LIFE-CYCLE COST COMPARISON OF ALTERNATIVE ALLOYS FOR FGD COMPONENTS

J.D. REDMOND, R.M. DAVISON,
AND Y.M. SHAH

Nº 10023

Presented at Air Pollution Seminar,
Buffalo, NY, U.S.A., Oct 1987.

Distributed by
NICKEL
INSTITUTE

knowledge for a brighter future

LIFE-CYCLE COST COMPARISON OF ALTERNATIVE ALLOYS FOR FGD COMPONENTS

Nº 10023

By J.D. Redmond, R.M. Davison, and Y.M. Shah, presented at Air Pollution Seminar, Buffalo, NY, U.S.A., Oct 1987.

LIFE-CYCLE COST COMPARISON OF ALTERNATIVE ALLOYS FOR FGD COMPONENTS

Dr. J. D. Redmond and Dr. R. M. Davison
Technical Marketing Resources, Inc.
3209 McKnight East Drive
Pittsburgh, PA 15237, U.S.A.

Y. M. Shah
PEI Associates, Inc.
11499 Chester Road
Cincinnati, OH 45246-0100, U.S.A.

ABSTRACT

Life-cycle cost analyses of the use of stainless steels and other corrosion-resistant alloys were compared with those of neoprene-lined carbon steel in the construction of flue gas desulfurization (FGD) components. The life-cycle cost analysis included all the cost components which are affected by the materials of construction and was based on standard costing procedures followed by the United States utility industry. Although the capital costs of the FGD components constructed of stainless steel and corrosion-resistant alloys are generally higher than those of the lined carbon steel components, the life-cycle costs are less in most cases, often substantially less. The additional benefits of using better construction materials are improved reliability and reduced downtime; even a minor improvement in these areas can add substantially to the life-cycle cost savings. The savings can be further increased by optimizing selection of materials for individual components by matching the operating environment of the component and the mechanical characteristics of the materials. Extensive field experience confirms the favorable conclusion of the study.

INTRODUCTION

Frequently, performance failures and the resulting shutdowns of utility flue gas desulfurization systems are directly related to materials of construction. The flue gas-handling components that promote the initial reactions between the flue gases and the absorbing slurry or quench water are most susceptible to material failures. The costs of these forced shutdowns are significant. Service experience has shown that flue gas-handling equipment constructed of stainless steel or nickel-base alloys can significantly reduce the number of shutdowns and their associated costs. The higher initial costs of these materials, however, have discouraged their widespread use. Because system selection cannot be based on initial costs alone, a life-cycle cost analysis of available alternatives should be performed to arrive at an economically justifiable decision.

This paper presents a life-cycle cost comparison of selected stainless steels and nickel-base alloys for major flue gas-handling equipment. Although the analysis presented is based on a lime/limestone FGD process, the conclusions are broadly applicable. Owners of FGD systems and engineers involved in selecting and specifying the materials of construction should benefit from this analysis.

COMPARISON OF MATERIALS OF CONSTRUCTION

Various high-alloy materials have been tried and found to be successful for use in FGD equipment. Based on a literature review and the FGD data base maintained by PEI, 12 materials were selected for the life-cycle cost analysis. These materials are grouped under three categories; the categories and materials under each category are:

☐ *Stainless Steels*

Type 316L
Type 317M
Type 904L
Duplex Alloy 255
Alloy 254 SMO*

☐ *Low-Molybdenum Nickel-Base Alloys*

Alloys Alloy 825
Alloy 20Cb-3**
Alloy G
Alloy 20Mo-6**

☐ *High-Molybdenum Nickel-Base Alloys*

Alloy 625
Alloy C-276
Alloy C-22

The life-cycle costs of these materials are compared with the baseline construction material, neoprene-lined carbon steel. Cost comparisons are presented for two types of construction options: 1 Solid alloy construction. 2 Alloy-clad carbon steel. The compositions of the corrosion-resistant alloys selected for this analysis are summarized in Table 1.

FGD COMPONENTS ANALYZED

To demonstrate the benefits of using corrosion-resistant alloys, the

---

* Trademark of AB Avesta.

**Trademark of Carpenter Technology Corporation.

life-cycle cost analysis was performed on three major components in the flue gas-handling area of an FGD system. These components are subjected to the most severe operating chemistry and environment. The FGD components included in the study are:

- ☐ Scrubber/presaturator
- ☐ Absorber
- ☐ Outlet ductwork

Figure 1 indicates the severity of environmental conditions within the various components of a typical FGD system. The environmental conditions are divided into three categories (chemical, abrasion/erosion, and temperature) and assigned a rating of 1 to 3. A rating of 3-3-3 represents the most severe environmental conditions.

It should be noted that the physical configuration of the components plays a major role in creating environmental conditions in FGD components. For example, a design that allows the formation of stagnant pockets may lead to premature material failures due to corrosion. This life-cycle cost analysis does not address the design aspect of the components and assumes that the compared systems use identical designs.

Scrubber/Presaturator

The scrubber/presaturator is the first component in the FGD system in which flue gases come in contact with the wet slurry or quench water. The high velocities created by the venturi configuration and sudden quenching of hot gases create the most severe environmental conditions. Solving the material failure problems in this component alone can result in a significant reduction in system downtime.

The design of the scrubber/presaturator differs widely among the FGD systems. Many systems eliminate the separate scrubber/presaturator unit, and the presaturator becomes an integral part of the absorber. The life-cycle cost analysis of this report is based on a design on which a separate venturi scrubber is placed ahead of the absorber because a separate unit facilitates the analysis of the life-cycle costs.

Absorber

The chemical reactions between the flue gases and the absorbing slurry take place in the absorber. Various absorber designs are used to promote adequate reaction times and intimate contact between the slurry and flue gases. A spray tower absorber design was selected for this analysis because this design is widely used in American FGD systems. Levels of environmental severity vary among the different parts of the absorber. In general, the environmental levels are less severe than in other flue gas-handling components, such as the presaturator and outlet ductwork.

Ductwork

The outlet ductwork is another flue gas-handling component that can benefit from better materials of construction. Because the clean gases exiting the absorber are wet, they create condensation in the ductwork and promote corrosion. The most severe environmental conditions, however, are created in the bypass mixing zone, where the hot uncleaned flue gases come in contact with the cool scrubbed gases. In most FGD systems, the chemical environment is further aggravated by horizontal ductwork, which allows condensation to collect on the duct floors.

LIFE-CYCLE COSTS

Methodology

Life-cycle costs take into account all the relevant costs of a system over its lifetime. For a meaningful comparison of available options, life-cycle costs must be all-inclusive, i.e., they must include all the direct and indirect costs. The following cost components were analyzed for a life-cycle cost comparison of FGD system materials of construction:

- ☐ Initial capital investment
- ☐ Major maintenance
- ☐ Routine maintenance
- ☐ Insurance and miscellaneous annual charges
- ☐ Investment tax credit
- ☐ Depreciation tax credit

All of the above cost components are affected by the material of construction. The operating costs (i.e., the costs of raw materials, utilities, and operating and supervisory labor) are assumed to be independent of the materials of construction and thus are not included in the analysis.

The Electric Power Research Institute (EPRI) has published guidelines for performing cost analyses of utility projects in a report entitled *Technical Assessment Guide* (TAG).[1] These guidelines provide a consistent set of economic factors, financial assumptions, and other cost-estimating parameters necessary for utility projects. PEI followed the TAG document for this life-cycle analysis.

The basis and assumptions for the analysis are summarized in Table 2.

Each of the cost components is discounted to the 1987 base year by use of the present-worth method. The calculations are performed in constant dollars, and a EPRI-recommended discount rate of 6.1 percent is used.

Capital Investment

The capital investment of a system component represents the initial installed cost. It includes equipment and auxiliary costs, costs of installing the component, and other related costs (indirect costs). The capital cost of neoprene-lined carbon steel components was estimated by using PEI's Integrated Air Pollution Control System Design and Cost Estimating Model.[2] The FGD module in the cost model is based on the latest version of TVA's Shawnee Model.[3] The model provided a detailed breakdown of equipment, installation, and indirect costs. The costs of corrosion-resistant alloy components were estimated by adjusting the equipment costs for higher material costs. The estimated material cost factors for the 1/4-in. (6.35-mm-) plate used for the analysis are shown in Table 3.

The capital cost of alloy-clad systems is based on a cladding thickness of 1/16 in. (1.6 mm) on 1/4-in. (6.35-mm)-thick carbon steel. It was determined that the life-cycle costs are not highly sensitive to the cladding thickness.

Major Maintenance Costs

Field experience indicates that nonmetallic linings for carbon steel components are gradually degraded in operation through chemical, abrasive, and thermal action. These materials may be subject to rapid or even catastrophic damage by significant excursions in scrubber operation. Coatings and rubber linings require major maintenance during the design life of an FGD scrubber; for this analysis, costs were estimated for liner replacement every five years.

In the first stage of this analysis, it is assumed that entire components are fabricated from a single grade of corrosion-resistant alloy. It is further assumed that the selected grade does not corrode in service and therefore requires no major maintenance. This simple approach is unrealistic. In the first place, lesser grades of alloy are not corrosion-resistant in all environments, and more corrosion-resistant grades are too costly for use throughout an FGD scrubber. In actual construction, combinations of corrosion-resistant alloys are used to attain adequate corrosion resistance most economically. Therefore, the life-cycle cost analysis of a single corrosion-resistant grade only provides information for use in combination with cost analyses of other grades for optimal system design.

Routine Maintenance Costs

The routine maintenance costs of corrosion-resistant alloy components are expected to be low because of their better performance characteristics. Nonmetallic-lined carbon steel components are expected to require more maintenance because of localized lining problems and repairs. The routine maintenance costs of any system are generally estimated as a percentage of capital investment. The EPRI TAG document indicates a range of 5 to 10 percent. The recommended percentage represents the weighted maintenance requirements for the entire FGD system. The maintenance percentages can vary from component to component depending on the operating environment of the individual component. PEI contacted various industry and utility specialists to obtain data for maintenance requirements for nonmetallic-lined carbon steel and corrosion-resistant alloy components. The maintenance costs of alloy systems were reported to be significantly lower. The case histories studied by PEI also support this conclusion.

The maintenance costs for a neoprene-lined carbon steel scrubber/presaturator and absorber are estimated as 12 percent of the capital cost. A maintenance factor of four percent is used for ductwork because ductwork routine maintenance requirements are significantly lower than those for the scrubber/presaturator and absorber. The maintenance costs of the alloy-constructed components are also estimated as a percentage of the capital cost of the neoprene-lined carbon steel components. For solid alloy construction, routine maintenance costs for a scrubber/presaturator and absorber are estimated by maintenance percentages of 6, 8, and 10 for high-molybdenum nickel-base alloys, low-molybdenum nickel-base alloys, and stainless steels, respectively. Estimated maintenance costs for the solid alloy ductwork are based on percentages of 2, 2.67, and 3.34 (1/3 of the scrubber/presaturator and absorber) for high-molybdenum nickel-base alloys, low-molybdenum nickel-base alloys, and stainless steels, respectively. The maintenance costs of alloy-clad systems are assumed to be 10 percent higher than those for the solid alloy construction.

Insurance and Miscellaneous Charges

Annual costs (such as property taxes, insurance, etc.) are estimated as a percentage of the capital investment. These charges are estimated to be two percent of the capital costs of the component.

Investment Tax Credit

The new U.S. tax laws do not allow an investment tax credit. Under the old laws, utilities were allowed to claim an immediate reduction in income taxes equal to a percentage of the installed cost of the new system. No investment tax credit is included in this life-cycle cost analysis.

Depreciation Tax Credits

Powerplants in operation in the U.S. before January 1, 1979, are allowed a 5-year tax depreciation for new, identifiable, pollution-control facilities completed or acquired after December 31, 1982. The deduction of this depreciation amount from their income reduces the utilities' tax liability. For this analysis, a straight-line depreciation method and a tax rate of 38 percent are used.

Comparisons of Life-Cycle Costs

Life-cycle costs for each material option were estimated for three FGD components. Cost relationships were formulated by estimating costs for three sizes: 285,000, 427,000, and 570,000 acfm (134.5, 201.5, and 269.0 m^3/s). The life-cycle costs were calculated by estimating the annual cash flows for each cost component and then discounting them to a common base year. The individual discounted cost components were then combined to obtain the total life-cycle cost of the system. The analysis was performed in constant dollars by using an EPRI-recommended discount rate of 6.1 percent.

Figures 2 through 8 present the life-cycle cost comparison for the analyzed options. A cost band is shown for each of the material categories and a curve for neoprene-lined carbon steel is presented. The costs of venturi scrubbers constructed of a solid alloy and of carbon steel with alloy cladding are shown in Figures 2 and 3, respectively. The life-cycle costs of venturi scrubbers constructed of high- and low-molybdenum nickel-base alloys are higher than those constructed of lined carbon steel. The life-cycle costs of those constructed of the strainless steels are lower than those constructed of lined carbon steel. The life-cycle costs of all venturis constructed of carbon steel clad with alloy are significantly lower than those constructed of neoprene-lined carbon steel.

Trends of life-cycle costs for absorbers (shown in Figures 4 and 5) are similar to those for venturis. The life-cycle costs of absorbers constructed of nickel-base alloys are higher than those constructed of neoprene-lined carbon steel. The costs for absorbers constructed of stainless steels and for all clad alloy options are lower than those constructed of lined carbon steel.

Figures 6 and 7 show a cost comparison for outlet ductwork. Life-cycle costs of solid alloy ductwork are generally higher than for those constructed of neoprene-lined carbon steel, with the exception of a few stainless steels. For the alloy-clad ductwork, life-cycle costs of high-molybdenum nickel-base alloys are higher than the neoprene-lined carbon steel ductwork. The costs of low-molybdenum nickel-base alloys and stainless steel options are lower than neoprene-lined carbon steel ductwork.

In actual application, material selection is optimized by using a combination of corrosion-resistant alloys and selecting the grade for each section in accordance with the demands of the operating environment.

For example, a particular FGD system might use: a scrubber/presaturator constructed of solid Alloy C-276; an absorber constructed of Alloy 904L; and ductwork constructed of 90% solid Alloy 904L and 10% clad Alloy C-276 on the areas expected to encounter the most severe corrosion environment.

Figure 8 shows a life-cycle cost comparison for three cases in which different alloys were selected and in which different combinations of solid and clad construction were evaluated. Table 4 provides the details of the three cases. Comparisons were made for three sizes of systems corresponding to gas flow rates of 200,000, 400,000 and 600,000 acfm.

All three cases result in life-cycle costs lower than the neoprene-lined carbon steel alternative. Depending on the choice of corrosion-resistant alloys needed for a particular environment and the relative amount of clad and solid alloy construction, the savings can be quite significant.

This life-cycle analysis understates the cost savings associated with corrosion-resistant alloys. These alloys also are resistant to catastrophic failures associated with excursions in operations (e.g., plugging of a line resulting in overheating or lack of neutralization). The analysis presented in this study does not account for the cost of downtime or shutdowns due to failure of materials. Even a small improvement in this area can result in large cost savings.

The design values (i.e., yield stress, ultimate tensile strength, etc.) of some of the corrosion-resistant alloys are substantially greater than those of carbon steel. Downgauging of the corrosion-resistant grades relative to the plate thickness required for carbon steel could substantially lower the initial cost of the use of corrosion-resistant alloys.

The performance of individual corrosion-resistant alloys in FGD components will vary depending on the composition of each material. The pitting and crevice corrosion resistance of the high- and low-molybdenum nickel-base alloys is greater than that of many stainless steels. Several utilities have successfully solved specific material failure problems in FGD components by switching to corrosion-resistant materials, specifically high-molybdenum nickel-base alloys. The switch to corrosion-resistant materials has been fairly recent, and adequate data are not availble to translate the improved corrision-resistance into a reduction in downtime and maintenance costs.

CONCLUSIONS

The analysis performed in this paper has led to the following conclusions:

1. Life-cycle cost studies based on conservative assumptions and the EPRI *Technical Assessment Guide* indicate that in most cases the use of corrosion-resistant alloys can result in significantly lower total costs than the use of neoprene-lined carbon steel in the construction of FGD systems.

2. Optimization of grade selection for each FGD component, including the use of the higher-alloy materials in the critical sections of each component as necessary and the use of lighter-gauge corrosion-resistant alloys, can lower costs even further.

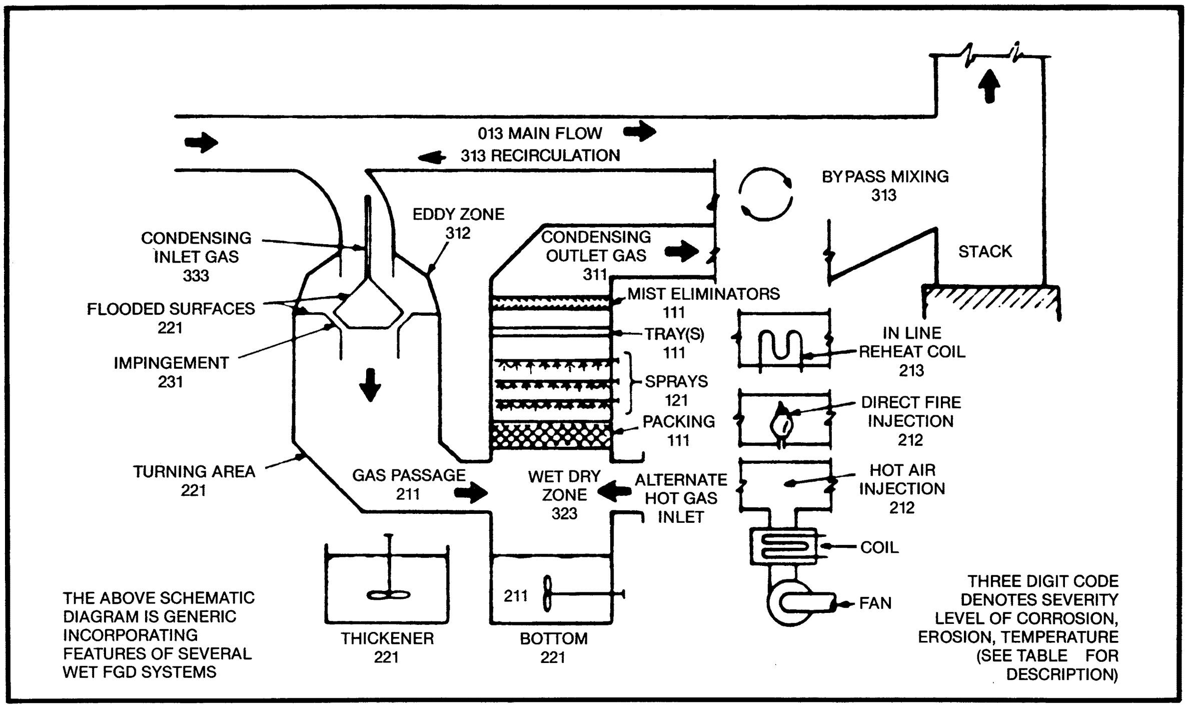
3. Field experience confirms the conclusions of cost studies indicating that combinations of corrosion-resistant alloys represent the lowest total cost approach to FGD scrubber construction.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Nickel Development Institute which made this study possible.

REFERENCES

1. *Technical Assessment Guide (TAG),* Volume 1: Electric Supply. 1986. Electric Power Research Institute. Palo Alto, CA, U.S.A. Publications N° P-4463-SR, December 1986.
2. PEI Associates, Inc., *User's Manual for the Integrated Air Pollution Control System Design and Cost-Estimating Model,* prepared for the United States Environmental Protection Agency under Contract N° 68-02-3995, Work Assignment 4, September 1986.
3. F. A. Sudhoff, R. L. Torstrick, *Shawnee Flue Gas Desulfurization Computer Model User's Manual,* EPA-600/8-85-006; TVA/OP/EDT-84/37, 1985.



THE ABOVE SCHEMATIC DIAGRAM IS GENERIC INCORPORATING FEATURES OF SEVERAL WET FGD SYSTEMS

THREE DIGIT CODE DENOTES SEVERITY LEVEL OF CORROSION, EROSION, TEMPERATURE (SEE TABLE FOR DESCRIPTION)

ENVIRONMENTAL SEVERITY LEVEL

Level	Chemical Environment	Abrasion/ erosion	Temperature
1	pH 3 to 8 Saturated flue gas. Process slurry continuous flow or immersion	Slow-moving liquids and gases. Tank walls	Ambient to 140 F (60°C) process slurry
2	pH 0.1 to 3 Up to 15% acid concentration. Saturated wet gas: Acidic liquids. Slurries	Spray impingement (20 FPS or more). Strong agitation. Spray zones. Some tank bottoms and wall areas	140 to 200°F (66 to 93°C). reheated gas
3	Acid concentration greater than 15%. Intermittent wet/dry zones	High energy venturi. Turning vanes. Struts. Targets	200 to 330°F (93 to 166°C). Inlet gas. Bypass gas. Reheat gas injection (hot air, fuel fired, inline reheat coil)

°Temperatures in the range of 420°F (216°C) to 440°F (227°C) have been recorded

Figure 1

Schematic diagram of FGD environmental severity levels.
(Reprinted, with permission, from STP 837. Copyright, ASTM, 1916 Race Street, Philadelphia, PA 19103, U.S.A.)

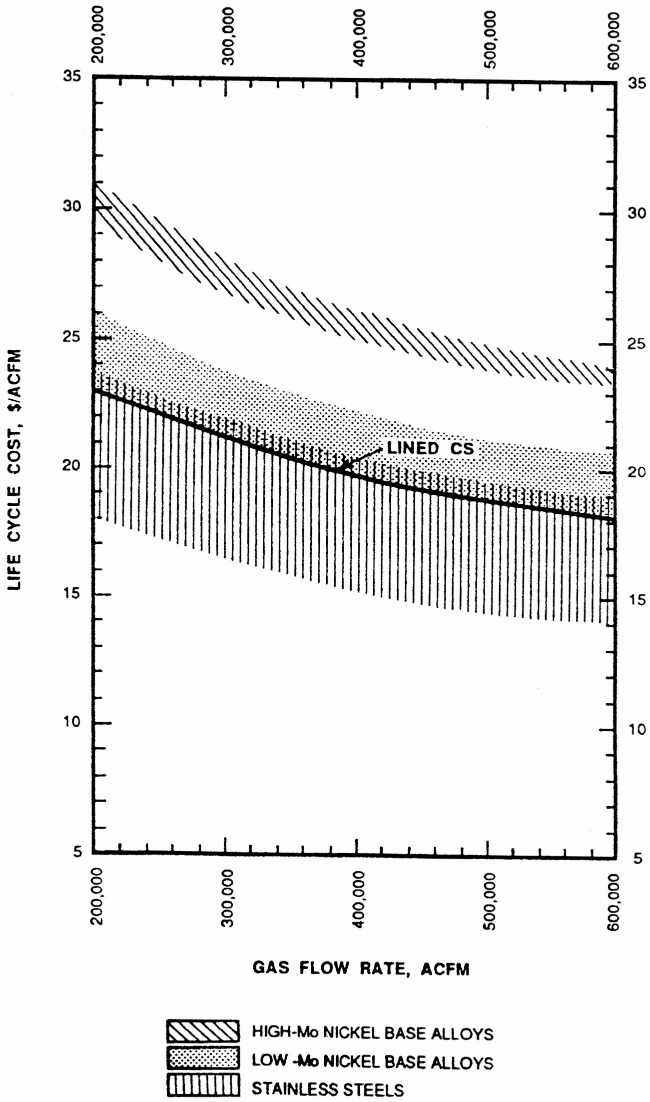


Figure 2
Life-cycle cost comparison, solid alloy venturi.
(1000 acfm = 0.472 m^3/s)

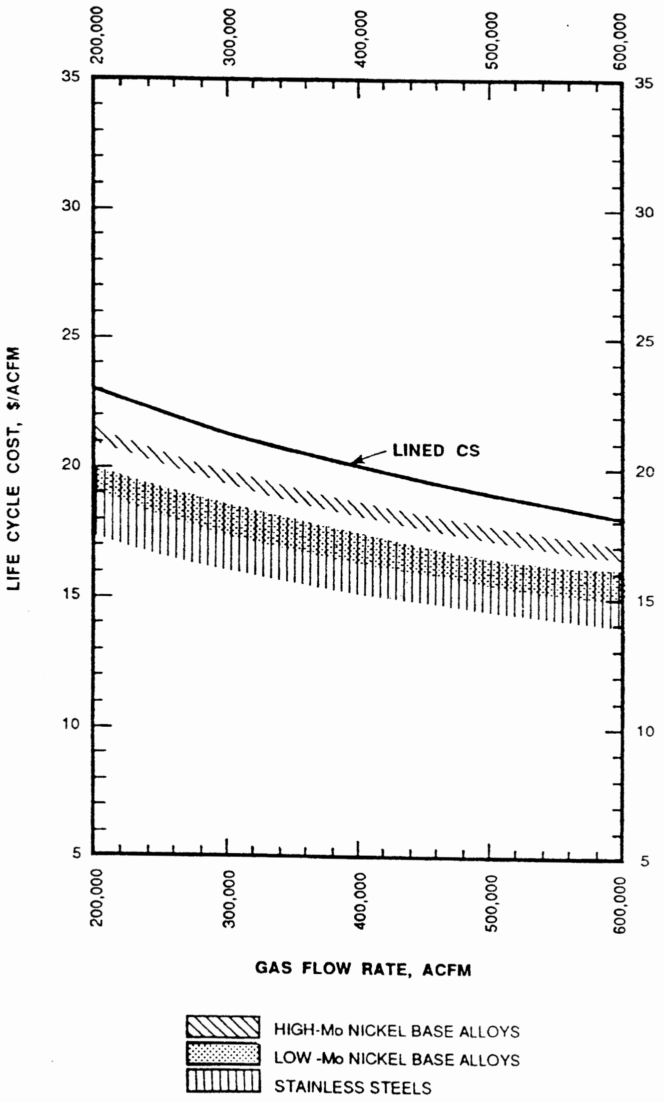


Figure 3
Life-cycle cost comparison, alloy-clad venturi.
(1000 acfm = 0.472 m^3/s)

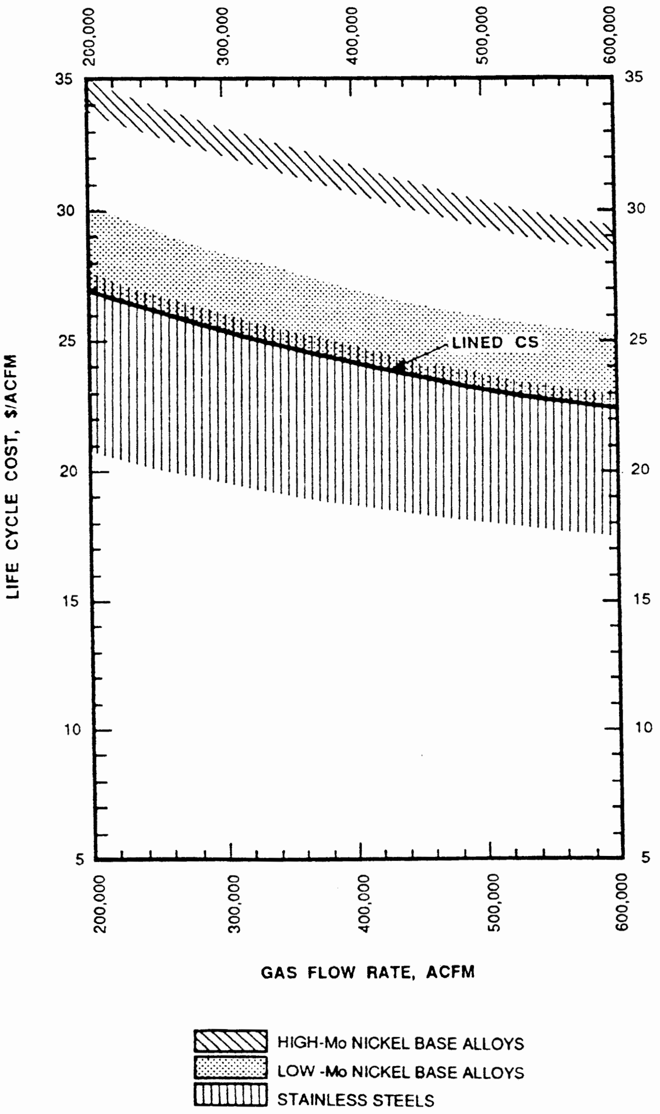


Figure 4
Life-cycle cost comparison, solid alloy absorber.
(1000 acfm = 0.472 m³/s)

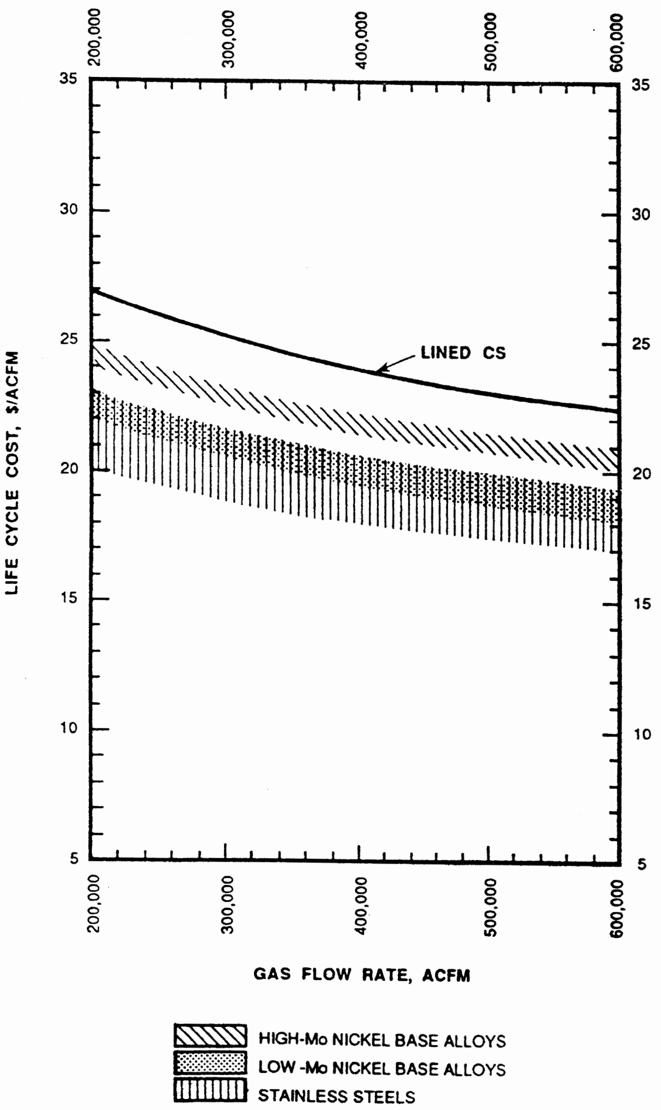


Figure 5
Life-cycle cost comparison, alloy-clad absorber.
(1000 acfm = 0.472 m³/s)

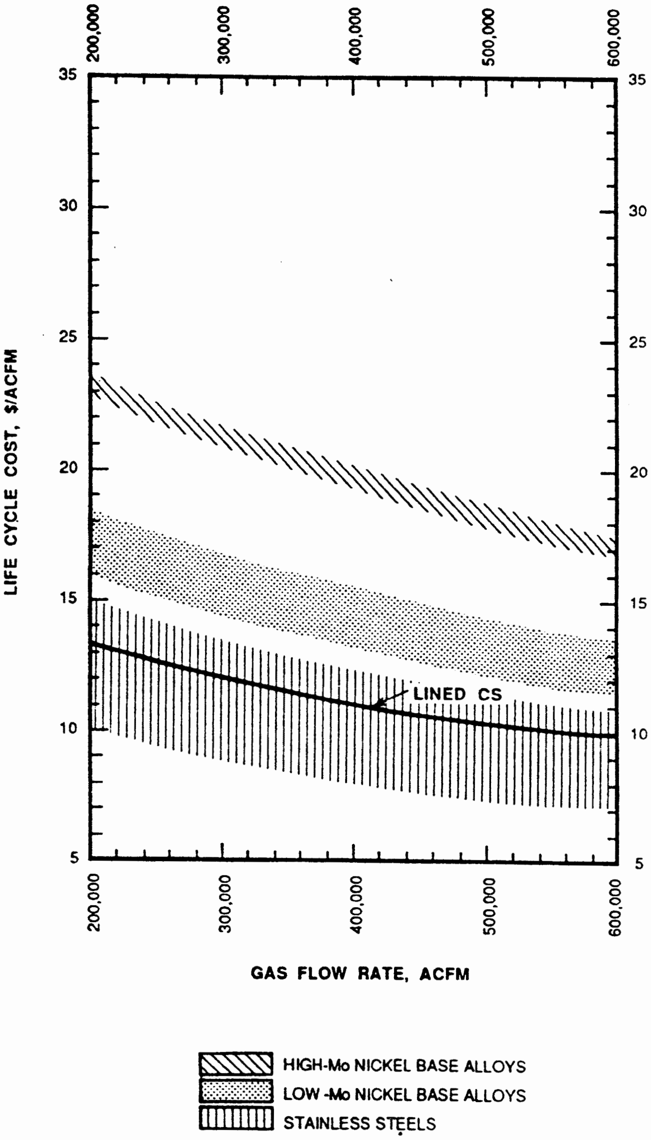


Figure 6
Life-cycle cost comparison, solid alloy ductwork.
(1000 acfm = 0.472 m^3/s)

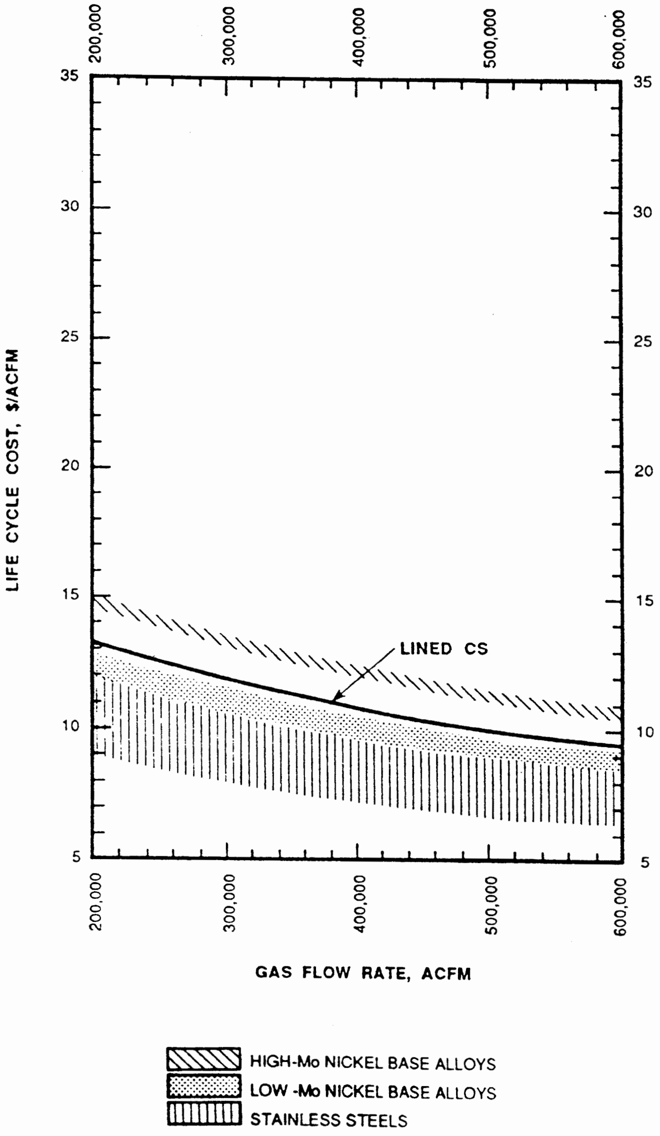


Figure 7
Life-cycle cost comparison, alloy-clad ductwork.
(1000 acfm = 0.472 m^3/s)

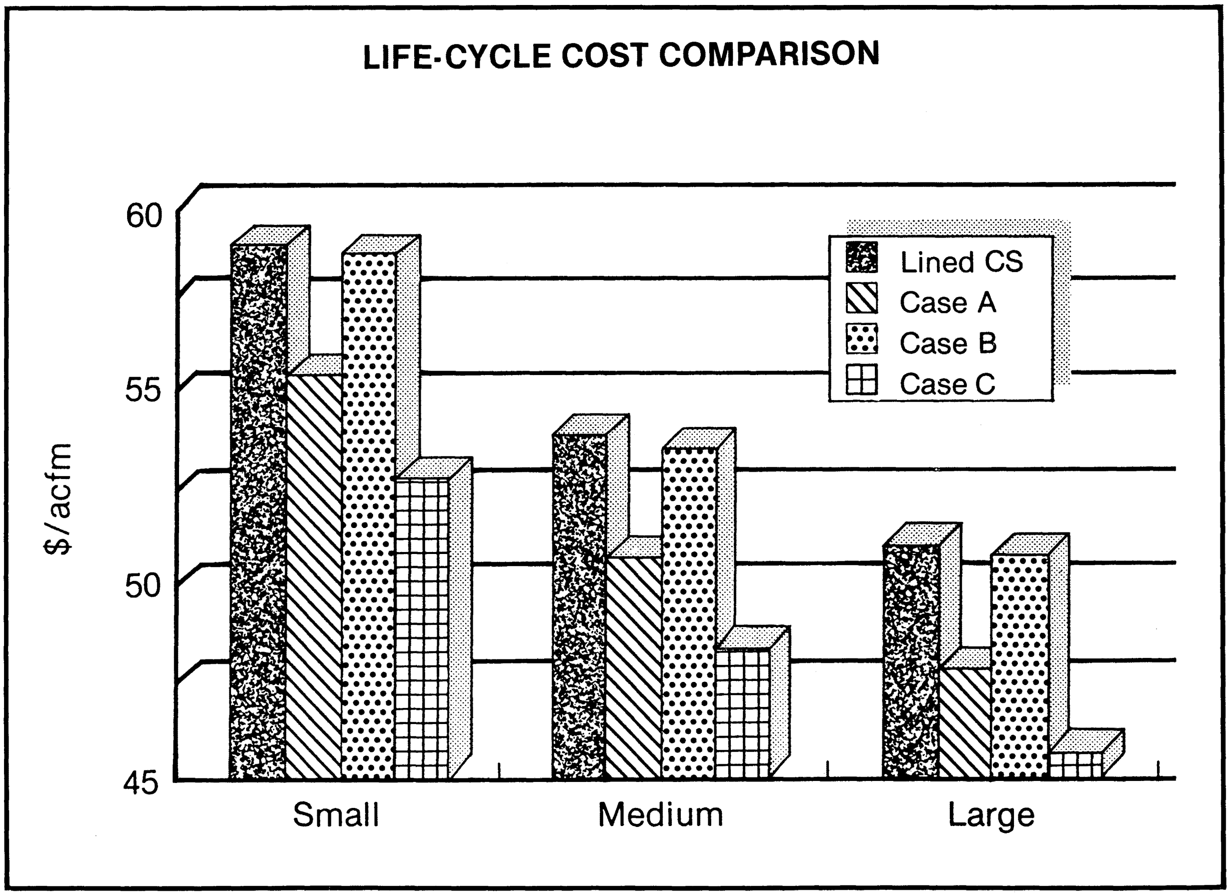


Figure 8
Life-cycle cost comparison, combined systems.
(1000 acfm = 0.472 m^3/s)

Table 1

COMPOSITIONS OF CORROSION RESISTANT MATERIALS

UNS* No.	Alloy	Nominal composition, weight percent								
		Ni	Mo	Cr	Fe	Cu	W	Cb	N	C, max. %
S31603	S.S. 316L	10	2	16	70	—	—	—	0.05	0.030
S31725	S.S. 317LM	15.5	4	18.5	62	—	—	—	0.06	0.02
N06625	Alloy 625	61	9	22	3	—	—	4	—	0.10
N08825	Alloy 825	42	3	22	30	2	—	—	—	0.05
N08904	Alloy 904L	25	5	21	45	2	—	—	—	0.020
N06007	Alloy G	44	7	22	20	2	1	2	—	0.05
N10276	Alloy C-276	56	16	16	5	—	3.5	—	—	0.010
S31254	Alloy 254 SMO	18	6.1	20	Bal.	0.7	—	—	0.20	0.020
S32550	Duplex Alloy 255	6	3	25.5	Bal.	2	—	—	0.20	0.04
N08026	Alloy 20Mo-6	34	6	23	Bal.	3	—	—	0.10	0.03
N08020	Alloy 20Cb-3	34	2	20	Bal.	3.5	—	0.5	—	0.07
N06022	Alloy C-22	Bal.	13	22	3	—	3	—	—	0.010

* UNS, Unified Numbering System

Table 2

LIFE-CYCLE COSTING BASES AND ASSUMPTIONS

Capital cost	Initial turnkey cost of the component; includes equipment, installation, and indirect costs
Major maintenance	For neoprene-lined carbon steel (baseline) components only: — Liner replacement every five years — No major maintenance for high-alloy systems
Routine maintenance	12 percent/year of capital cost for neoprene-lined carbon systems 6 to 10 percent for other solid-alloy constructions, and for all alloy-clad systems. (Routine maintenance for ductwork = one third of above values)
Annual insurance and miscellaneous	Two percent of capital cost
Depreciation tax credit	Based on a depreciation period of five years and straight-line depreciation method. Tax credit equals 38 percent of depreciation.
Operating labor, raw materials, and utilities	Assumed to be independent of material of construction and not included in the life-cycle costs.
Present-worth basis	Constant dollars
Discount rate	6.1 percent (constant dollar basis)
System life	30 years

Table 3

ESTIMATED MATERIAL COST FACTORS

Neoprene-lined carbon steel	1.0
Type 316L	1.0
Type 317LM	1.4
Alloy 904L	1.9
Duplex Alloy 255	2.0
Alloy 254 SMO	2.6
Alloy 825	3.0
Alloy 20Cb-3	3.0
Alloy G	3.8
Alloy 20Mo-6	3.8
Alloy 625	5.3
Alloy C-276	5.6
Alloy C-22	5.6

Table 4

COMBINED SYSTEM CONFIGURATION DETAILS

	SCRUBBER	ABSORBER	DUCTWORK
Base case	Lined carbon steel	Lined carbon steel	Lined carbon steel
Case A	20% solid C-276 80% clad C-276	100% clad 254 SM0	100% clad Alloy G
Case B	100% solid 625	100% clad 904L	100% clad Alloy 825
Case C	20% solid C-276 80% clad C-276	100% clad 904L	100% clad Alloy 825