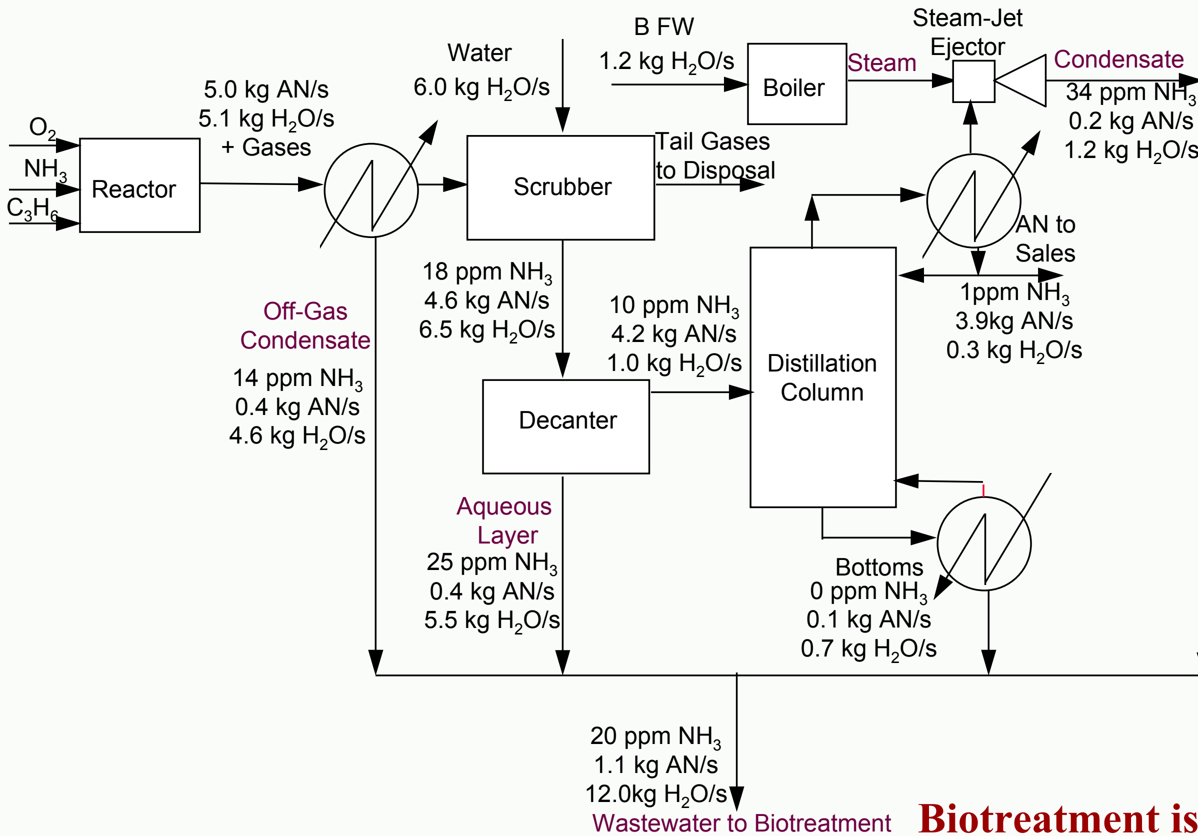


Critique project proposed by engineer:
Recycle Condensate I to Scrubber
➔Reduce fresh water to 8,000 kg/hr (down from 18,000 kg/hr)



GRAPHICAL TECHNIQUES FOR MASS INTEGRATION

Motivating Example: Debottleneck Acrylonitrile Process and Minimize Fresh Water Usage



Biotreatment is current bottleneck

Insights from flowsheet?

Target for water usage and discharge?

Minimum cost strategies to attain target

Ref. El-Halwagi, M. M., "Pollution Prevention through Process Integration: Systematic Design Tools", Academic Press (1997

Critical Need:

A systematic methodology that provides fundamental understanding of the global flow of mass within a process and employs this understanding in identifying performance targets and optimizing the generation and routing of species throughout the process.

→ **Mass integration**

To:

- Determine performance **targets** ahead of detailed design (e.g., minimum raw material consumption, maximum process yield, minimum waste discharge, maximum recovery, etc.)
- Identify optimum:

1. Allocation (routing) of streams and species
2. Changes in generation/depletion of species
3. New units to be added to the process
4. New materials/streams to be added to the process

Identify optimum revisions in flowsheet to reach target

Big picture first, details later

Design Tasks:

Can we determine:

⇒**Target for minimum wastewater discharge?**

⇒**Recycle opportunities?**

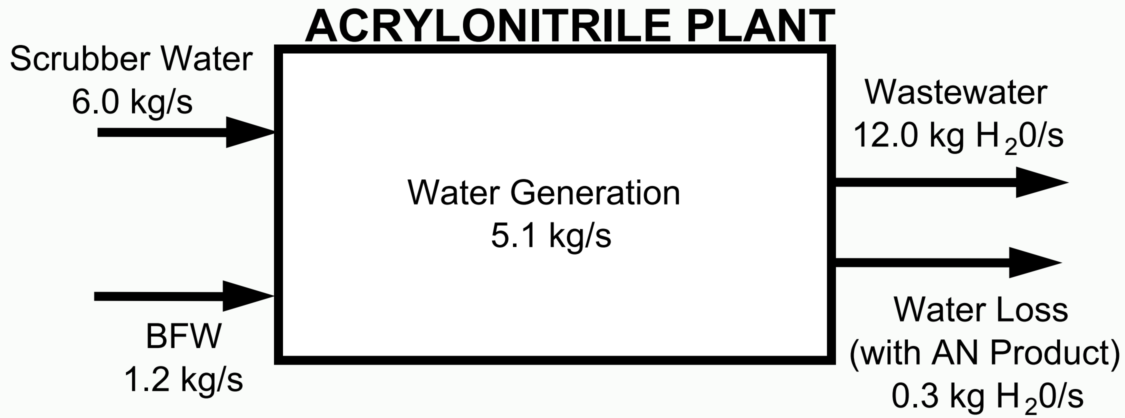
⇒**Separation needed?**

⇒**Unit replacement?**

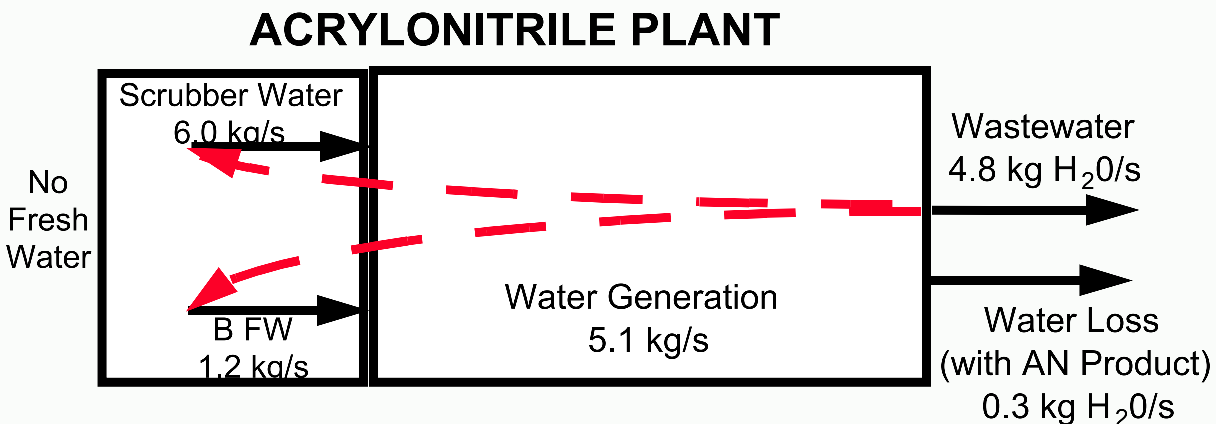
We will learn how to do all of that systematically using mass integration techniques.

Targeting

- Water generation is fixed by AN production & stoichiometry (= 5.1 kg/s)
- Get overall data on fresh and terminal water from flowsheet



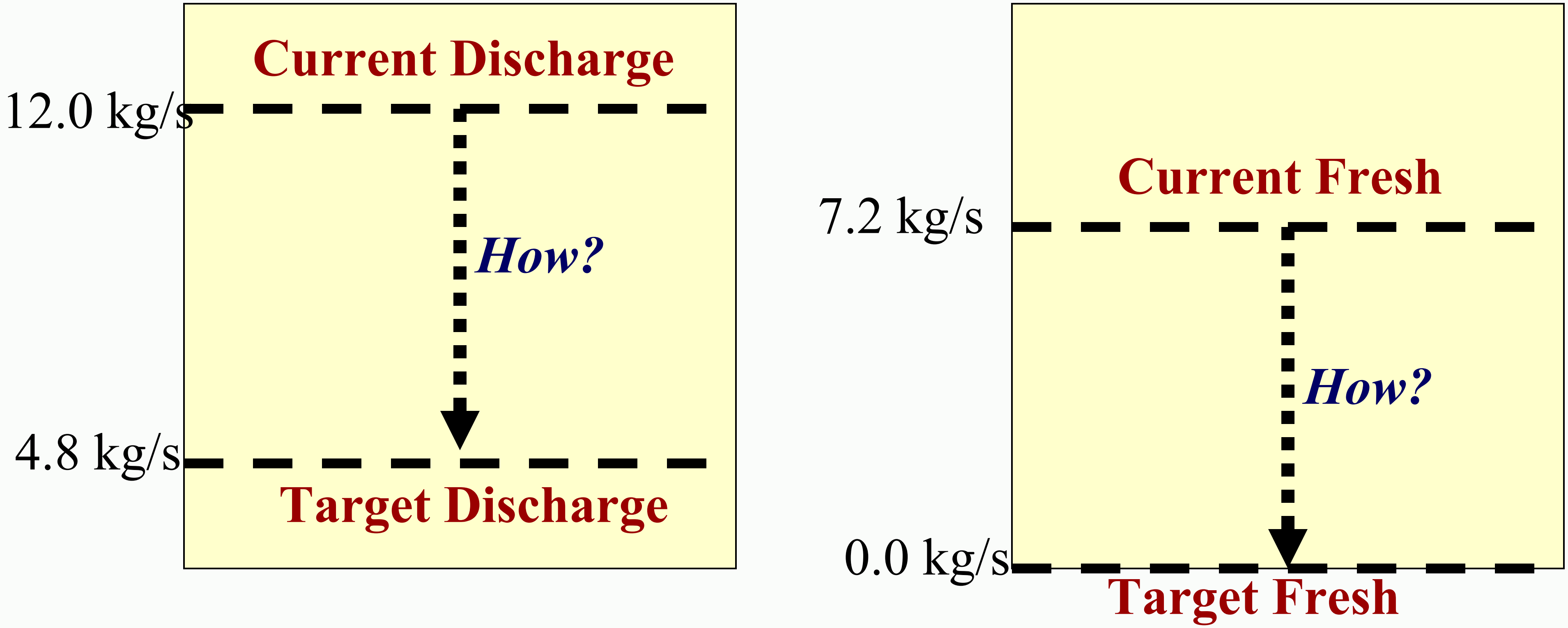
(a) Overall Water Balance Before Mass Integration



(b) Overall Water Balance After Mass Integration

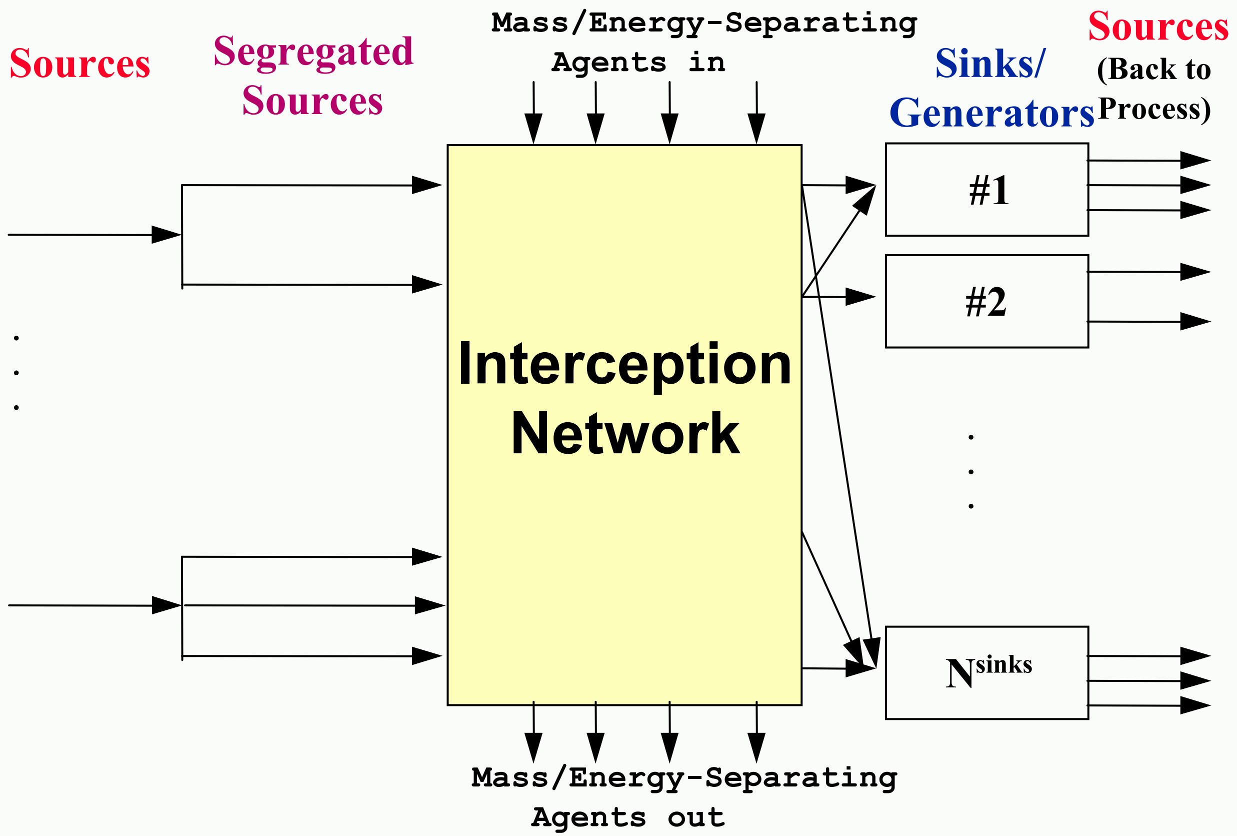
Target for minimum wastewater discharge = 12.0 – 7.2 = **4.8 kg/s**

Target for minimum water usage = 0.0 kg/s


Current Discharge
12.0 kg/s
How?
4.8 kg/s
Target Discharge
Current Fresh
7.2 kg/s
How?
0.0 kg/s
Target Fresh

DEVELOPMENT OF MASS INTEGRATION STRATEGIES TO REACH THE TARGET

Process from a Species Perspective

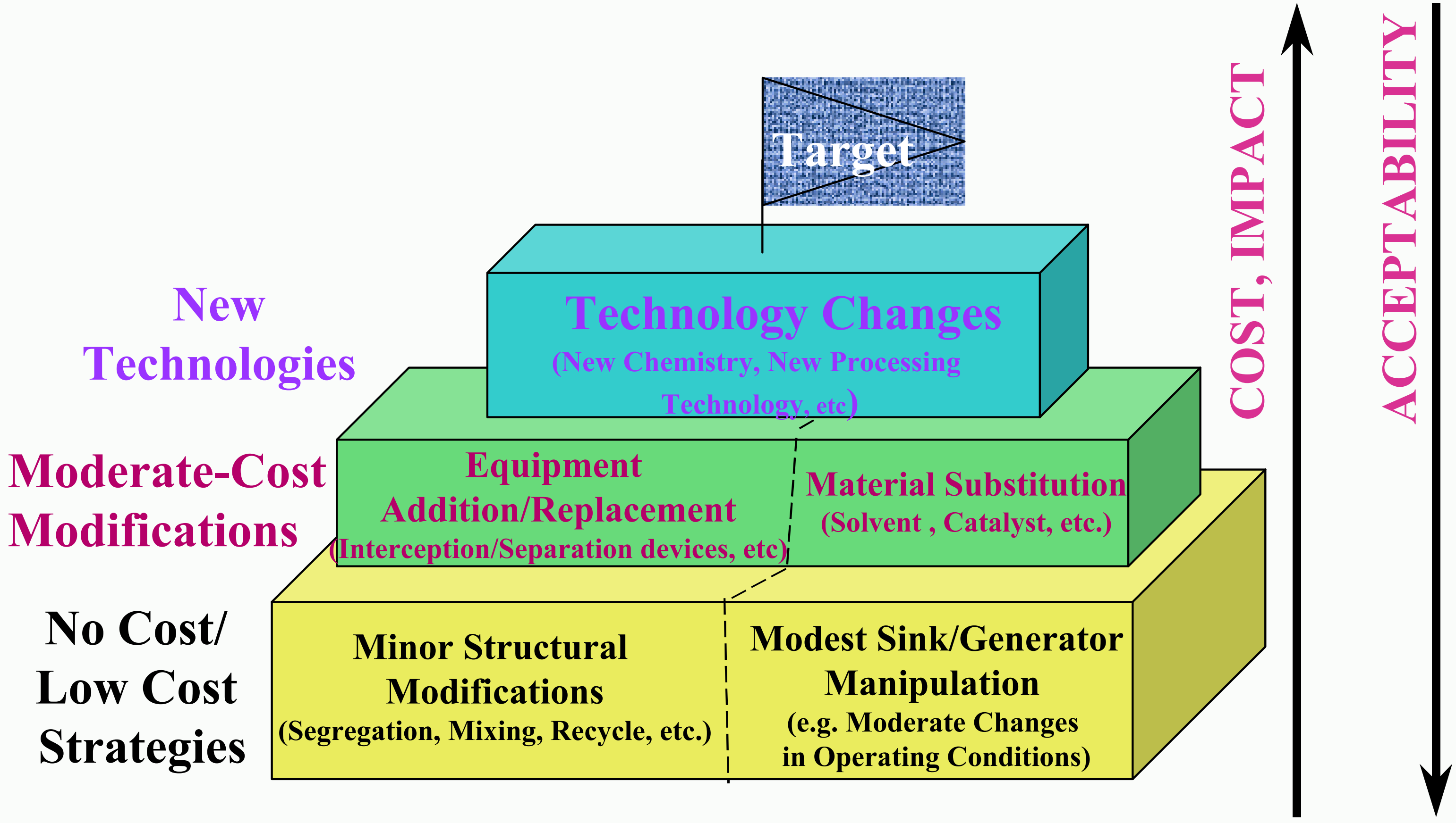


Source: A stream which contains the targeted species

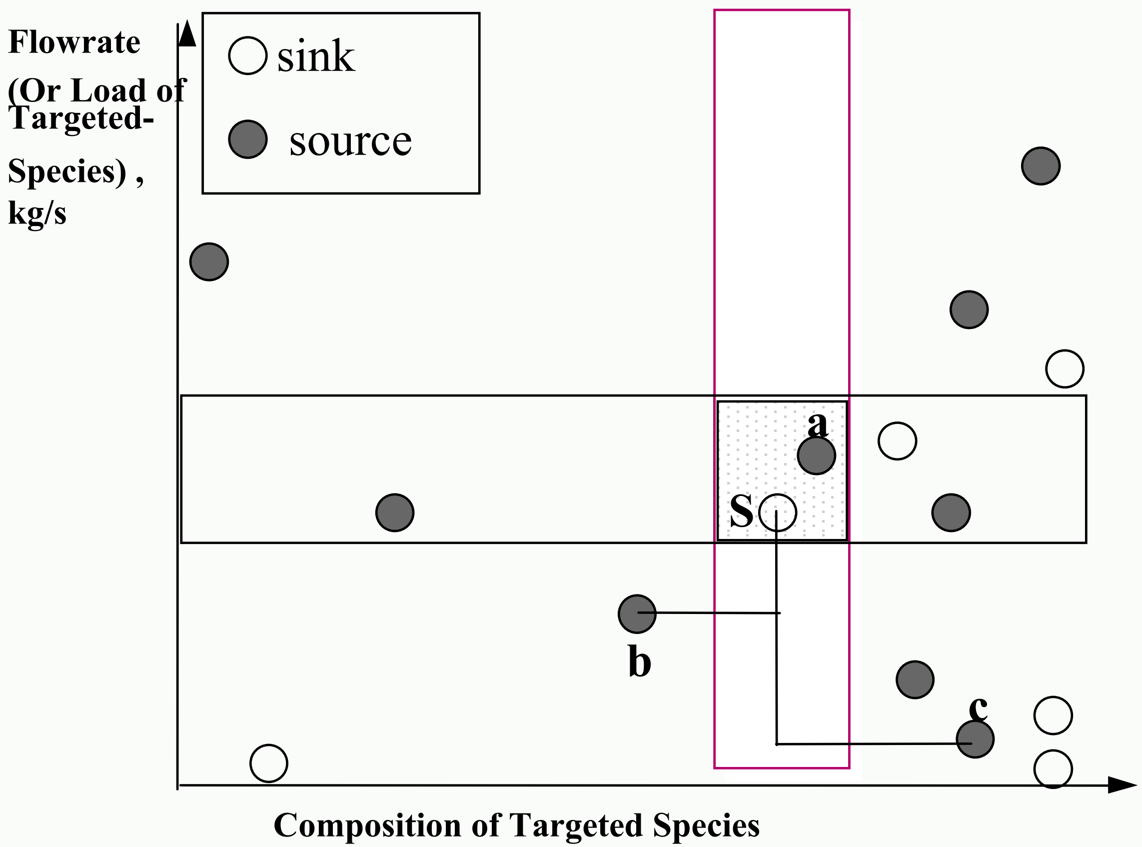
Sink: An existing process unit/equipment that can accept a source

Interceptor: A new unit/equipment that can process a source

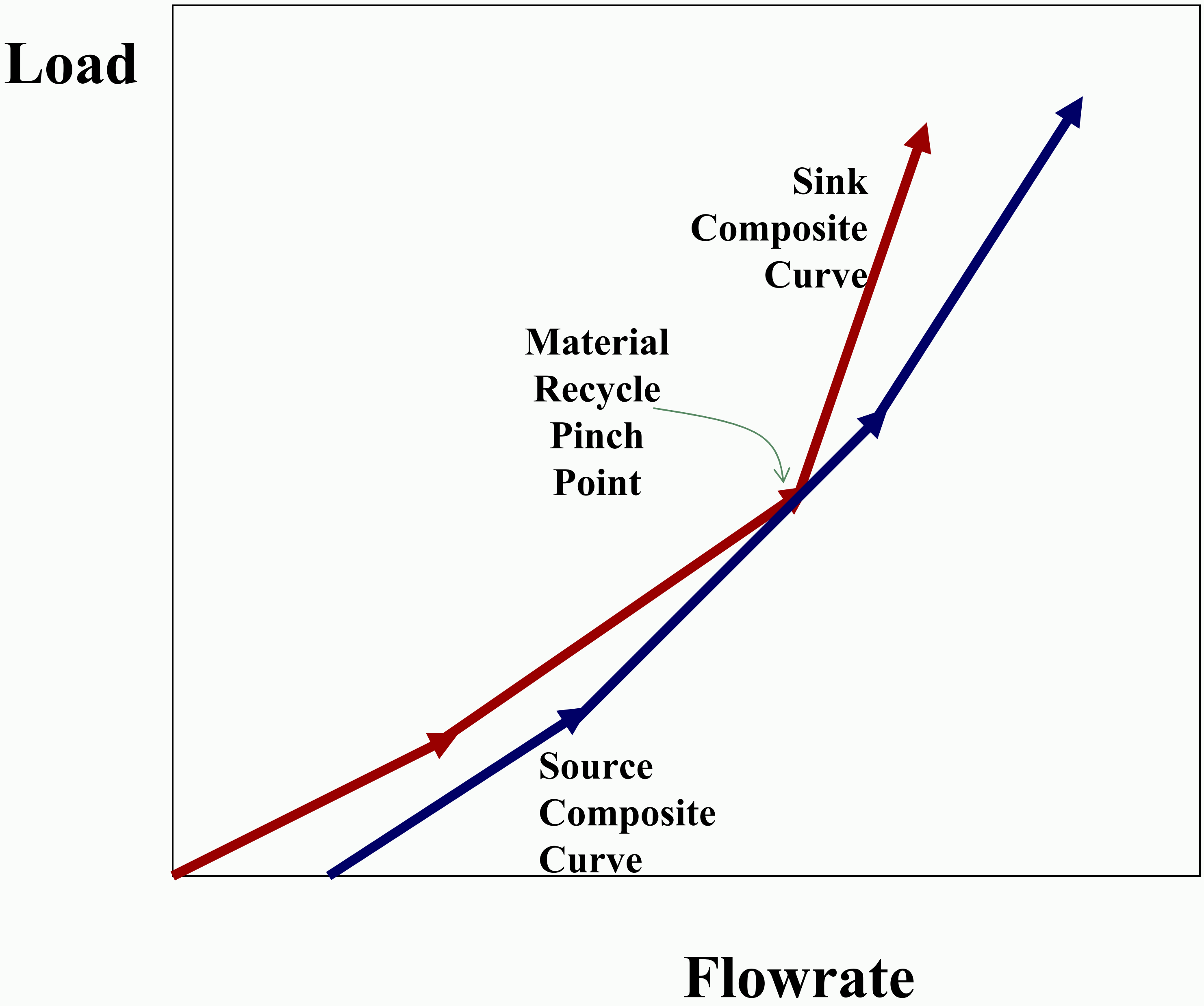
Mass Integration Strategies



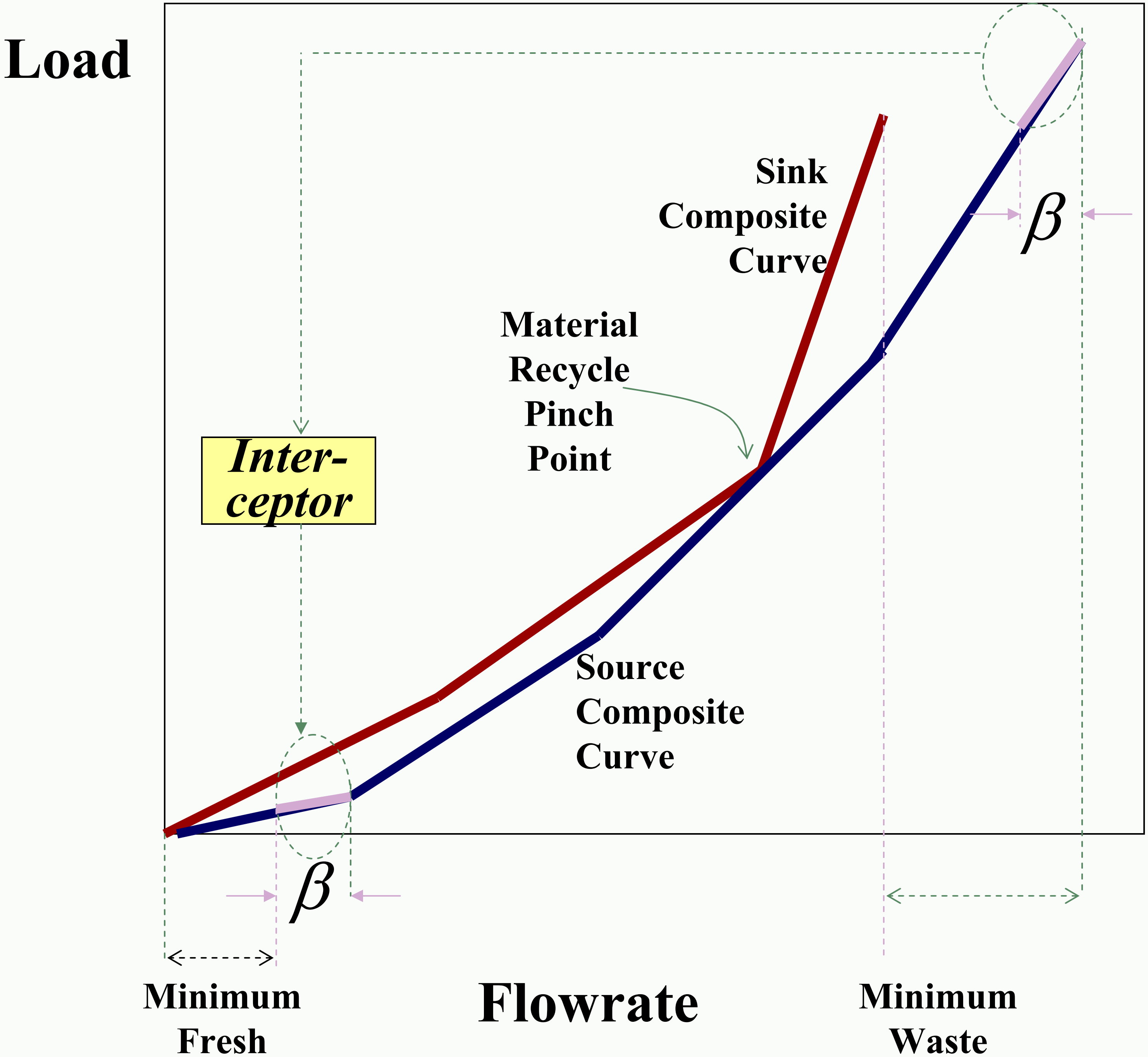
Source-Sink Mapping Diagram for Direct Recycle

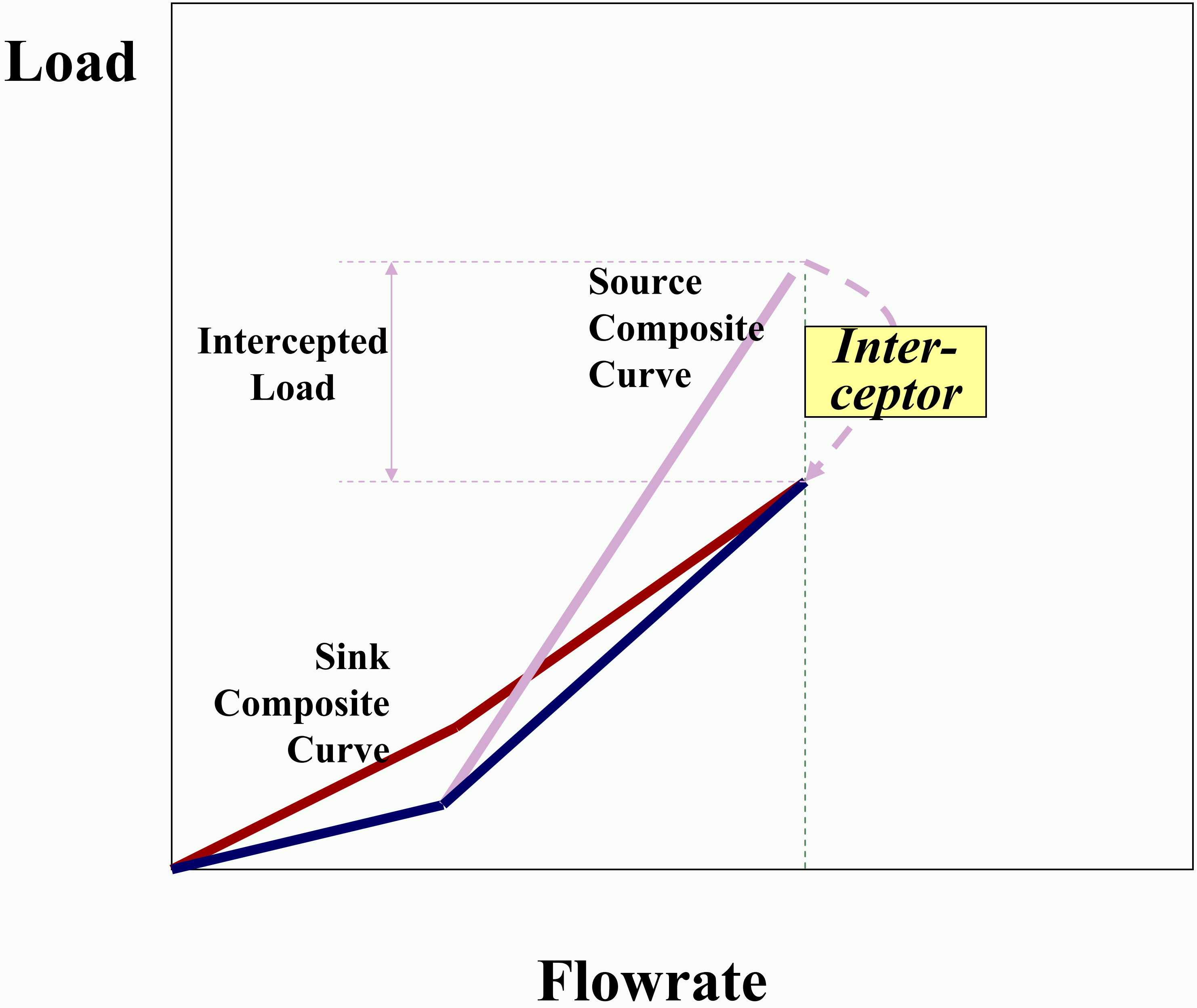


Integrating Source and Sink Composites



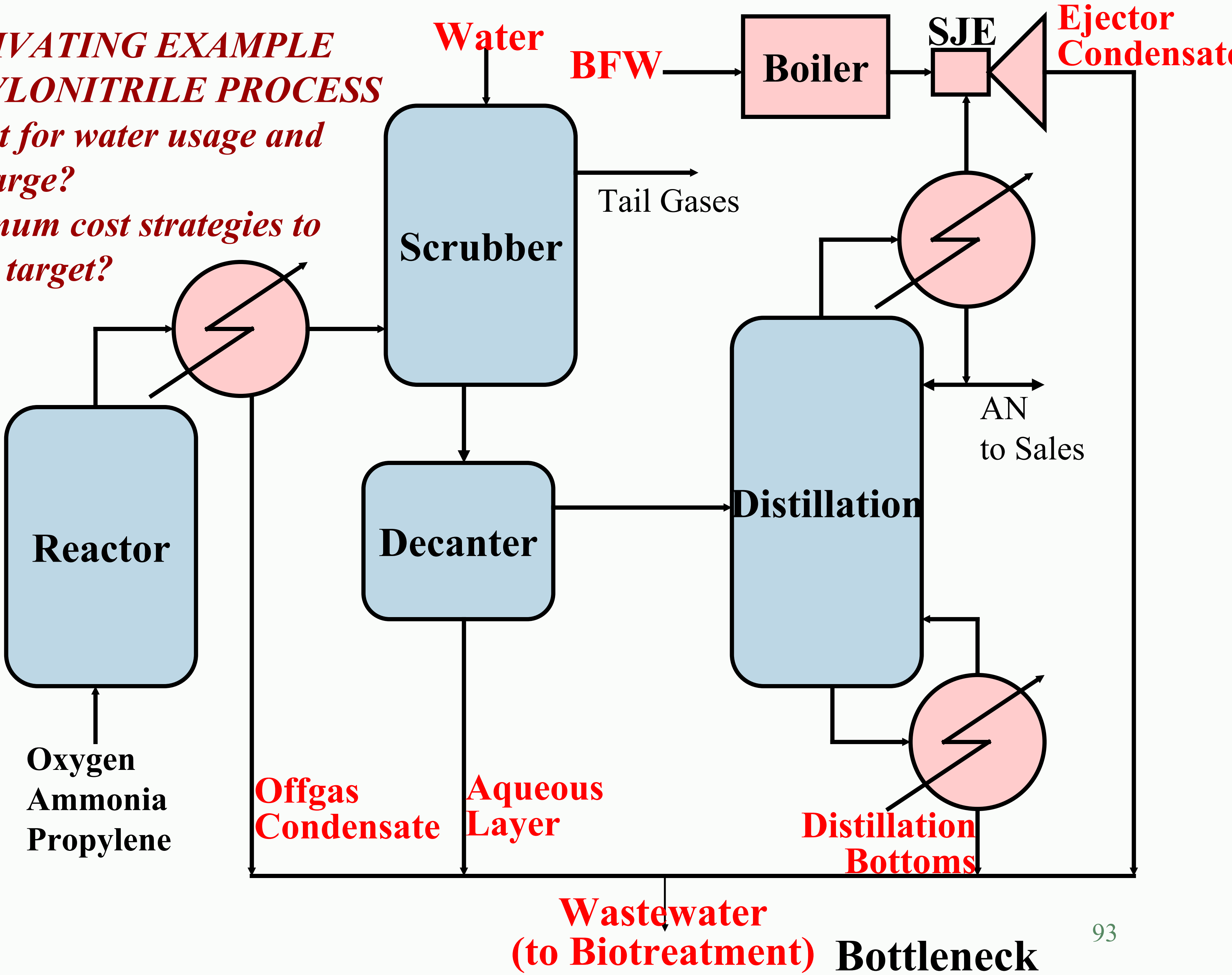
Effect of Interception




Load
Intercepted
Load
Source
Composite
Curve
Inter-
ceptor
Sink
Composite
Curve
Flowrate

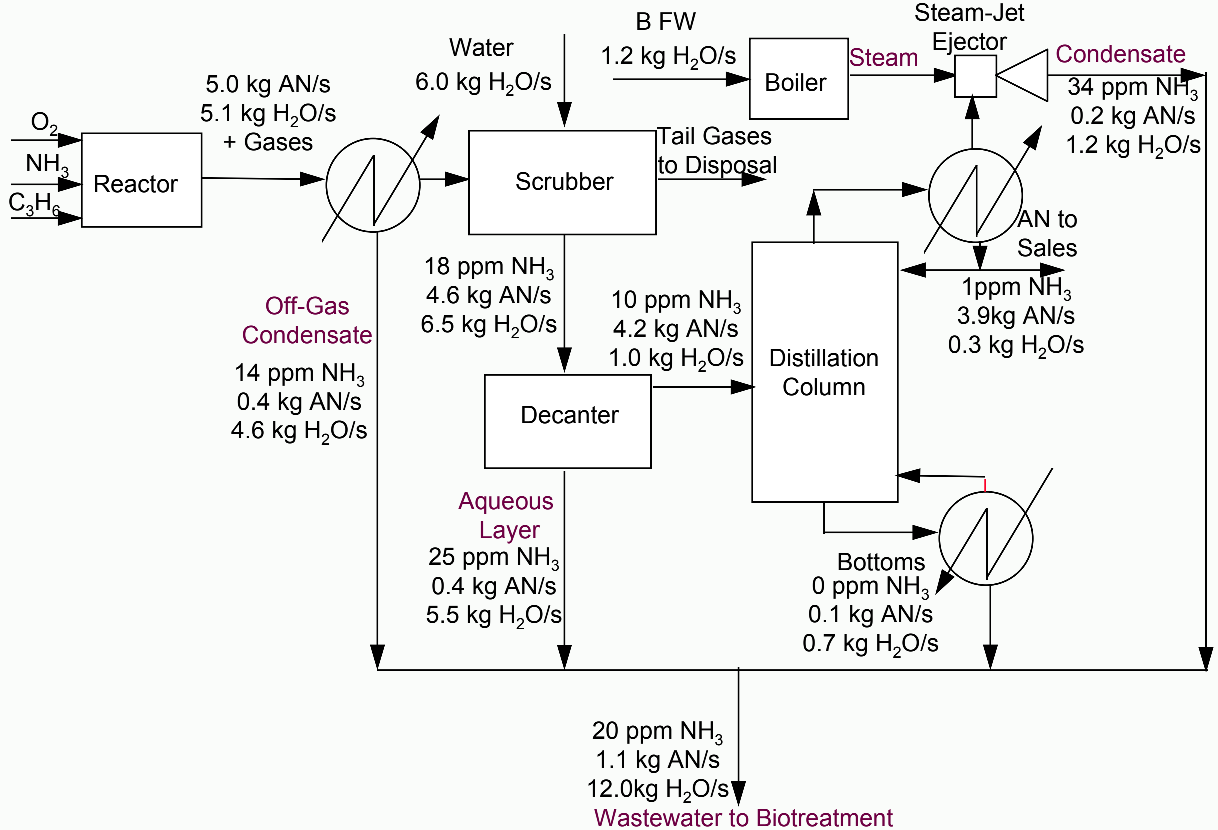
DETAILING
MASS INTEGRATION STRATEGIES

MOTIVATING EXAMPLE
ACRYLONITRILE PROCESS
Target for water usage and discharge?
Minimum cost strategies to attain target?



Ref. El-Halwagi, M. M., "Pollution Prevention through Process Integration: Systematic Design Tools", Academic Press (1997

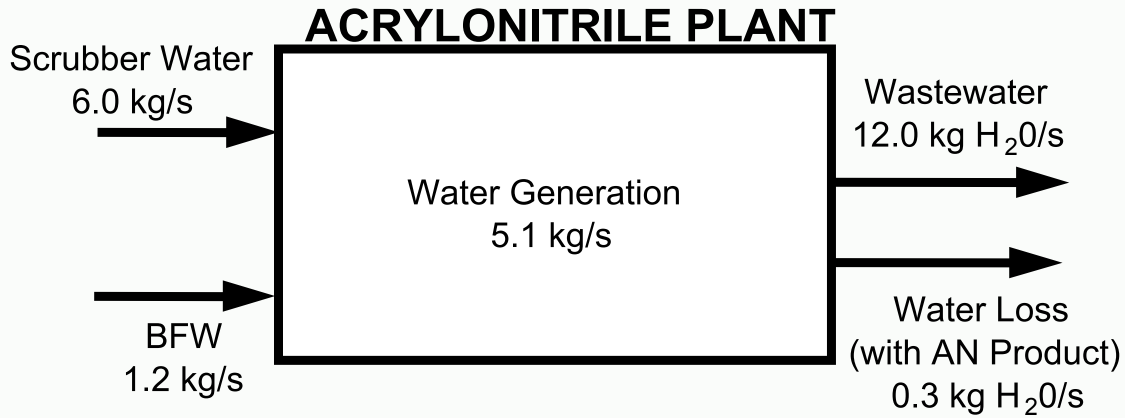
Motivating Example: Debottleneck an Acrylonitrile Process



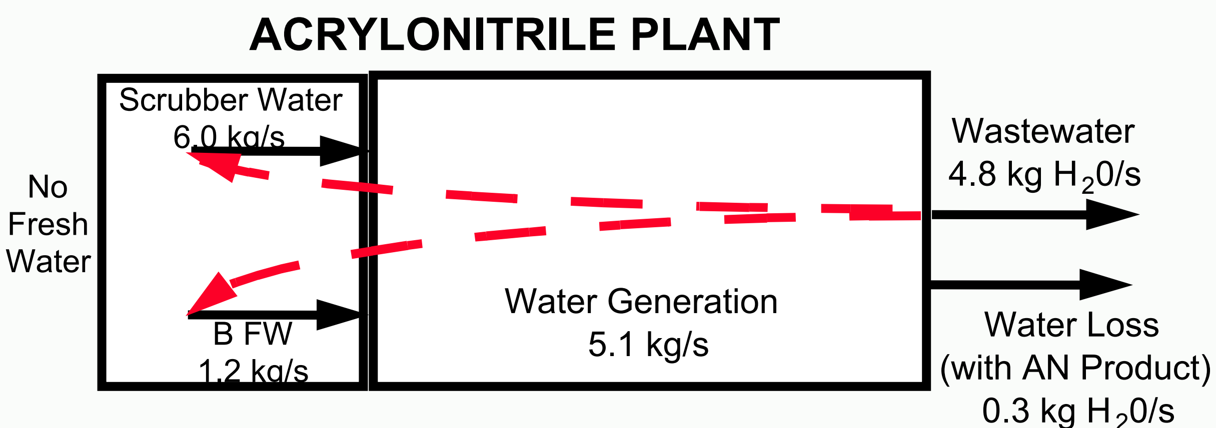
- Sold-out product, need to expand. Biotreatment is bottleneck.
- Intuitive solution: install an additional biotreatment facility ($4 million in capital investment and $360,000/year in annual operating cost)! Should we?????
- Can we use mass integration techniques to devise cost-effective strategies to debottleneck the process?

Targeting

- Water generation is fixed by AN production & stoichiometry (= 5.1 kg/s)
- Get overall data on fresh and terminal water from flowsheet



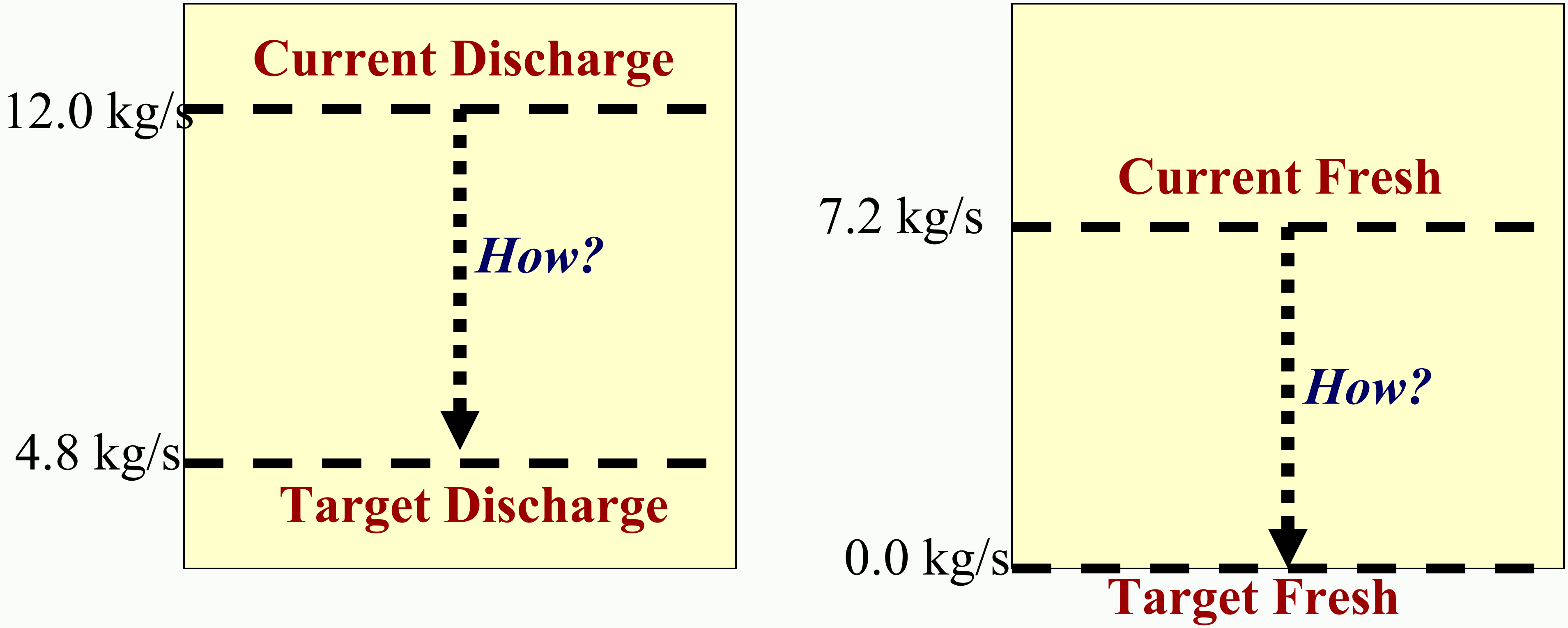
(a) Overall Water Balance Before Mass Integration



(b) Overall Water Balance After Mass Integration

Target for minimum wastewater discharge = 12.0 – 7.2 = **4.8 kg/s**

Target for minimum water usage = 0.0 kg/s


Current Discharge
12.0 kg/s
How?
4.8 kg/s
Target Discharge
Current Fresh
7.2 kg/s
How?
0.0 kg/s
Target Fresh

Constraints and Data

Scrubber:

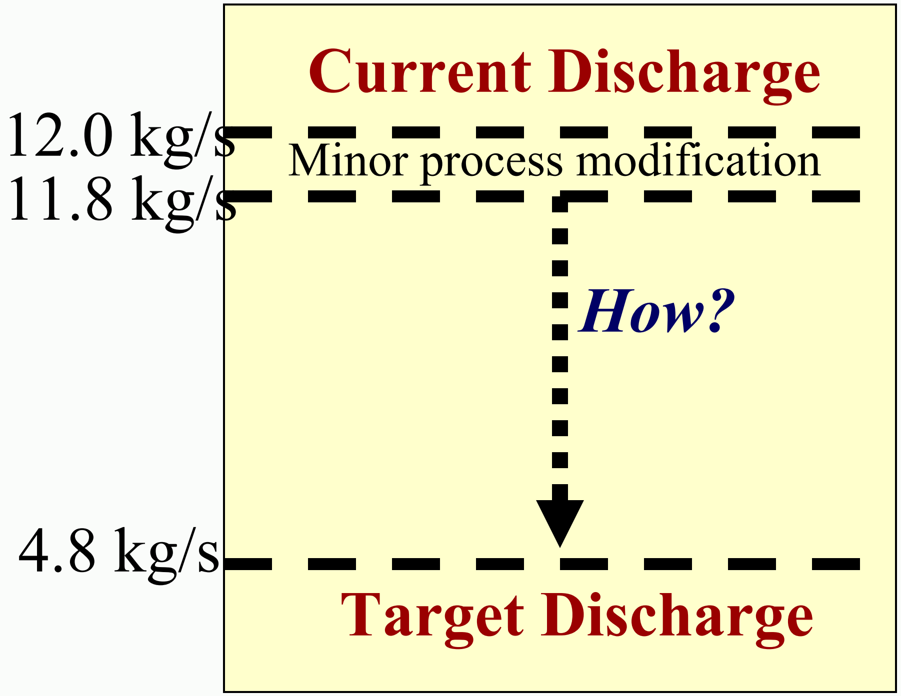
- 5.8 < Feed flowrate of scrubbing agent (kg/s) < 6.2
- 0.0 < ammonia composition in scrubbing agent (ppm) < 10

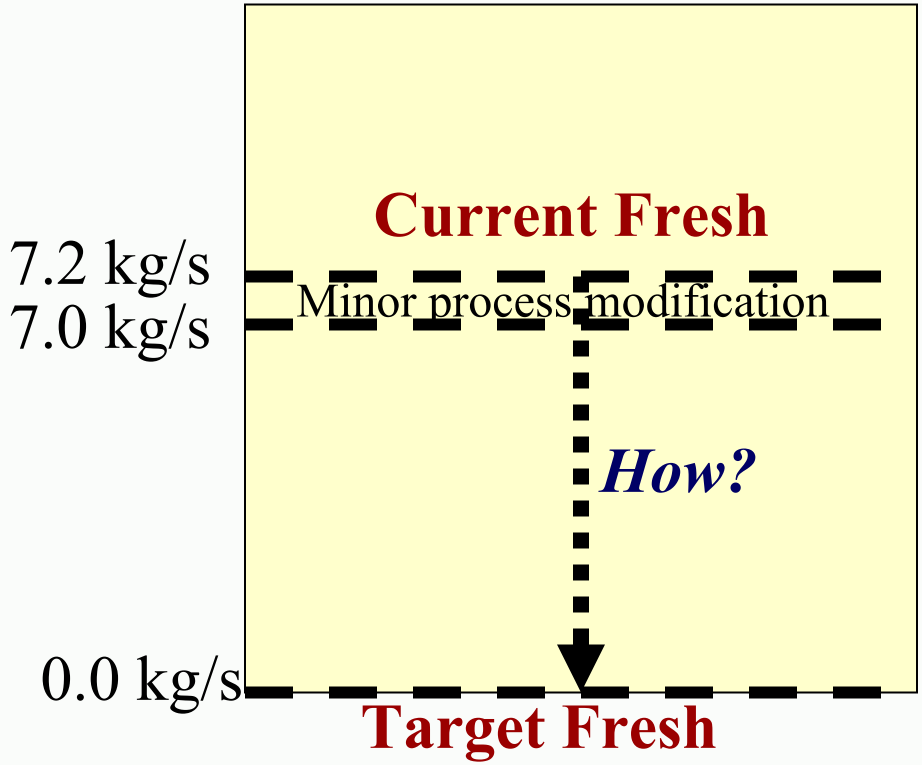
Boiler Feed Water "BFW":

- Flowrate of BFW = 1.2 kg/s
- Ammonia content in BFW (ppm) = 0.00
- AN content in BFW (ppm) = 0.00

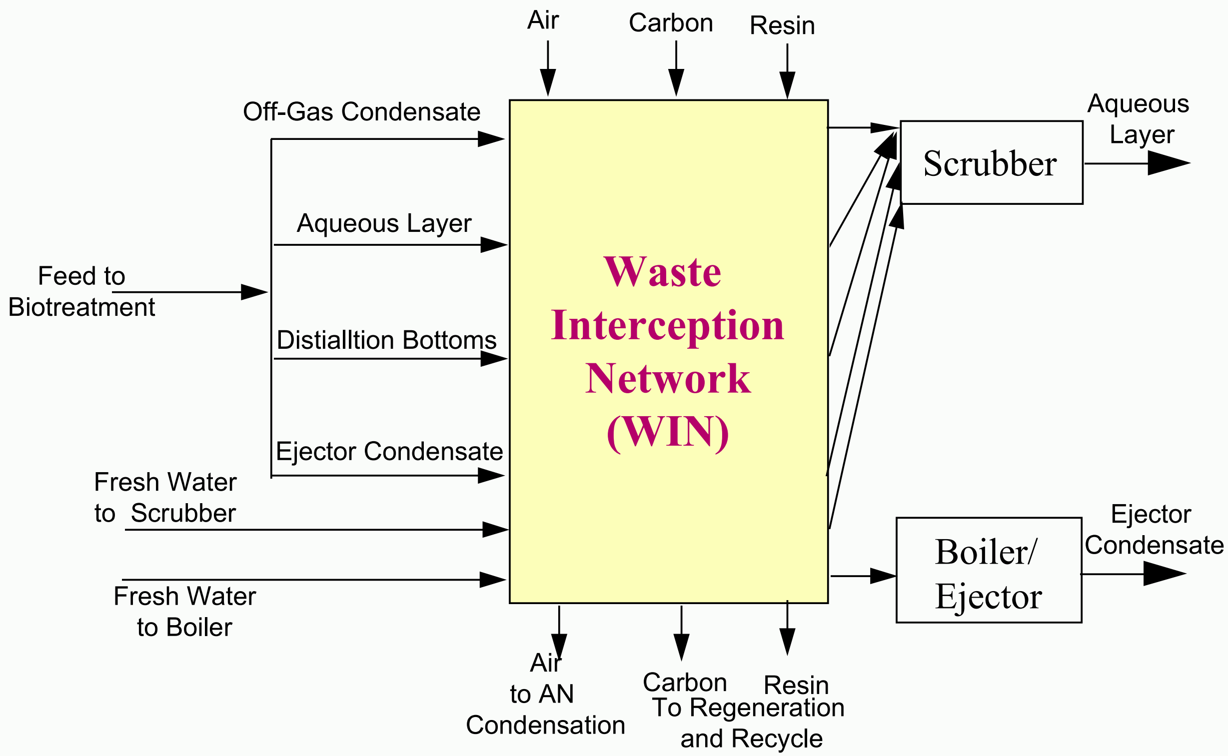
For separation of ammonia, use adsorption.

Minor Process Modification:
Constraint on scrubber feed flowrate allows reduction of Fresh water from 6.0 kg/s to 5.8 kg/s


Current Discharge
12.0 kg/s
Minor process modification
11.8 kg/s
How?
4.8 kg/s
Target Discharge

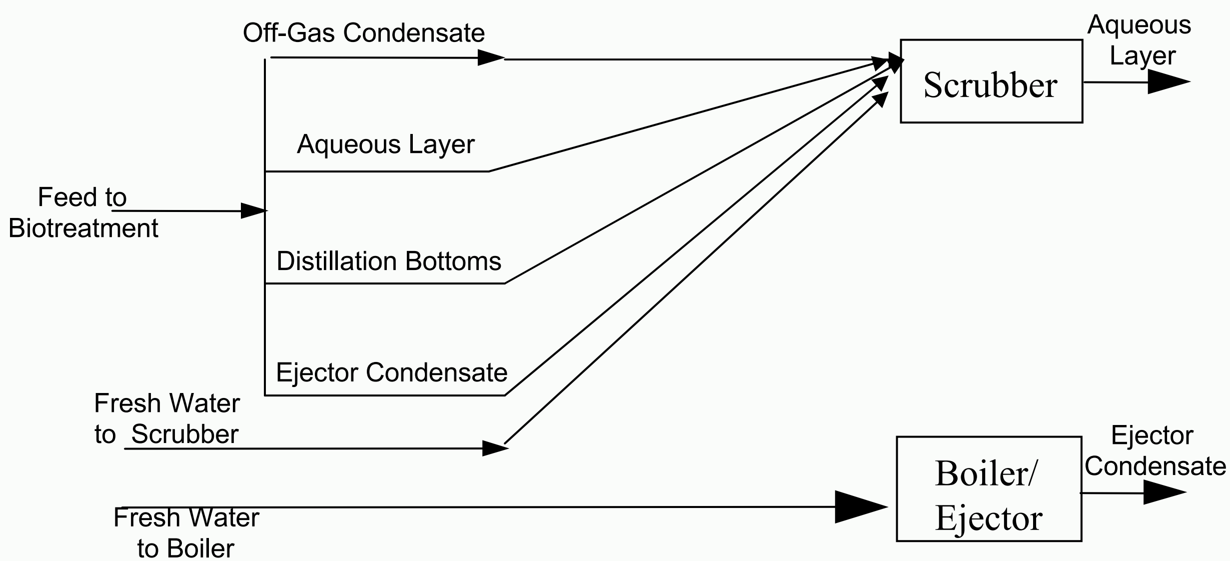

Current Fresh
7.2 kg/s
Minor process modification
7.0 kg/s
How?
0.0 kg/s
Target Fresh

Source-Interception-Sink Representation

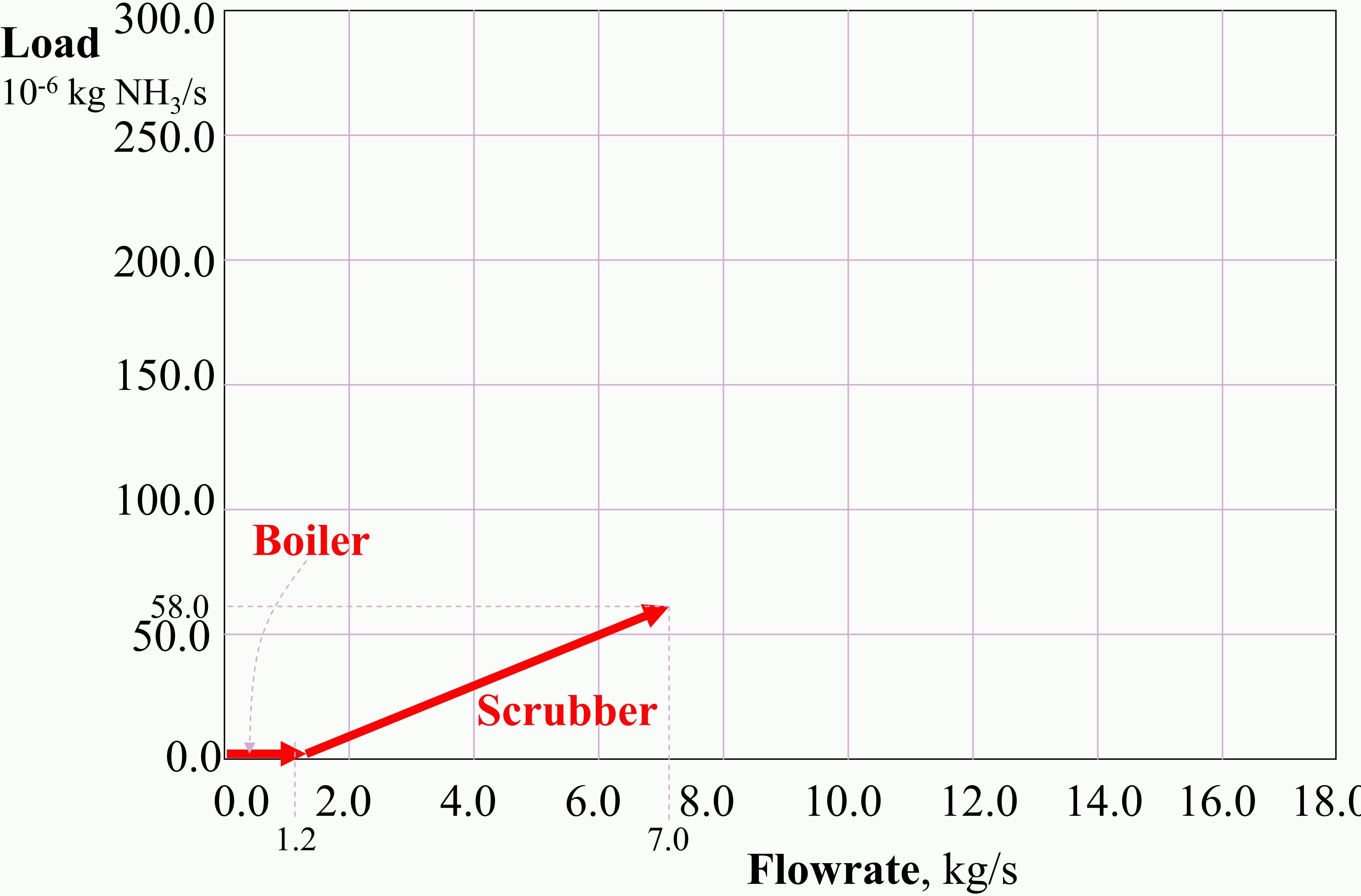


Note: Recycle to sinks that employ a fresh resource (scrubber and boiler)

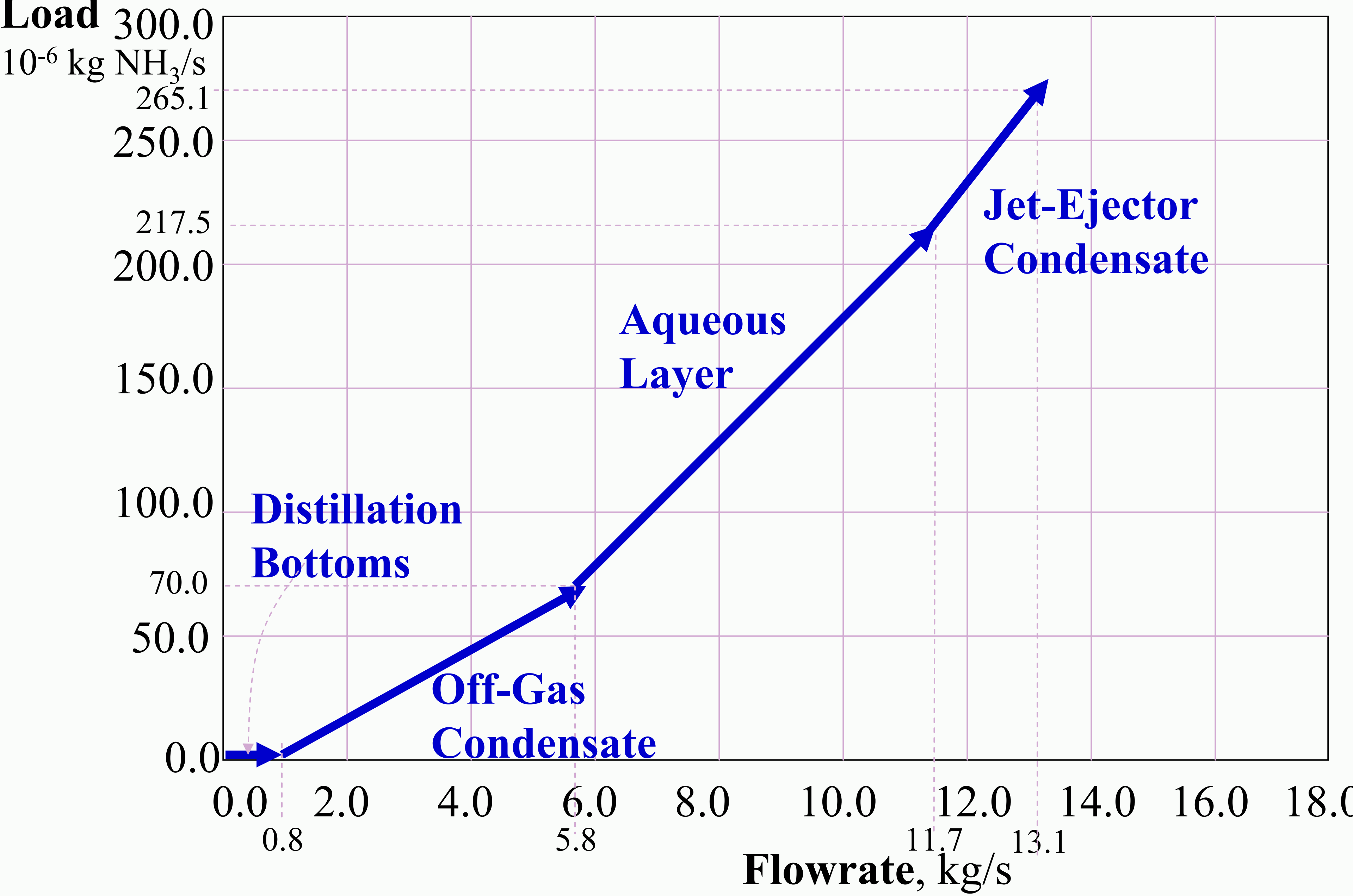
Direct-Recycle Alternatives



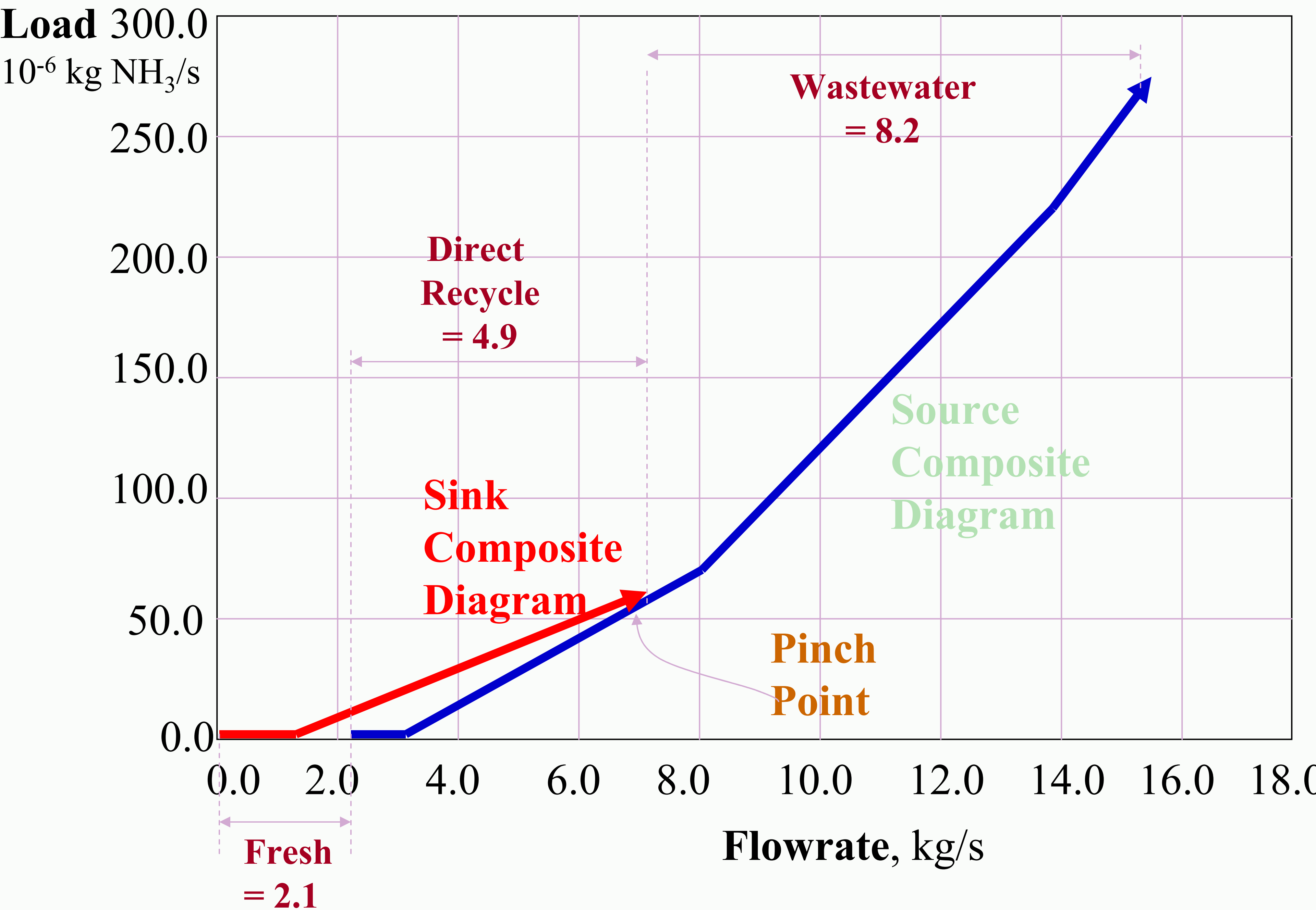
Note: No recycle to boiler because of 0.0 ppm constraints



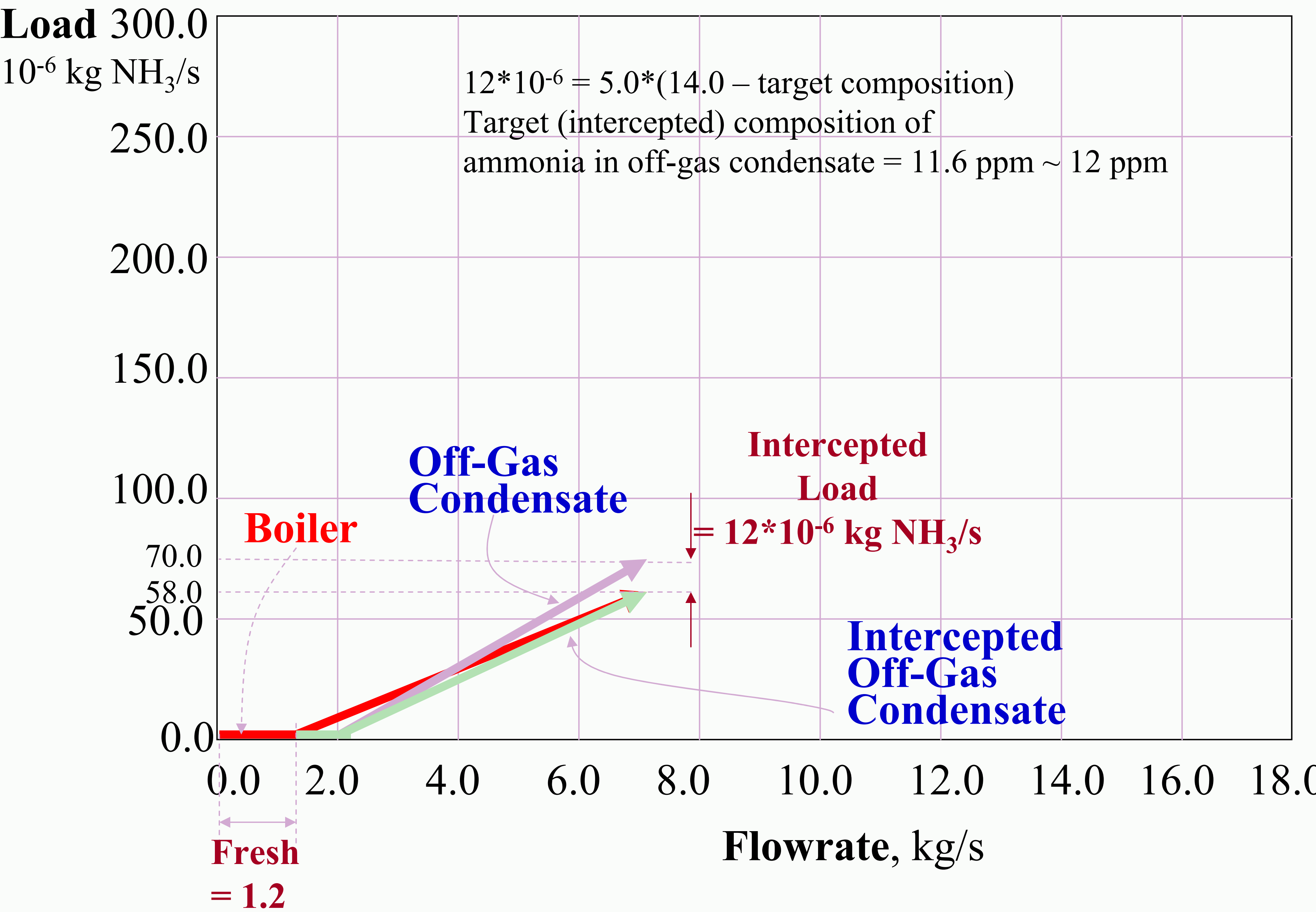
Sink Composite Diagram for the AN Example



Source Composite Diagram for the AN Example

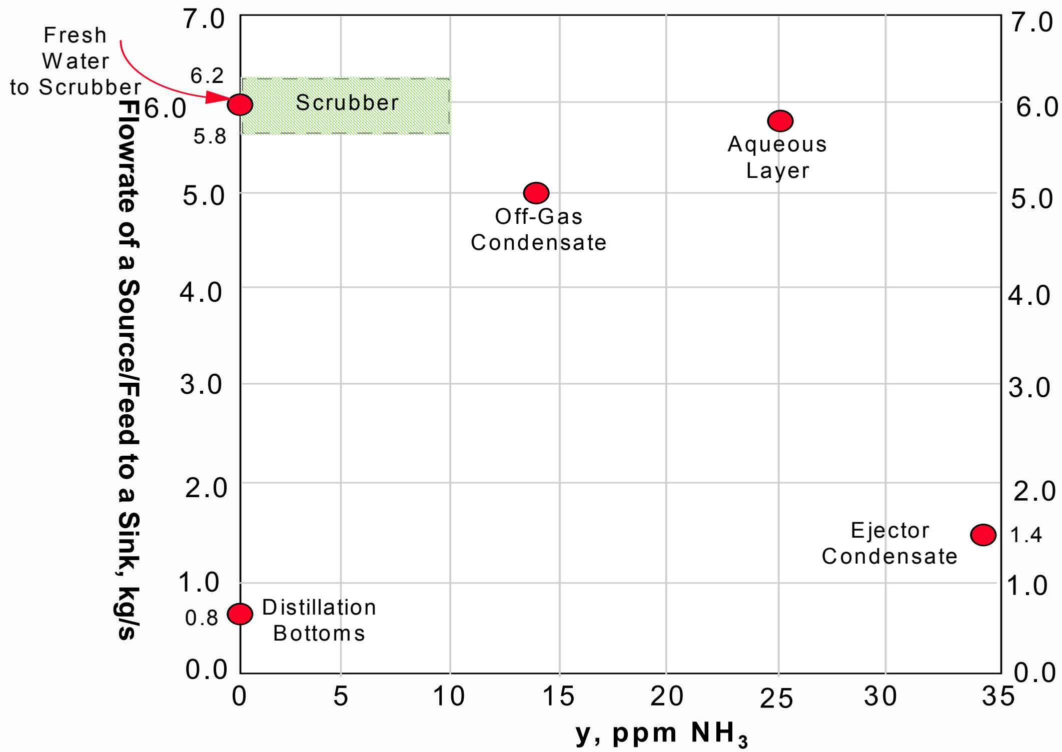


Material Recycle Pinch Diagram for the AN Example

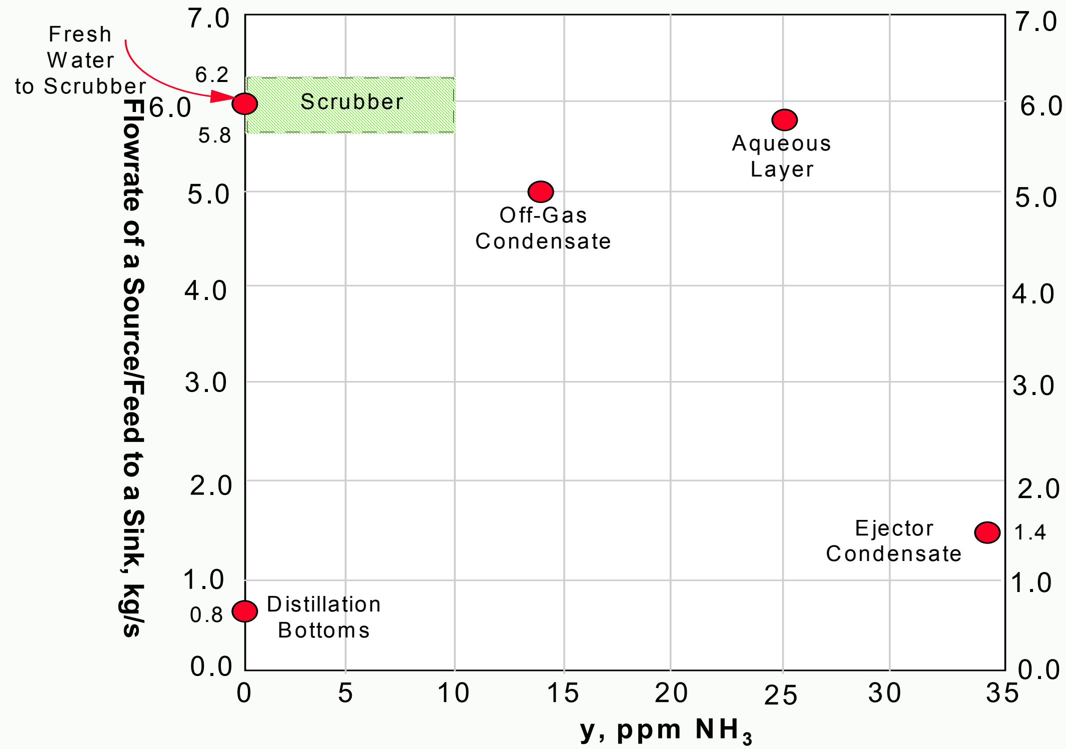


Material Recycle Pinch Diagram for the AN Example

Source-Sink Mapping Diagram



To use minimum fresh water, start with sources closest to the sink.
First distillation bottoms.
Then off-gas condensate.



The flowrate resulting from combining these two sources (5.8 kg/s) is sufficient to run the scrubber. However, its ammonia composition as determined by the lever-arm principle $\frac{(5.0\ kg/s).14\ ppm\ NH_3 + 0}{5.8\ kg/s} = 12\ ppm\ NH_3$

which lies outside the zone of permissible recycle to the scrubber!!!!

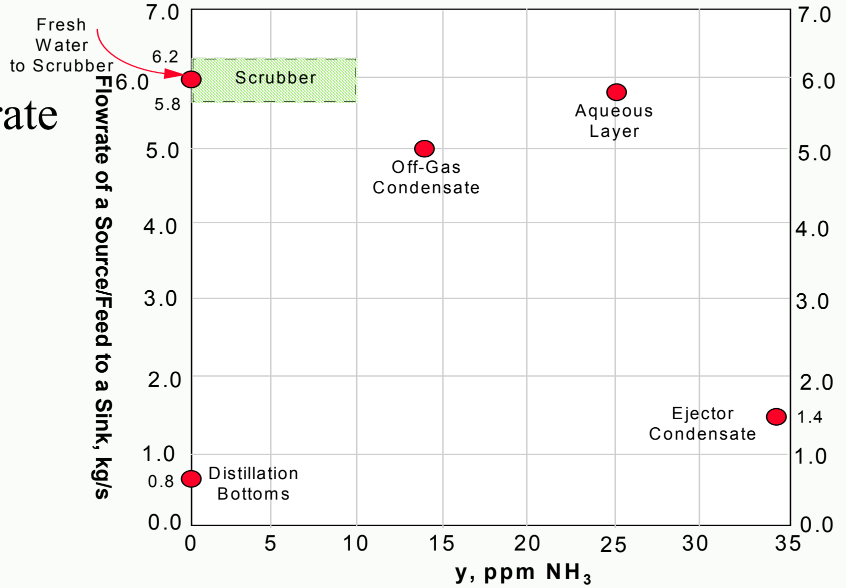
Can't recycle all off-gas condensate.

What is maximum recycle from off-gas condensate?

Constraint allows reduction of scrubber feed flowrate from 6.0 to 5.8 kg/s

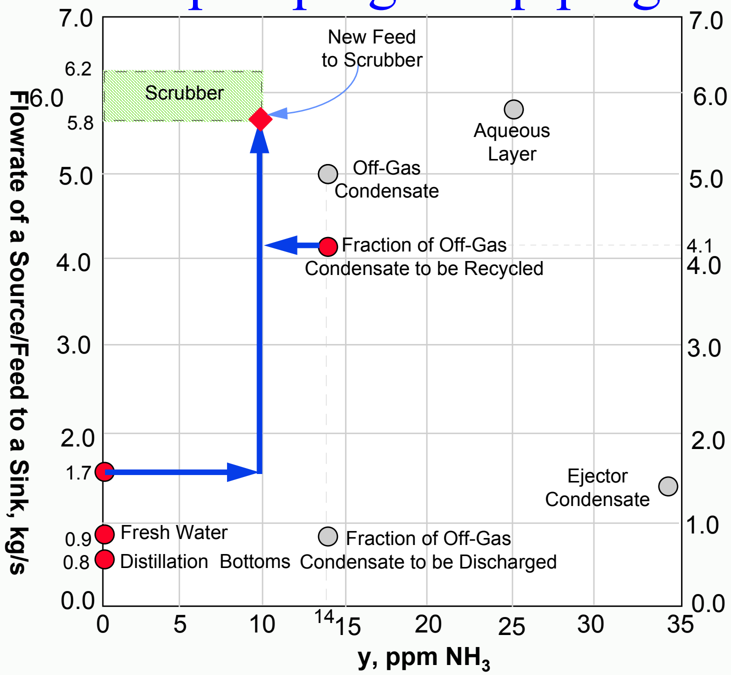
Recycled flowrate of offgas condensate*14

+ 0.8*0.0 + Fresh*0.0 = 5.8*10



➔ maximum flowrate of the off-gas condensate to be recycled to the scrubber is 4.1 kg/s
and the flowrate of fresh water is 0.9 kg/s (5.8 - 0.8 - 4.1).
Therefore, direct recycle can reduce the fresh water consumption (and consequently the influent to biotreamtment) by 5.8 – 0.9 = 4.9 kg/s.

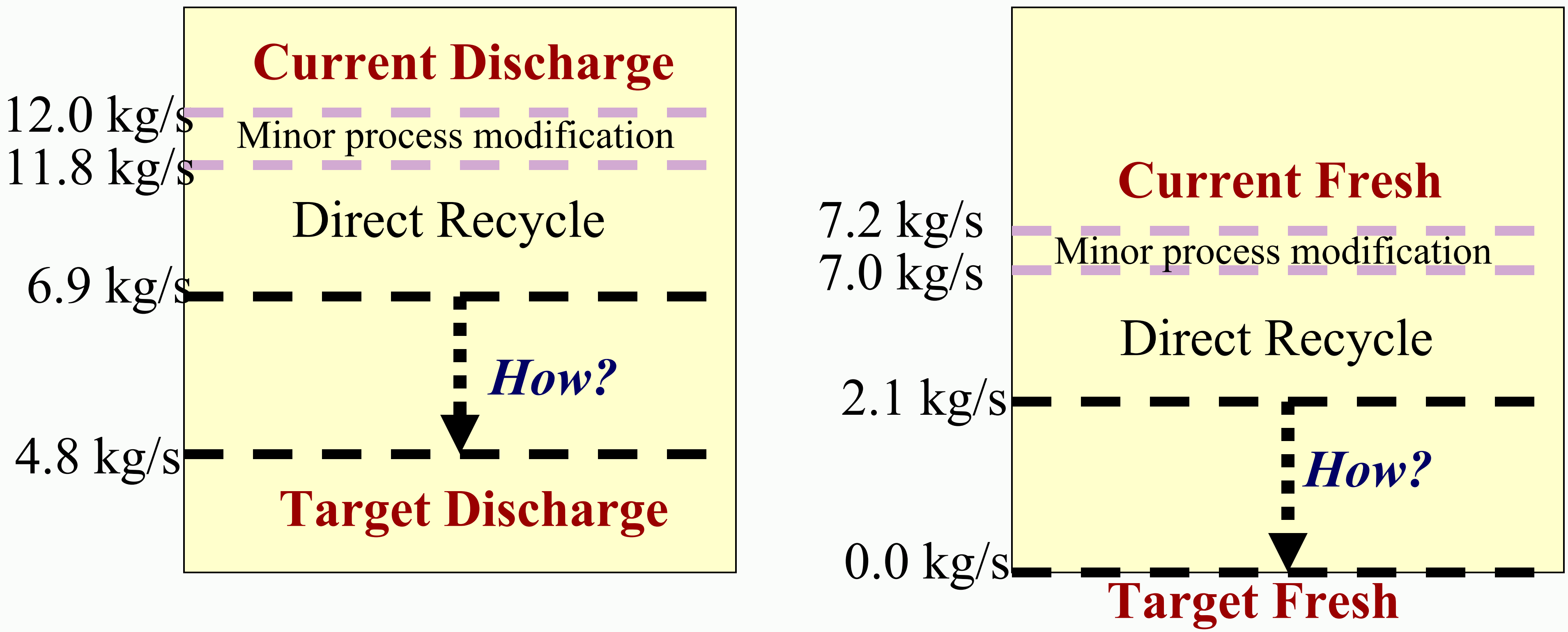
The primary cost of direct recycling is pumping and piping. Assuming that the TAC for pumping and piping is $80/(m.yr) and assuming that the total length of piping is 600 m, the TAC for pumping and piping is $48,000/year.



After Direct Recycle:

Fresh water reduction = 6.0 - 0.9 = 5.1 kg/s

Still, 7.2 - 5.1 = 2.1 kg/s to go



Next, need to spend capital cost

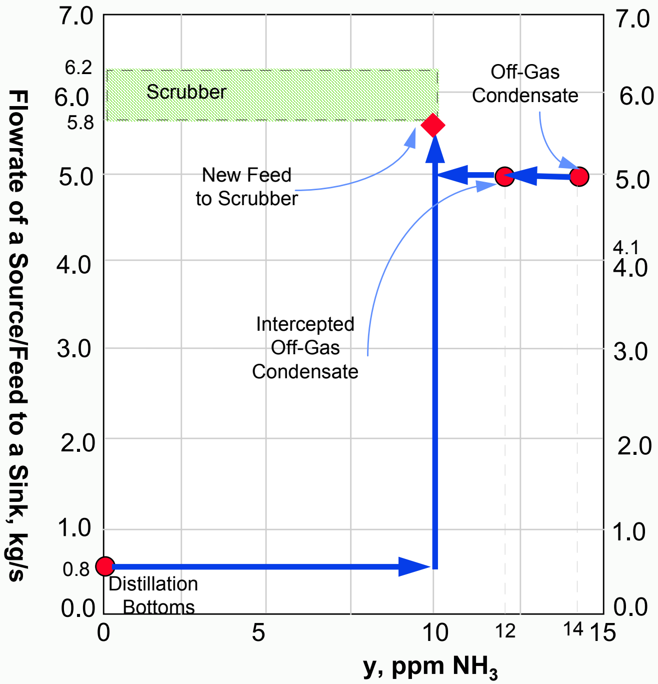
Next, we include **interception**

In order to eliminate fresh water from the scrubber, what should be the composition of ammonia in the off-gas condensate?

$$\frac{(5.0\,kg/s).y^{t}\ ppm\ NH_3 + 0}{5.8\,kg/s} = 10\ ppm\ NH_3$$

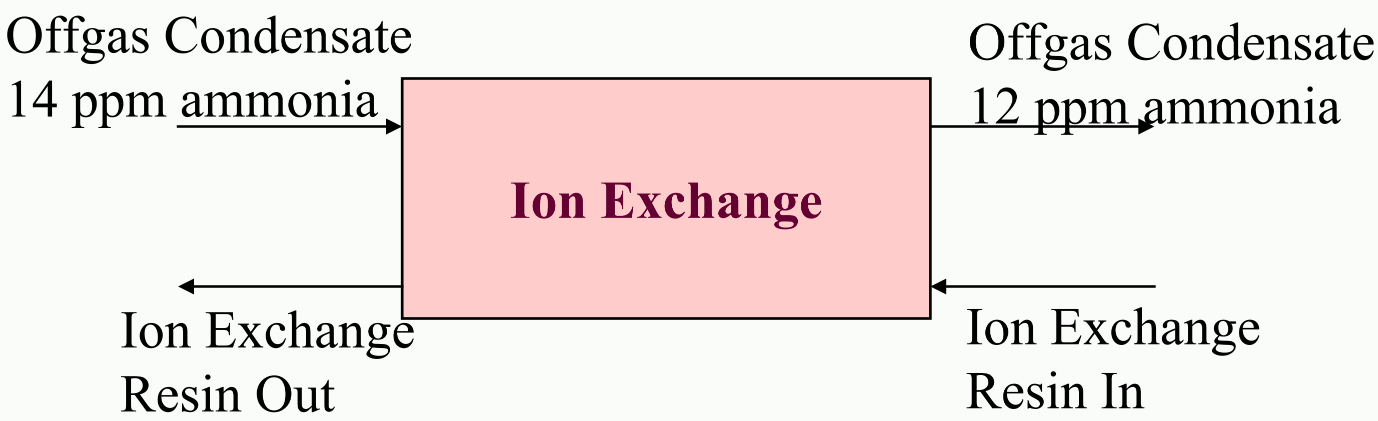
i.e. $y^t = 12$ ppm.

➔ need to intercept off-gas condensate to reduce ammonia content from y^s=14 ppm to y^t=12 ppm

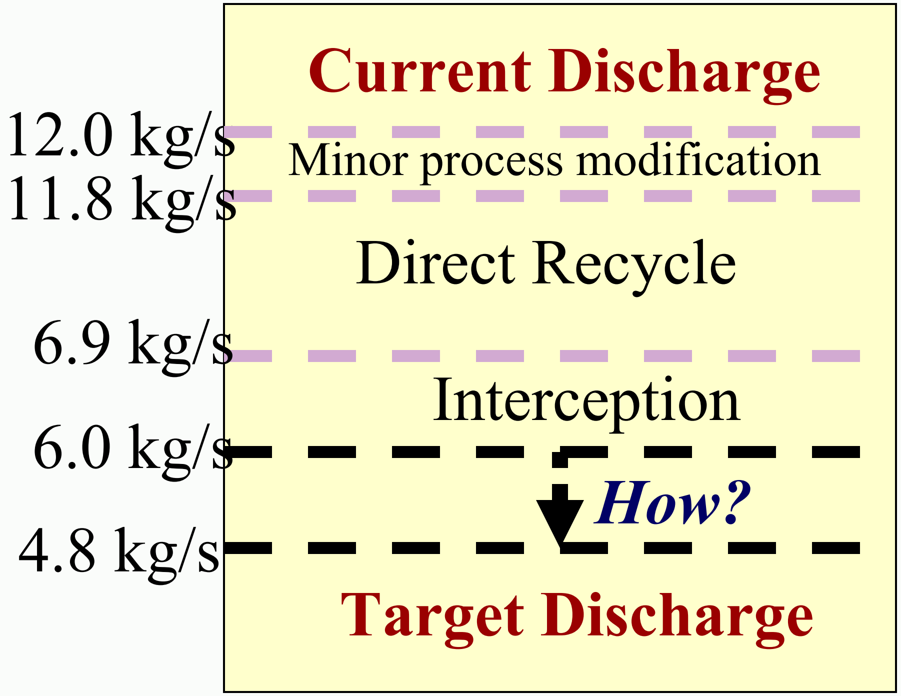


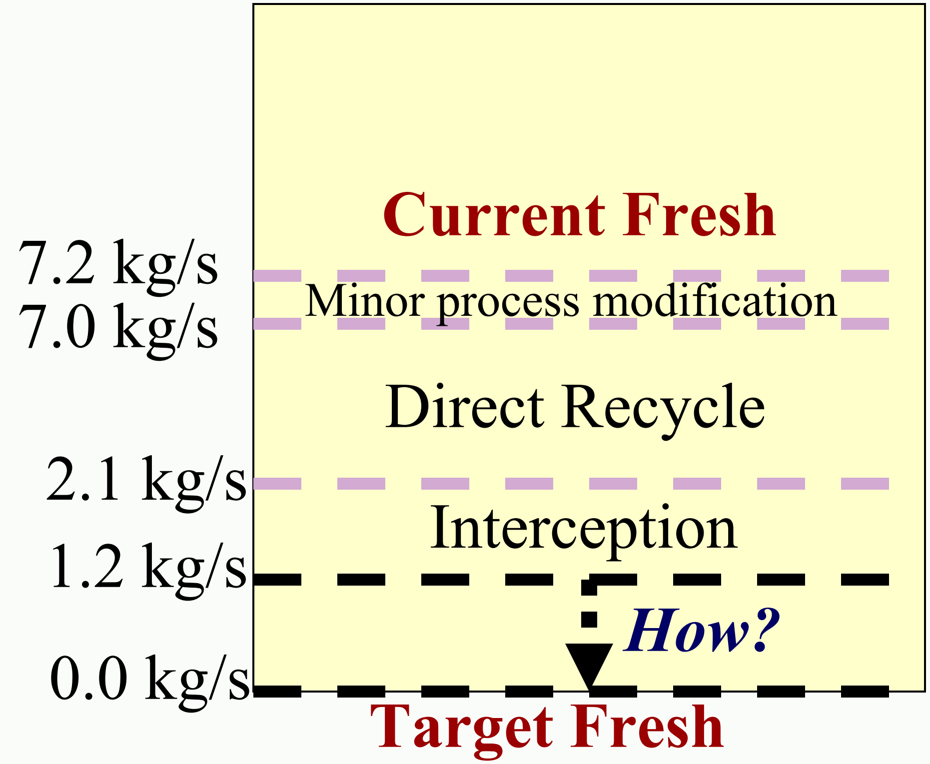
. Interception and Recycle Opportunities for the AN Case Study

Separation Unit:



TAC for the separation system is $119,000/yr.





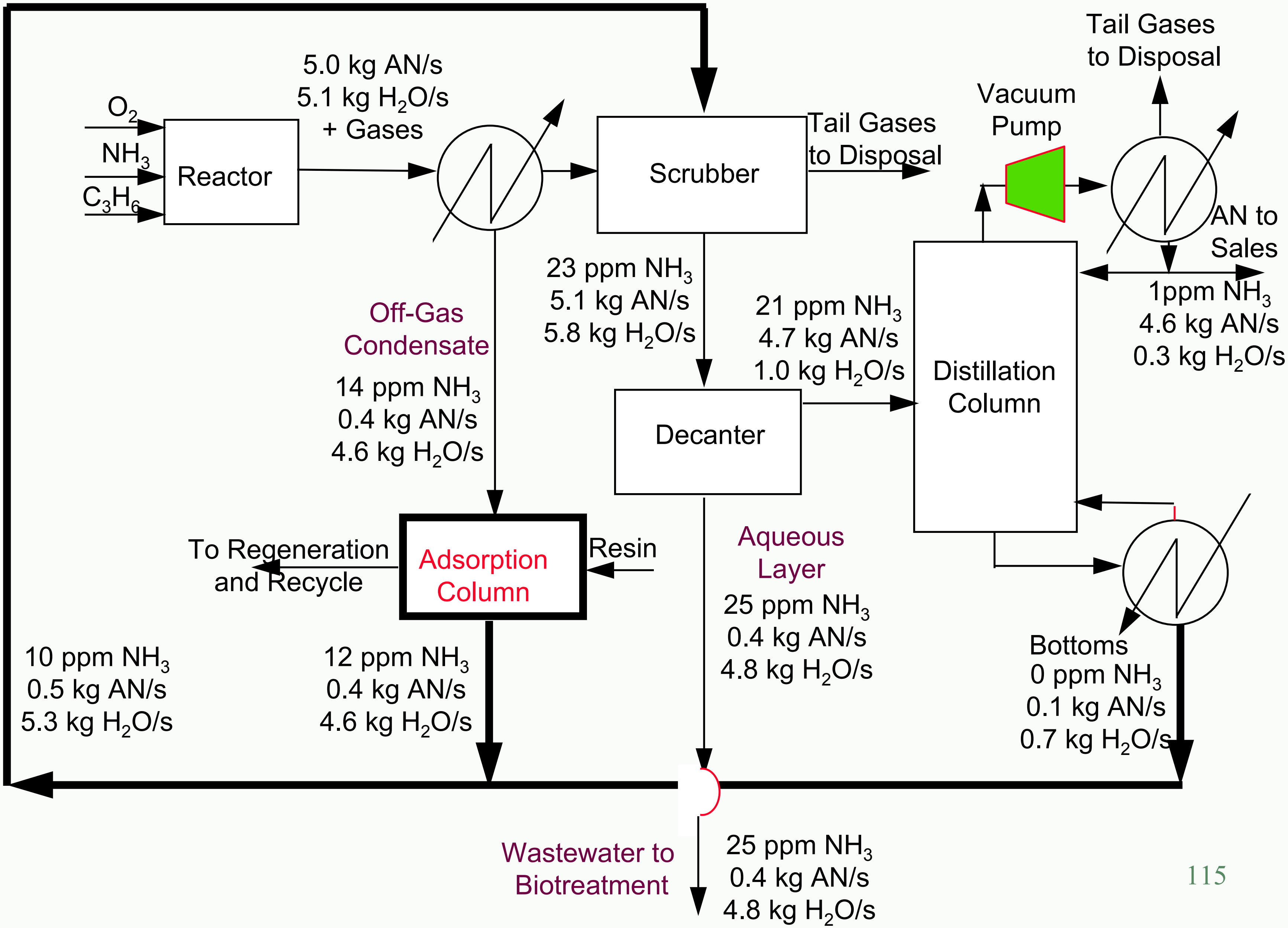
As a result of minor process changes, segregation, interception and recycle, we have eliminated the use of fresh water in the scrubber leading to a reduction of fresh water consumption (and influent to biotreatment) by 6.0 kg/s.

We still have 7.2 - 6.0 = 1.2 to go (related to steam jet ejector)

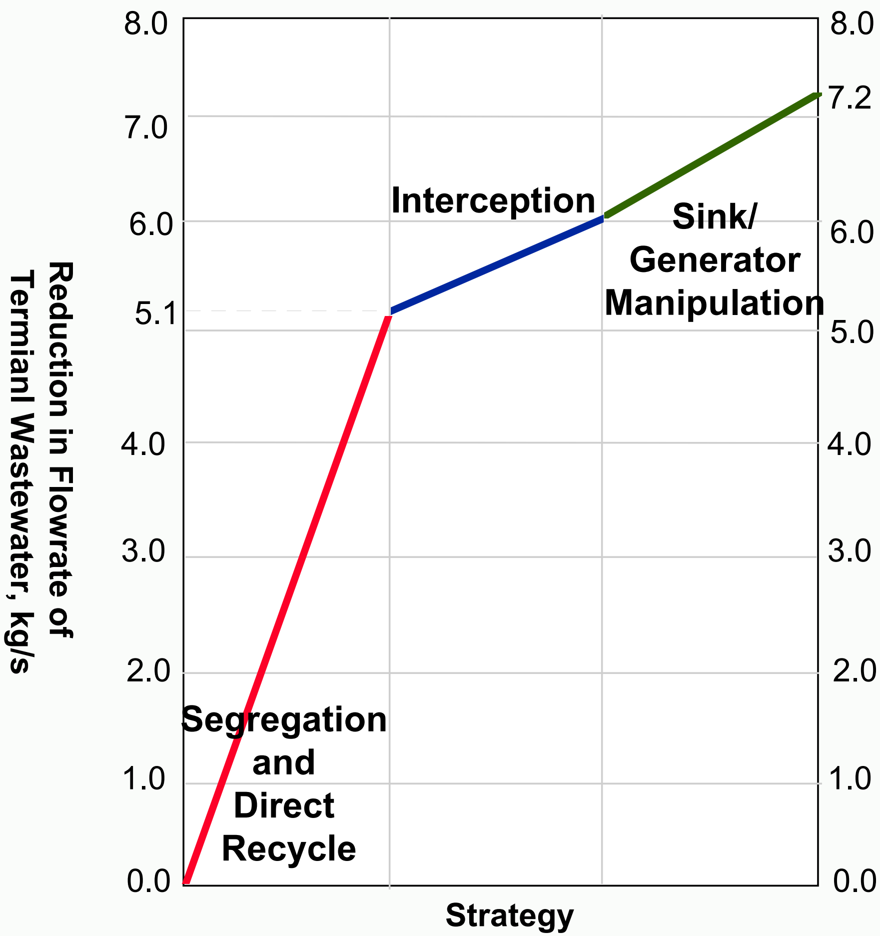
ALTERNATIVES TO STEAM JET EJECTOR

- Replacement of the steam-jet ejector with a **vacuum pump**. The operating cost of the ejector and the vacuum pump are comparable. Annualized fixed cost of the pump is **$15,000/year**.
- Operating the column under **atmospheric pressure** → No steam. A simulation study is needed to examine the effect of pressure change.
- **Relaxing the requirement on BFW quality** to few ppm's of ammonia and AN.

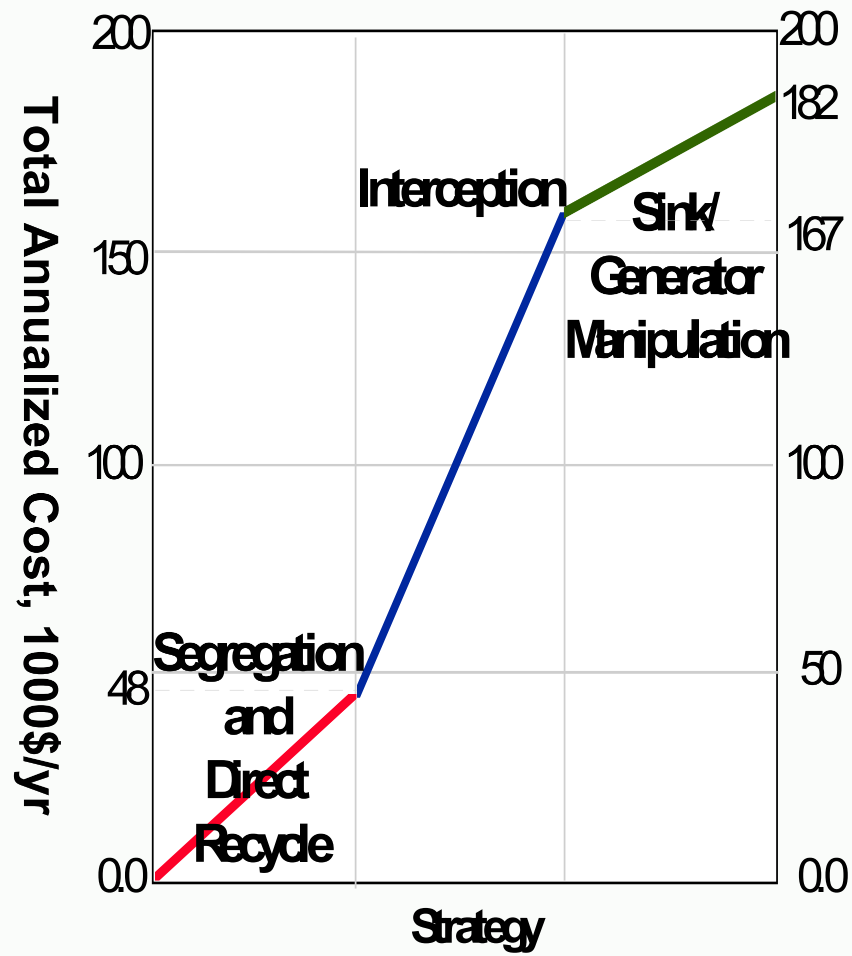
Optimum Solution



Impact diagrams (Pareto charts) for the reduction in wastewater and the associated TAC



Impact



Cost

MERITS OF IDENTIFIED SOLUTION

- Acrylonitrile production has increased from 3.9 kg/s to 4.6 kg/s which corresponds to an **18% yield enhancement for the plant**. For a selling value of $0.6/kg of AN, the additional production of 0.7 kg AN/s can provide an annual revenue of **$13.3 million/yr**!

- **Fresh-water usage** and influent to biotreatment facility are **decreased by 7.2 kg/s**. The value of fresh water and the avoidance of treatment cost are additional benefits.

- **40% Debottlenecking:** Influent to biotreatment is reduced to 40% of current level. Therefore, the **plant production can be expanded 2.5 times** the current capacity before the biotreatment facility is debottlenecked again.

Superior solution to the installation of an additional biotreatment facility!

OBSERVATIONS

- Target for debottlenecking the biotreatment facility was determined ahead of design.
- Then, systematic tools were used to generate optimal solutions that realize the target.
- Next, an analysis study is needed to refine the results " big picture first, details later".
- Unique and fundamentally different approach than using the designer's subjective decisions to alter the process and check the consequences using detailed analysis.
- It is also different from using simple end-of-pipe treatment solutions. Instead, the various species are optimally allocated throughout the process.
- Objectives such as yield enhancement, pollution prevention and cost savings can be simultaneously addressed.

AND YOU CAN (AND SHOULD) TRY IT!