# Calculation Sets

Engineering calculation sets comprise the original work sheets produced in the course of a project. These calculations include such things as mass and energy balances, experimental tests, sizing of equipment items, design of components, and estimation of economics. When completed, these calculations remain as the permanent record of how the engineers on the project arrived at the final project report or design. If properly organized, these calculations can be followed and understood by any competent engineer trained in the same discipline.

## Definition

For convenience, a calculation set is defined as a set of calculations that is organized as a unit and can stand alone. Each engineer defines what encompasses a calculation set for the problem at hand. In some cases, a set is concerned with parts of the process, and, in other cases, a set is for a single item of equipment or part of a process. A calculation set appears wherever the subsection *Calculations* appears in a Project Notebook/File/Report outline.

## The Need for Calculations - Reviews

There are many reasons to review calculations. During reviews of experimental projects, questions need to be answered concerning the experimental conditions and other details. During patent applications, the calculation details are needed to determine if the claims are valid. During design, questions arise which must be answered concerning calculations previously made. During startup, problems may arise which require consulting the calculations before arriving at a course of action. After startup, there may be the need to modify the plant to suit some new objective, and again the calculations are needed. Later on, the decision may be made to duplicate the existing facility, or scale it up, or design one similar to it, and the calculations will eliminate the need for doing this work over again.

## The Need for Organized Calculations

In any of these cases, the calculations must be well organized in order for someone else (and even the originator) to follow and understand them. There is nothing more irritating and frustrating than having to review poorly organized definitions, assumptions, references, computations, and conclusions.

## Guides and Specifications

Each calculation set should be self-explanatory, able to stand alone, and meet the criteria given in the following documents:

# Calculation Set Format

While the format and contents cannot be rigidly specified because of the wide differences in character of problems and solutions, the following format should be followed to the extent it is possible. A project will typically be subdivided into many little problems with the following calculation format repeated for each problem identified. The specific contents of each of the items in any calculation set format outline are described below:

## 1. Problem Statement

A statement of the problem or objective of the calculation preceding the solution permits ready reference to the conditions and data known about the problem.

## 2. Process Sketches

Diagrams are used as an aid in visualizing problems. Sketches should be large enough to include basic data without excessive crowding. Sketches may be free-hand but must be legible. Use of a straight edge and templates is preferred.

## 3. Plan of Attack

Outline a general plan of attack for the solution. State your solution plan in words before calculating with numbers. Frequently there are alternate design or analysis methods available, and it is critical to know which has been employed. Thus, it is extremely important that the design/analysis methods employed be clearly recorded in the calculation set.

## 4. Basis of Calculations

Unless the basis of calculation is explicitly stated, it is often difficult to determine how to compare the solution to another solution, which may have a different basis. If it is necessary or convenient to change basis within the body of the calculations, clearly indicate the change of basis.

## 5. Body of the Calculations

Detail should be tailored to the requirement for clarity. The detail content should be sufficient so that any qualified person could follow the step-by-step sequences and locate both the sources and destinations of information without the need to make their own calculations. Specifications on the calculation format are given in the following section.

## 6. Error Analysis

Crosschecks of the calculations are needed to verify assumptions and their effect on the results. This may include comparisons to other data/information.

## 6. Conclusions

Clearly state any conclusions drawn from the results of the calculations.

## 7. Nomenclature

Explicitly define all variables used in the solution of the problem. The units of all variables must be stated.

## 8. Information Sources

Give a list of complete references for all sources included in the problem solution.

# Calculation Set Specifications

Defines minimum acceptable procedures and uniform practice for the preparation of manually recorded engineering calculations, to control the quality of the work, legibility and suitability for normal uses. Introduces specific organization techniques: indexing, design methods, physical properties, nomenclature and units, references, flow diagram, standard forms, and details of the calculation format. Numerous examples are included.

## A. Index

The most important single element for organization of a calculation set is the index. Without an index it is impossible for any one else (and possibly even yourself) to find what specific information without paging through the entire calculation set.

### 1. Indexing Plan

An effective method of indexing calculations is technically known as the classified subject index. This is an index of subjects which are arranged according to some logical classification as is illustrated in Figure 1.

This type of index is best known as a table of contents in books.

### 2. Preparing the Index

Start the index when the calculations are begun. Add to the index as additional calculations are prepared thus keeping the index current with the calculations. Then you can quickly find what you did yesterday, last week, or last month. If your work on the project is interrupted and have to temporarily lay it aside, then when you can resume work on it the index will prove to be a big time saver.

## B. Standard Calculation Sheet Forms

Use standard calculation paper, unless pre-printed forms prepared for repetitive types of calculations peculiar to a particular calculation are used. In any event, essential calculations should not be made on "the back of an envelope", where they are lost for future reference.

Figure 2 illustrates the standard form, which has been designed for calculations. The form is ruled with light lines to assist in tabulating data and constructing drawings.

### 1. Title Blocks

The title blocks at the top of the form provide a place to fill in designer identity, the date, and the subject of the calculations on each page. Fill in the blocks completely, including subject, starting date, name of designer, date of completion, and page number.

### 2. Use Front Side Only

Begin each calculation set on a new page and use only the front side of the calculation paper. There is a loss of continuity when a part of the calculation set is on one side of a sheet and another part is on the opposite side.

### 3. Oversized Sheets

For calculations which will not fit the standard 8-1/2" x 11" calculation forms, use reproducible paper in a manner and of a size which can be neatly folded to fit standard binders without impairing the legibility of the contents (such as paper from quadrille-ruled 11" x 17" pads, folded to 8-1/2" x 11" size).

### 4. Page Numbering

Number the pages consecutively as calculations are completed. Thus, the pages are chronological with respect to their execution. As a result, the calculations tell the story, in sequence, of how they were performed.

a. Added Sheets. Identify sheets, which are inserted at a later time, by the first preceding numbered page and a letter. For example, if it necessary to insert a few extra pages following "page 5", number them 5a, 5b, 5b....

b. Do Not Renumber Pages. By not renumbering calculation pages, the index never needs correction of page numbers. Also, page numbers can freely be used as references in other parts of the calculations, e.g. "see page 57".

## C. Illustrations

### 1. Flow Diagrams

The most valuable devices for coordinating process design calculations are the process and the material and energy balance flow diagrams. These instruments conveniently and explicitly tie together all the bits and pieces of process information. They show the interrelation of all of the working parts: equipment items, material balance, operating conditions, heat balance, utilities requirements, etc.

An effective method of constructing a flow diagram is to develop it as the process engineering calculations proceed. Start with a simple flow sketch. Add to or modify the sketch as your calculations proceed. When necessary, start with a fresh sheet and redo the flow diagram. When your calculations are completed, your process and material balance flow diagram is final and ready for the drafting room.

The above describes the design control device (flow diagram) most used by process engineers. Similar and analogous design control devices are used in other engineering disciplines.

### 2. Sketches

Sketches are highly desirable as parts of the calculations. For example, in Figure 3 is illustrated a sketch of a refrigeration cycle. The calculations that follow would be very difficult to follow without the sketch. The sketch ties all of the pieces together.

## D. Calculation Body Details

### 1. Headings

Headings should be used to organize the calculations. For example, in Figure 3, lines 3, 5, 27 and 30 are shown with three generic levels of headings, together with the appropriate subject codes.

### 2. Subject Code

Note the convenient subject code pattern

**A-1-a**

used in the example figures. For a more complex calculation set requiring more hierarchal levels, one might use the following subject code pattern:

**I-A-1-a-(1)-(a)**

It really does not matter what code is used so long as it is consistent. These codes and headings are keyed to the calculation set index.

### 3. Indentation

An example of indentation is shown in Figure 4, lines 5-23. Here are shown five subjects, the details of each indicated by indentation.

### 4. Identification of Results

Underline and clearly label all important intermediate results. Final answers should be boxed and clearly identified as for example:

## E. Calculations

### 1. Equations
A good method of documenting the solution of equations is to list the equation first, and then substitute numerical values in it below. Examples of this are shown in Figure 5, lines 33-57.

### 2. Arithmetic
Although arithmetic is elementary, it can become involved, and fraught with opportunities for errors. An example of one way to handle this problem is shown in Figure 5, lines 7-26. Note the use of braces to indicate the various steps in the arithmetic operations. With this form of record, anyone can easily double-check the arithmetic. At the same time, the notation is compact and easy to record.

### 3. Trial-and-Error
These kinds of calculations present special problems in recording calculations. It is very tedious to repeat the calculations for each trial with complete detail. One way of handling this is illustrated in Figure 6. First, the basic model equation is presented. This is followed by a tabulation of trials. The independent trial variable is identified on line 20, and the dependent variable to be satisfied, on line 40. The lines in between record the calculations. The final answer is recorded on line 44.

### 4. Tabulation
Tabulations make calculations compact and easy to follow. For example, Figure 4, lines 44-52 illustrate a tabulation of calculations. The headings of all columns and rows should be labeled and include units.

### 5. Graphics - Identification/Labeling
The use of graphics to present results of calculations is highly recommended. All graphics must be clearly and properly identified. The variables and units of all coordinates must be indicated on the appropriate axis. An identification box should include all conditions and parameters of the plot.

### 6. Notes
At the time of performing calculations, it may seem that everything is obvious. However, with the passage of time and changing of personnel, the original logic may become elusive. One of the most valuable aids to original calculations is the introduction of extensive notes. These notes may be in any of the following categories:

> Basis
> Assumptions
> Literature Citations
> Explanations
> Objectives
> Conclusions
> Recommendations
> Interpretations
> Comparisons to Known Criteria
> Voided Calculations

Examples of these types of notes are indicated in Figure 4, lines 6, 23, 54, 63; in Figure 5, line 45; in Figure 3, line 57.

### 7. Legibility
The use a No.2 or HB black pencil and keep it sharp. Pens and colored pencils are not to be used as they do not reproduce well on many copy machines. The calculations may be recorded either in printing or writing. If you print easily, this is preferred. However, if you are not used to printing, handwriting is acceptable.

Do not recopy your calculations at the end. Recopying may result in typographical errors and is considered a waste of time. With a little experience, you can learn to do your calculations neatly and legibly the first time.

### 8. Computer Output
When computers are used to complete portions of the calculations, insert the actual computer printout as part of the original calculations. Some computer programs confirm all input data in the output. In the event this feature is not part of the program, it is essential to list by machine all input data. Without this, it is impossible to interpret the significance of the output.

## F. Analysis Methods
The analysis methods used are basic to the calculation. If the analysis methods are unreliable, so will be the calculations resulting from them. Frequently there are alternate analysis methods available, and it is critical to know which was employed.

## 1. Standard Procedures

If the design method is taken from a book, literature article, or report, then a citation will suffice. However, if you made any departures from the published design method, you should explicitly record these in your calculations.

## 2. Computerized Procedures

If the calculation method is implemented as a standard computer program, then the computer program should be explicitly identified.

If you develop a special computer program to complete your current project, you should include in the recorded calculations all information necessary for others to understand and use your program. This includes as a minimum the following:

> Listing of source code
> Definitions and units of all program variables
> Subprogram linkage diagram
> Basis of the model
> Example Input
> Example Output

## G. Property Data/Estimation

The physical properties employed in the calculations are extremely important. Even though the calculation method is perfect, the use of unreliable physical property values/estimation procedures will result in an unreliable plant design.

## 1. Sources

For this reason, the physical properties employed should be clearly defined. This should include the sources of the physical property data or prediction methods, ranges of applicability, and any assumptions made where data were unavailable.

## 2. Tables/Correlations

When physical property tables and/or charts are extracted from the literature, it is convenient to include a photo-reproduction of the actual charts as part of the calculations.

Where certain physical properties are used repeatedly during the process engineering calculations, it is frequently advantageous to prepare charts or graphs of these properties, as for example vapor pressure vs. temperature, etc.

In any event, the physical properties should be documented in such a way that anyone reviewing the calculations can determine precisely where all physical/chemical/thermodynamic property values came from.

## H. Citations

Literature citations can be used to precisely define a calculation method or property source. By citation of these references, the method need not be copied into the calculations. One practical method is to start a section on references. Then these references can be cited by author and date anywhere during the course of the calculations.

Besides the public literature, internal letters, memos, and reports can become reference citations.

## I. Nomenclature

Symbols and unusual abbreviations should be clearly defined, preferably in a single list. Symbols that are a part of the nomenclature of recognized standard design procedures need not be defined.

## 1. Symbols

The use of mathematical symbols for variables can be of considerable assistance toward making calculations explicit, compact, and easy to follow. However, much of these advantages will be lost for future reference if the nomenclature is not explicitly defined. You should make certain that every symbol of nomenclature you employ is properly defined somewhere. All symbols should be carefully listed and defined in the calculations.

## 2. Units

Equally important as the mathematical symbols are the units employed. These may seem obvious to you at the time the calculations are made, but at some later date you or someone else will have no idea the units employed unless they are specified in the record.

Figure 6 illustrates the convenient technique of including the definitions at the point of use in the calculation set. Whenever a significant conglomeration of variables or terms are accumulated, they are assigned special symbols, as for example 1, 2, 3, etc. These symbols can be freely reused on succeeding lines. Note that all such special symbols are automatically defined without any additional notes.

## J. Specification and Rating Forms

Certain types of process information are required so often that standard forms have been developed for this purpose. Employ these forms wherever applicable. These forms provide a valuable checklist to make sure that nothing important has been overlooked. In addition, those familiar with the forms can read them much more quickly and efficiently than unformatted information.

## K. Error Control

No engineer is perfect. We all make errors in calculations.

### 1. Checking for Errors

The trick is to find the errors before the plant is built that won't operate. Methods for checking your calculations are discussed in a separate guide.

### 2. Correcting Errors

A disturbing problem arises when an error occurs early in the calculations, particularly when the erroneous value is used again and again in subsequent calculations. One practical method of handling this problem is to strike through the first erroneous value, and then all other key values computed on succeeding pages. In this way the corrected values are clearly apparent, and at the same time the original values are still readable, thereby permitting verification that the error was properly corrected.

## L. Filing the Calculation Sets

Regardless of how many calculation sets are produced on the project, each and every one should be easily retrievable from the project files.

### 1. Working Calculations

The Project Notebook/File provides a place for each engineer to file his/her working calculations. File related calculations together preferably by equipment item number. Further discussion of the preparation of Project Notebooks is available.

### 2. Retention

Calculations are not disposable. After completion of the project, the Project Notebooks shall be sent to Records Storage for archiving with other documents on the specific project. The Project Notebooks also bring together in one place those calculations that are designated permanent files

### 3. Retrieval

The procedure given for Project Files provides a place for each engineer to file his calculations and then provides for bringing together in one place those calculations that are designated permanent files

Consider how this works when you have need for certain calculations on a project. Given a project name or number, you find the total project files. Referring to the outline, you determine the particular file covering the subject of your current needs. If all has been done properly, this file should contain the calculation set you are seeking, and the calculation set should provide all the information you need.

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# Calculation Set Checklist

Calculation sets can be considered in much the same light as other products of a company. In many efforts, calculation sets may be the only tangible products. Therefore quality assurance is as important in the preparation of calculation sets as it is in the manufacture of hardware items or complex systems. Quality assurance and control must be exercised by knowledgeable and objective individuals with sufficient authority to initiate corrective action as appropriate. The checklists presented below are for use in accomplishing the review and quality control of various facets of a calculation set.

## Checklist for Table of Contents
✓ Do the contents accurately and consistently reflect what the calculations cover?
✓ Do the main divisions or heads follow some logical principle?
✓ Does each subsequent subdivision follow some logical principle (not necessarily the same as for the main heads)?
✓ Is each main problem sufficiently subdivided to bring out all of the significant ideas?
✓ Is the numbering system consistent throughout?
✓ Do the titles on the lists of figures and tables accurately reflect the type and general content?
✓ Do the lists of figures and tables include any obvious or approximate duplications?
✓ Checklist for the Problem Statement
✓ Is a statement of the problem being considered presented?
✓ Are the purpose and objectives of the calculation set defined?
✓ Are the circumstances or conditions associated with the problem clarified?
✓ Are the highlights of the information presented in the detailed sections summarized?
✓ Is attention focused on the key conclusions and recommendations?
✓ Is the plan or organization of the calculation set defined?

## Checklist for the Detailed Calculations
This checklist is intended for the evaluation of presentation for a particular problem or problem set. The checking should actually be accomplished in six separate and distinct reviews, each focused on a particular characteristic. These six reviews should consider the following:

✓ Structure and coherency.
✓ Completeness and conciseness.
✓ Accuracy of facts.
✓ Clarity and exactness.
✓ Overall integrity and appearance.

In actual practice it would be best for a reviewer to subdivide each one of these reviews into smaller parts that focus on a single particular point. This requires the reviewer to make more passes through the material. But since a single point is involved, each pass can be a simple scanning operation. Such a procedure will result in detecting more errors and omissions with minimum time and effort. The following are brief checklists for each pass through the calculation set:

### Structure and Coherency
✓ Are any calculations out of logical order?
✓ Is each subdivision complete within itself and logically positioned within the overall outline?
✓ Is the logic within each subdivision consistent?
✓ Does the problem statement agree with the detailed and conclusions?
✓ Are appropriate transitions and introductory material included where necessary?

### Completeness and Conciseness
✓ Are any important calculations omitted or not fully covered?
✓ Are any calculations omitted which, by their absence, will beg a question?
✓ Are any calculations unnecessarily duplicated?
✓ Are complete and appropriate solutions presented where problems have been noted?
✓ Have all necessary facts been included without any unnecessary or unrelated information?
✓ Has all irrelevant, nonessential, and trivial matter been omitted?
✓ Can any material be deleted or moved to an appendix without affecting the quality of the presentation?

### Accuracy of Facts
✓ Have all relevant physical and chemical phenomena been correctly described?
✓ Has the significance of the information presented been recognized and correctly interpreted?
✓ Are all statements of fact consistent with the original sources of data?
✓ Are all assumptions properly identified and defined?

- ✓ Are all arithmetic and mathematical presentations complete, consistent, and accurate?
- ✓ Are all references complete and accurate?
- ✓ Are all dates, physical data, performance data, names of people and places, and other similar items consistent with the original sources?
- ✓ Are individual facts consistently presented from one calculation set to another?
- ✓ Do all totals accurately reflect the sum of the associated parts?

## Clarity and Exactness
- ✓ Does the narrative say exactly what it is supposed to say in the final version?
- ✓ Do the illustrations depict exactly what they are supposed to depict.
- ✓ Do all of the words and phrases accurately reflect the ideas being presented?
- ✓ Are numbers and numerals used appropriately and consistently?
- ✓ Are abbreviations used in the calculations? If so, would the presentation be clearer if the words were spelled out?
- ✓ Have all symbols been identified in a glossary with corresponding words or abbreviations?
- ✓ Where used, are abbreviations either in accordance with standard definitions or properly defined?
- ✓ Are the headings appropriate and consistent throughout?
- ✓ Is the item-numbering system appropriate and consistent throughout?
- ✓ Are all illustrations and formal tables referenced in the appropriate locations?
- ✓ Do the figure and table references accurately correspond to the material being referenced?

## Final Overall Review
- ✓ Does the calculation set present a complete and logical development of the solution?
- ✓ Is the calculation set clear and easy to read?
- ✓ Does the calculation set reflect an appropriate balance between narrative and illustrations?
- ✓ Does the theme come through forcefully?
- ✓ Does the narrative reflect proper balance between important and secondary problems?
- ✓ Does the calculation set reflect the basic "problem identification, plan of attack, basis, details, summary' theme at the overall level and at appropriate major subdivisions?
- ✓ Are the calculations easy to follow?
- ✓ Has sufficient prose been included to read the calculations?
- ✓ Have conclusions of the calculations been given?
- ✓ Are headings given and are the calculations indexed?
- ✓ Are the calculations accurate and have error limits been noted?

## Checklist for the Conclusions Sections
- ✓ Are logical conclusions presented that easily relate the information contained in the detailed sections?
- ✓ Is the achievement of the objectives or goals established in the problem statement recognized?
- ✓ Are intelligent and practical recommendations commensurate with the conclusions developed?
- ✓ Are appropriate summary statements included so as to make the closing relatively independent of the detailed sections?
- ✓ Are statements with regard to future action presented where appropriate?

Adapted from: Woelfle, R.M. "Technical Reports". In S. Jordan, J.M. Kleiman, and H.L. Shemberg, eds. Handbook of Technical Writing Practices. Wiley-Interscience, N.Y. (1971).

<u>Tab</u>:   MASTER INDEX

<u>CEA 0000 – Ethylene Plant</u>

<u>Process Design Calculations</u>

<u>Master Index</u>

Design Basis
Process
Physical Properties
Equipment Design
Economics
References

<u>Tab</u>:    PHYSICAL PROPERTIES

<u>Physical Properties</u>

<u>Index</u>

Figure 1. Example table of contents

5/10/01  D.S. Adam          Ethylene Plant    Refrigeration E. Bal  3/5

Date

Your Name

Project Title

Calculation Identification

Page Number

Number of
Pages in Set

Figure 2. Standard Form for Engineering
Calculations
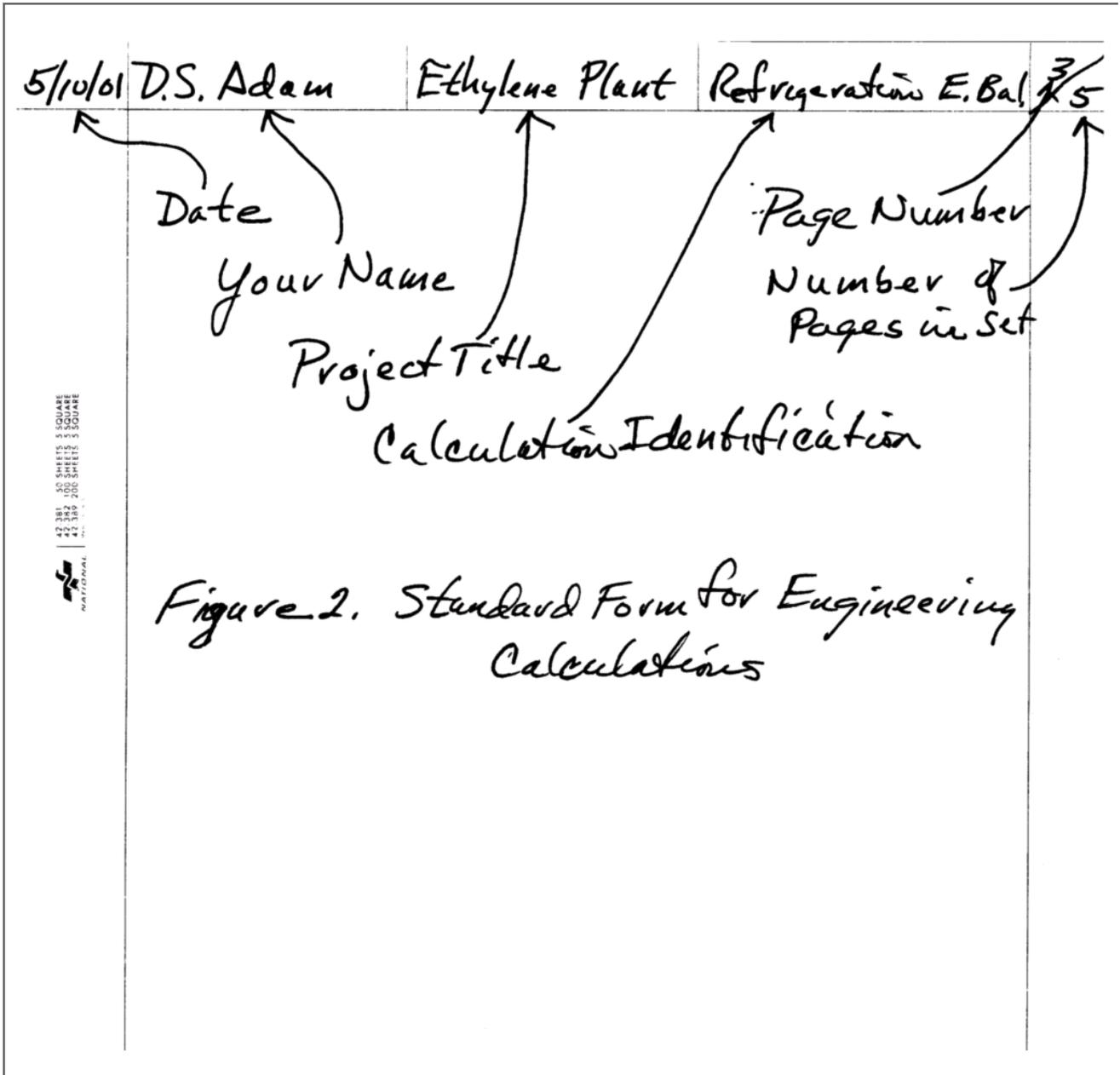
Figure 2. Page layout

## G. Refrigeration Design

### 1. Process and Requirements

Flash Chiller
1,100,000 Btu/hr

Ethylene Column
T. of refrig. Cond.
4,500,000 Btu/hr

−140°F    −120°F          −2.°F    −20°F
−160°F    −150°F          −8.°F    −35°F

−25°F

17 psia  270 psia  100°  −35°F          18 psia  190 psia          92°F
                                                                    Cooling Water

$C_2H_4$ System          −26°F          $C_3H_8$ System   100°F   87°F
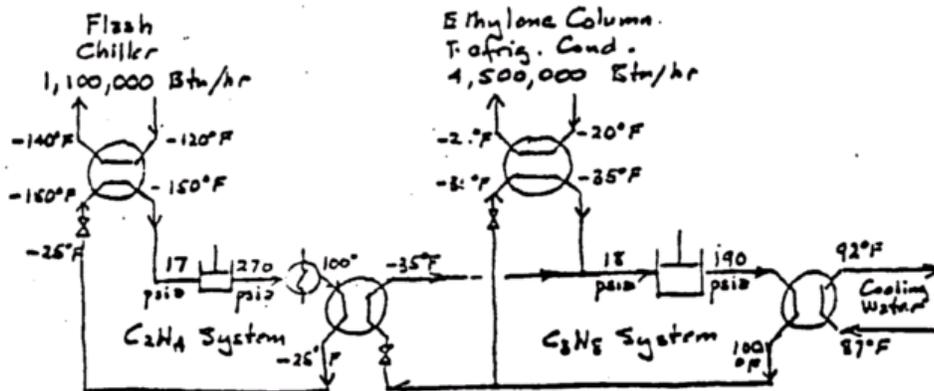
### 2. Ethylene System

#### a. Circulation Rate

Duty                               1,100,000  Btu/hr
Enthalpy
  Vapor, 17 psia, −150°F         1022 Btu/lb
  Liquid, −25°F                    893  "
        ΔH                          129  "

Circ. rate = 1,100,000/129 = 8,500 lb/hr

#### b. Compression

|                        | Suction | Discharge |
|------------------------|---------|-----------|
| Pressure, psia         | 17      | 270       |
| Temperature, °F        | −150    | +150      |
| Entropy, Btu/lb-°R     | 1.70    | 1.70      |
| Enthalpy, Btu/lb       | 1022    | 1112      |
| ΔH                     |         | 90.       |

Power
  8,500 × 90 = 765,000 Btu/hr = 213 Btu/sec
  213 × 778 = 165,000 ft-lb/sec
  165,000/550 = 300 HP

#### c. Condenser Duty    Assuming water cooling to 100°F

Enthalpy of vapor at 270 psia, 100°F    1090 Btu/lb
   "    of liquid at −25°F                893   "
                            ΔH =          197   "

Duty        8,500 × 197 = 1,700,000 Btu/hr

Figure 3. Schematic Diagrams

## 4. Feed Temperature

**Objective** — Want to avoid 2-phase flow in reactor because model derived for single phase.

**Composition**

| Comp | lb | MW | mols | mol frac |
|---|---|---|---|---|
| $C_2H_6$ | 1.00 | 30 | .0333 | .75 |
| $H_2O$ | .20 | 18 | .0111 | .25 |

**Steam partial pressure**
Total pressure — 5.5 atm × 14.7 = 81 psia
Steam part. press. — 81 × 0.25 = 20 psia

**Dew point**
Saturated steam at 20 psia = 228°F
Therefore any feed temperature above 228°F will insure single phase

**Selected feed temperature** — 250°F

## 5. Hand Calculation of First 50-Ft Increment

### a. At Start of Increment

Fluid temp. — 250°F + 460 = 710°R
Fluid press. — 5.5 atm × 2120 = 11,660 lb/ft²
Fluid composition

| i | Comp | $X_i$ |
|---|---|---|
| 1 | $C_2H_6$ | .833 |
| 5 | $H_2O$ | .1667 |
| | | 1.000 |

### b. Fluid Properties (Start of Increment)

#### (1) Molecular Weight & Mol Fractions

| i | Comp | $X_i$ | $M_i$ | $X_i/M_i$ | $y_i$ |
|---|---|---|---|---|---|
| 1 | $C_2H_6$ | .833 | 30 | .0278 | .750 |
| 2 | $C_2H_4$ | .000 | .28 | .000 | .000 |
| 3 | $H_2$ | .000 | 2 | .000 | .000 |
| 4 | $CH_4$ | .000 | 16 | .000 | .000 |
| 5 | $H_2O$ | .1667 | 18 | .00926 | .250 |
| | Total | 1.000 | 27.0 | .0371 | 1.000 |

Above based on:

$\qquad\qquad\qquad = 27.0 \qquad\qquad (12)^*$

Figure 4. Example calculations

d. Kinetic Rate Constants       710°R

$$K_1 = 1.535 \times 10^{14} \exp(-63,500/T_f) \cdot \sec^{-1} \quad (4a)$$

$$K_1 = 1.535 \times 10^{14} \exp\underbrace{(-63,500/710)}_{-89.5}$$

$$\underbrace{\log_{10}\exp = -89.5 \times 0.435 = -39}_{10^{-39}}$$

$$K_1 = 1.5 \times 10^{14} \times 10^{-39} = 1.5 \times 10^{-25} \sec^{-1}$$

$$k_2 = 2.58 \times 10^{16} \exp\underbrace{(-78,000/710)}_{-110} \sec^{-1} \quad (4b)$$

$$\underbrace{\log_{10}\exp = -110 \times 0.435 = -48}$$

$$k_2 = 2.58 \times 10^{16} \times 10^{-48} = 2.5 \times 10^{-32} \sec^{-1}$$

e. Heat Transfer

(1) Radiation      2360°R

$$\Omega = S/D_o + \arctan\sqrt{(S/D_o)^2 - 1} - \sqrt{(S/D_o)^2 - 1} \quad (35)$$

$$S/D_o = 8.0/4.5 = 1.780$$
$$(S/D_o)^2 = 3.15$$
$$\sqrt{(S/D_o)^2 - 1} = \sqrt{2.15} = 1.465$$

$$\Omega = 1.780 + \underbrace{\arctan 1.465}_{55.7° = 0.97} - 1.465 = 1.285$$

For single row of tubes, irradiated from both sides:

$$\frac{1}{\varphi} = \frac{1}{\epsilon} - 1 + \frac{\pi}{2\Omega} \quad (33)$$

$$\frac{1}{\varphi} = \underbrace{\frac{1}{0.90}}_{1.11} - 1 + \underbrace{\frac{\pi}{2 \times 1.285}}_{1.221} = 1.332$$

$$\varphi = 1/1.332 = 0.750$$

Figure 5. Calculations

## (4) Iterative Heat Transfer Calculations

$$\frac{\overline{\overline{T_0}}}{100} = \left[310,000 - 7.80 \, dQ/dA_o\right]^{1/4}$$

$$T_i = T_0 - \frac{dQ/dA_o}{600}$$

$$\frac{dQ}{dA_o} = 58.3 \, (T_i - 250)$$

| Trial | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Assumed $dQ/dA_o$ | 20,000 | 30,000 | 35,000 | 35,500 | 35,200 |
| 310,000 | 310,000 | 310,000 | 310,000 | 310,000 | 310,000 |
| ① = 7.80 $dQ/dA_o$ | 156,000 | 234,000 | 273,000 | 277,000 | 275,000 |
| ② = 310,000 − ① | 155,000 | 76,000 | 37,000 | 33,000 | 35,000 |
| ③ = √② | 393 | 275 | 192.4 | 181.6 | 187.0 |
| $\overline{\overline{T_0}}/100$ = √③ | 19.8 | 16.6 | 13.85 | 13.45 | 13.67 |
| $T_0$, °R | 1980 | 1660 | 1385 | 1345 | 1367 |
| 460 | 460 | 460 | 460 | 460 | 460 |
| $T_0$, °F | 1520 | 1200 | 925 | 885 | 907 |
| ④ = ($dQ/dA_o$)/600 | 33 | 50 | 58 | 59 | 58 |
| $T_i$ = $T_0$ − ④ | 1487 | 1150 | 867 | 826 | 849 |
| 250 | 250 | 250 | 250 | 250 | 250 |
| ⑤ = $T_i$ − 250 | 1137 | 900 | 617 | 576 | 599 |
| Calc. $dQ/dA_o$ = 58.3 ⑤ | 66,300 | 52,500 | 36,000 | 33,500 | 35,000 |
| Calc./Ass. $dQ/dA_o$ | 3.31 | 1.75 | 1.03 | 0.94 | 0.995 |

Answer: $dQ/dA_o$ = 35,200 Btu/hr-ft²

Figure 6. Iterative Calculations