Evaluation of repowering in a gas fired steam power plant based on exergy and exergoeconomic analysis

Mohammad Baghestani[1], Masoud Ziabasharhagh [1*], Mohammad Hasan Khoshgoftar Manesh[1]

[1]*Mechanical Engineering Faculty K.N.Toosi University of Technology, Tehran, Iran*
** Corresponding author. Tel: +982184063255, E-mail: mzia@kntu.ac.ir*

Abstract: Increased competition among power generating companies, changes in generating system load requirements, lower allowable plant emissions, and changes in fuel availability and cost accentuate the need to closely assess the economics and performance of older electric generating units. Generally, decisions must be made as to whether these units should be retired and replaced with new generation capacity, whether capacity should be purchased from other generation companies, or if these existing units should be repowered. These decisions usually require the evaluation of many factors. The analysis is usually complicated due to the interaction of all the factors involved. In this paper, evaluation of a 156MW steam power plant and proposed repowered scenario has been performed. The exergy and exergoeconomic analysis method was applied in order to evaluate the proposed repowered plant. Simulation of each case has been performed in Thermoflow software. Also, computer code has been developed for exergy and exergoeconomic analysis. It is anticipated that the results provide insights useful to designers into the relations between the thermodynamic losses and capital costs, it also helps to demonstrate the merits of second law analysis over the more conventional first law analysis techniques.

Keywords: *Repowering; Combined cycles; Gas turbines; Steam injection*

Nomenclature

c	*cost per unit exergy ($/MW)*	*($/MW)*
C	*cost flow rate*	*($/hr)*
e	*exergy rate per mass*	*(MW/kg)*
E	*specific exergy*	*(MW)*
Z	*capital cost rate of unit*	*($/hr)*
GT	*gas turbine*	
CRF	*capital recovery factor*	
PWF	*Present worth factor*	
LHV	*Lower heating value*	
PW	*Present worth*	

1. Introduction

Deregulation and competition are further fueling the demand for new power generation equipment worldwide. Due to the availability and cleanliness of gas, and the ease of consent, gas turbine applications have increased over the last few years. This development is driven by the addition of capacity, but also by major replacement programs.[1] Almost all industrialized countries are now facing some degree of electric power shortage. The major problem is probably the lack of suitable sites for building new power plants of whatever type or size. Moreover, increasing environmental awareness has resulted in more demanding requirements in terms of preliminary analysis, prolonging and complicating the plant commissioning process. All these problems have led many utilities to consider extending the life of existing plants by repowering. Basically, these interventions have been done on gas fired steam plants by addition of a natural gas fired turbine. This reduces specific emissions of the existing steam plant while maintaining or even slightly improving its efficiency. As a rule, a repowered plant can be expected to give a lower cost per kW h produced as well as per kW installed repowering of steam plants can be achieved in two ways: feed water repowering and boiler repowering. The first option uses heat from the turbine exhaust to raise the feed water temperature instead of bleeding steam. This means that increased steam flow has to be managed by the low pressure section of the original steam turbine, requiring either extensive modification of the steam turbine or impairing the repowered plant performance. The other option, boiler repowering, entails major steam generator redesign[2]. Energy systems involve a large number and various types of interactions with the world outside their physical boundaries. The designer must, therefore, face many issues, which deal primarily with the energetic and economic aspects of the system. Thermodynamic laws govern energy conversion processes, costs are involved in obtaining the final products (expenses for the purchase of equipment and input energy resources, operation and maintenance costs), and the effects of undesired fluxes to the ambient must be evaluated in order to answer environmental concerns. Second law analysis has been widely used in the last several decades by many researchers. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components [3]. Furthermore, exergoeconomic analysis estimates the unit cost of products such as electricity, steam and quantifies monetary loss due to irreversibility. Also, this analysis provides a tool for the optimum design and operation of complex thermal systems [3], [4], [5].

In this study, exergetic, thermoeconomic and exergy analyses have been performed for 156MW steam cycle and repowered gas fired steam power plants. In these analyses, mass and energy conservation laws were applied to each component. Quantitative balance of the exergies and exergy costs for each component and for the whole system was carefully considered. The exergy-balance equation developed by Oh et al. [6] and the corresponding exergy cost-balance equations developed by Kimet al. [7] were used in these analyses. In this regard, computer program has been developed for energy, exergy, exergoeconomic and exergy analysis of both of cases in different load conditions. Furthermore, it can also used to study plant characteristics, namely, thermodynamic performance and sensitivity to changes in process and/or component design variables. In this paper, the authors evaluate and compare repowered power planet and steam power plants in view of exergy and thermoeconomic analysis.

2 Process description

In this paper, GHAZVIN steam cycle power plant has repowered and compared with old steam cycle. The steam cycle power plant encompasses three turbines, that work with three different pressures and 6 feed water heaters. The Steam cycle has been modeled by MATLAB code and STEAM PRO (THERMOFLOW). Results of modeling steam cycle have been introduced and compared with real data in table.1.

Table1. Compare result of modeling steam cycle

	THERMOFLOW	Simulation code	Real
Plant Gross power(kW)	156300	156305	156294
Plant Gross Heat Rate(kJ/kWh)	9010	9120	8976
Plant Gross Efficiency (LHV)	39.9%	39.4%	40.1%
Superheater Capacity(kg/s)	133	130	136
Reheater Capacity(kg/s)	115	114	117

3. Repowering

There are several alternatives to combine and integrate a gas turbine into an existing steam power plant. For 156MW steam power plant unit in Iran, the best alternative is full repowering because its boiler is very old and boiler life time is concluded. Full repowering is defined as complete replacement of the original boiler with a combination of one or more gas turbines (GT) and heat-recovery steam generators (HRSG), and is widely used with very old

plants with boilers at the end of their lifetime. It is considered as one of the simplest ways of repowering for existing plant.
For this power plant, Full Repowering with SGT5-4000F (formerly known as CC 2.V94.3A) with triple pressure reheat cycle was found to be the most economic approach.
Schematic flow diagram of combined cycle with the components is shown in Fig. 2. The gas cycle is selected as a topping cycle. The heating devices in the HRSG are arranged from the high temperature (HT) to the low temperature (LT) exchangers in the flue gas path to get the minimum temperature difference between the flue gas and the water/steam.

4. Exergoeconomic Analysis

All costs due to owning and operating a plant depend on the type of financing, the required capital, the expected life of a component, and so on. The annualized (levelized) cost method of Moran [9] was used to estimate the capital cost of system components in this study. The amortization cost for a particular plant component may be written as:

$$PW = C_i - S_n PWF(i,n) \tag{1}$$

$$\dot{C}(\$/year) = PW \times CRF(i,n) \tag{2}$$

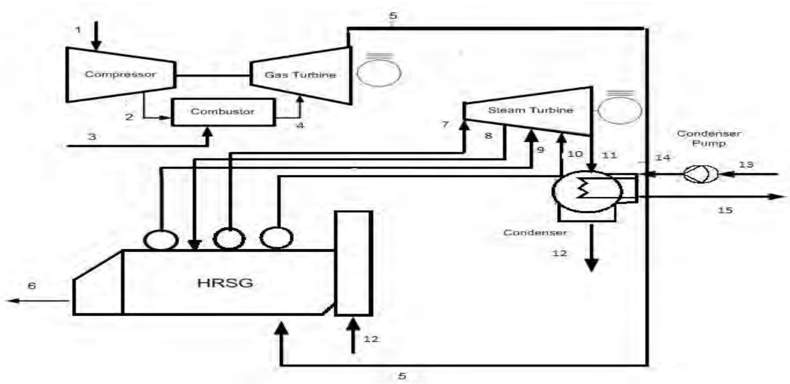

Fig 1.- combined cycle power plant

The present worth of the component is converted to annualized cost by using the capital recovery factor CRF(i,n), i.e [4]. Dividing the levelized cost by 8000 annual operating hours, we obtain the following capital cost for the kth component of the plant.

$$Z_k = \Phi_k \dot{C}_k / (3600 \times 8000) \tag{3}$$

The maintenance cost is taken into consideration through the factor $\Phi_k = 1.06$ for each plant component whose expected life is assumed to be 15 years [6].

4.1 Thermoeconomic Modeling

The results from an exergy analysis constitute a unique base for exergoeconomics, an exergy-aided cost reduction method. A general exergy-balance equation, applicable to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics [4].
The cost balance expresses that the cost rate associated with the product of the system (C_P), the cost rates equals the total rate of expenditure made to generate the product, namely the fuel cost rate (C_F), the cost rates associated with capital investment (Z^{CI}), operating and

maintenance (Z^{OM}) [12].In a conventional economic analysis, a cost balance is usually formulated for the overall system (subscript tot) operating at steady state [11]:

$$C_{P,tot} = C_{F,tot} + Z_{tot}$$
(4)

Accordingly, for a component receiving a heat transfer and generating power, we would write [4]:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} - \sum_i \dot{C}_{i,k} + Z_k$$
(5)

To solve for the unknown variables, it is necessary to develop a system of equations applying Eq. (5) to each component, and it some cases we need to apply some additional equations, to fit the number of unknown variables with the number of equations [12]. A general exergy-balance equation, able to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics. In a conventional economic analysis a cost balance is usually formulated for the overall system operating at steady state. To derive the cost balance equation for each component, we assigned a unit cost to the principal product for each component. Depending on the type of fuel consumed in the production process different unit cost of product should be assigned [13].

Table2. Combined cycle results

	Repowering
Gas Turbine(kW)	278041
Steam Turbine(kW)	125655
Plant Total (kW)	403695
Plant net LHV efficiency (%)	55.27
Plant net LHV heat rate(kJ/kWh)	6514
Gas turbine LHV efficiency (%)	39.05
Steam turbine efficiency (%)	34.59

5. Results and discussion

In this paper, computer codes have been developed for thermodynamic simulation and analysis of 156-MW old steam cycle and 400-MW repowered combined power plants. The enthalpy and entropy of non-interacting gas species were calculated by using appropriate polynomials fitted to the thermophysical data in the JANAF Tables [14]. Also the values of physical properties such as enthalpy and entropy for water and steam were evaluated by using equations suggested by the International Association for the Properties of Water and Steam IAPWS-IF97) [14].
Table 2 indicates specification of repowered plant. It shows that, 68% of total power is produced by gas turbine cycle with 39% efficiency, in addition remained power are produced by steam cycle with 34% overall efficiency. Repowered cycle produces 250MW more than old power plant. Heat rate in repowering power plant is 6500(KJ/KWh) and 1500(KJ/KWh) more than old power plant. As a result of repowering, overall efficiency rises 15% and new power plant produce net power with less reduction of energy. The combined cycle results have been developed for gas turbine partial load. Load condition varied from 30% to 100% of full load and figure 2 presents load variation and net power of cycles. Further, entire rate of

exergy destruction has been shown in this figure. However full load has the most exergy destruction, ratio of exregy destruction to supplied energy is less than partial load. In figure 3 efficiency of combined cycle accompaniment gas turbine cycle and steam cycle exhibited. Gas turbine efficiency severely depends on design load and it is decreased when works at partial load states. Since supplied energy for steam cycle depends on exit flow stream of gas turbine, steam cycle efficiency is just independent of load condition. Combined cycle efficiency varied from 40% to 55% and deteriorates with variation from design load.

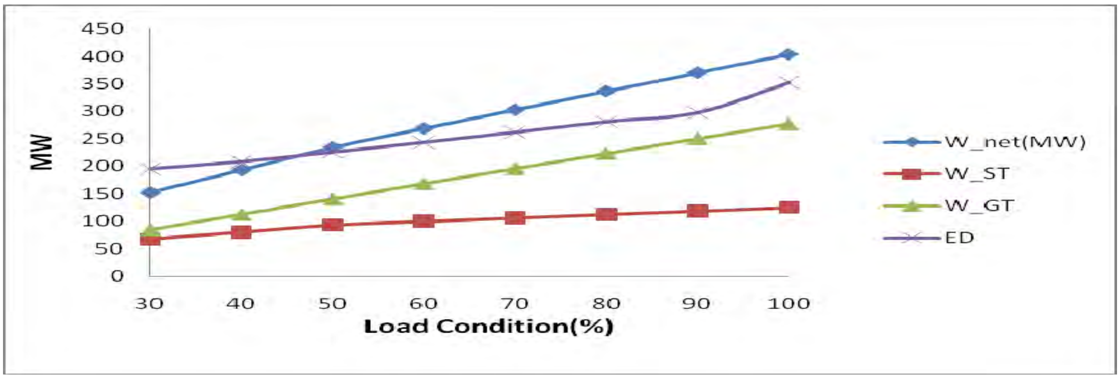

Fig 2. Variation of output power

In this regard, exergy flow and cost flow rates of exergy with and without considering capital investment for each stream in old power plant and repowering plant have been calculated. Also, Table 3 and 4 show Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in old and repowered power plants. These results represent that boiler in old steam power plant and that combustion chamber and heat recovery steam generator in repowered combined cycle has most exergy and exergy cost destruction due to nature of combustion; however combustor in gas fired combined cycle plant shares about 51% TED, 44% TCD0 and 43% TCD. In next steps, compressor and steam generator of repowered have most exergy and exergy cost destruction. Cost product of steam turbine and gas turbine for combined cycle with and without considering capital investment at various load conditions has been presented in figure 4. As results shown, CP_0 and CP increase when load condition reduces because the thermal efficiency decreases. Therefore full load has the best and minimum cost product. In figure 5 rate of total cost exergy destruction has been shown at different load. As results shown, TCD0 and TCD0 reduce when load condition decreases and vice versa because the fuel consumption decreases when load condition reduces and vice versa, so TCD0 and TCD have direct relation with load conditions. In steam cycle power plant 430 MW exergy is destructed and more than 85% of exergy destruction happened in boiler. However combined cycle produced 250 MW net power more than steam cycle, Total exergy destruction in combined cycle is 296 MW and 70% of steam cycle exergy destruction. Since cost product of gas turbine in combined cycle is less than steam turbine and majority of output power produced with gas turbine, combined cycle cost product is reasonable. Therefore repowered power plant generated more power than old power plant with recuperated efficiency and more reasonable cost product.

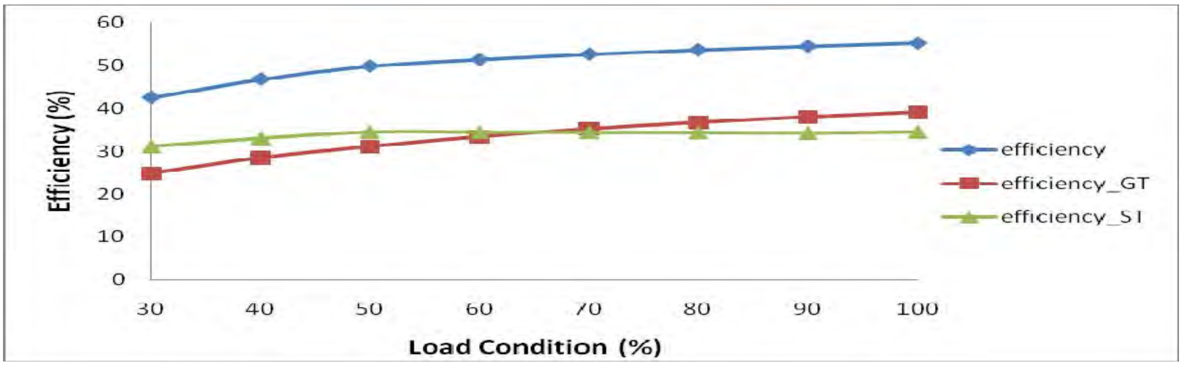

Fig 3. Partial load efficiency

Table 3. Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in steam cycle power plant

Component	Exergy Destruction	CF0 ($/MW)	CP0 ($/M	CD0 ($.s)	CF ($/MW)	CP ($/MW	CD ($/s)
FWH1	1.2437	0.0054	0.0086	0.0067	0.0056	0.009	0.0069
FWH2	0.3984	0.0054	0.0059	0.0021	0.0056	0.0062	0.0022
FWH3	0.3295	0.0054	0.0399	0.0017	0.0056	0.0414	0.0018
FWH4	0.5141	0.0187	0.0193	0.0096	0.0196	0.0203	0.0100
FWH5	0.539	0.0055	0.0062	0.0029	0.0057	0.0065	0.0030
FWH6	0.5659	0.0057	0.006	0.0032	0.0059	0.0064	0.0033
CONDENSER	6.0506	0.0054	0.0103	0.0326	0.0056	0.0109	0.0338
LP St Turbine	9.1386	0.0057	0.0068	0.0520	0.0059	0.0072	0.0539
IP St Turbine	2.4625	0.0054	0.0056	0.0132	0.0056	0.0059	0.0137
HP St Turbine	18.5699	0.0054	0.0061	0.1002	0.0056	0.0064	0.1039
Boiler	388.9632	0.0014	0.0043	0.5445	0.0014	0.0044	0.5445
CP	0.3484	0.003	0.0038	0.0010	0.0031	0.004	0.0010
FPT	1.3422	0.003	0.0042	0.0040	0.0032	0.0045	0.0042

6. Conclusion

In this paper, an exergy-costing method has been applied to both cases to estimate the unit costs of electricity produced from steam turbines. The computer program that was developed which shows that the exergy and the thermoeconomic analysis presented here can be applied to any energy system systematically and elegantly. If correct information on the initial investments, salvage values and maintenance costs for each component can be supplied, the unit cost of products can be evaluated.

Table 4. Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in repowered power plant

Component	Exergy Destruction(MW)	CF0 ($/MW)	CP0 ($/MW)	CD0 ($.s)	CF ($/MW)	CP ($/MW)	CD ($/s)
COMP	46.2489	0.0061	0.0073	0.2821	0.0064	0.0078	0.2959
COMB	152.5663	0.0049	0.0059	0.7475	0.0051	0.0061	0.7780
GT	17.0101	0.0059	0.0061	0.1003	0.0061	0.0064	0.1037
ST	36.2881	0.0083	0.0092	0.3011	0.0089	0.0101	0.3229
HRSG	38.6824	0.0063	0.0073	0.2436	0.0065	0.0078	0.2514
COND	4.8385	0.0083	0.2376	0.0401	0.0083	0.2603	0.0401
FWP	0.0236	0.0064	0.0113	0.0001	0.0064	0.0177	0.0001
CWP	0.6226	0.0064	0.0006	0.0039	0.0064	0.0007	0.0039

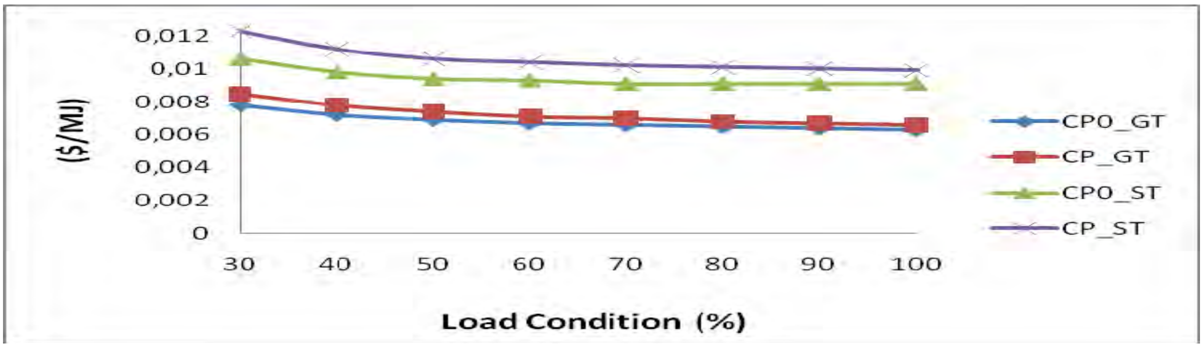

Fig4. C_p and C_{P0} of repowered power plants at different loads

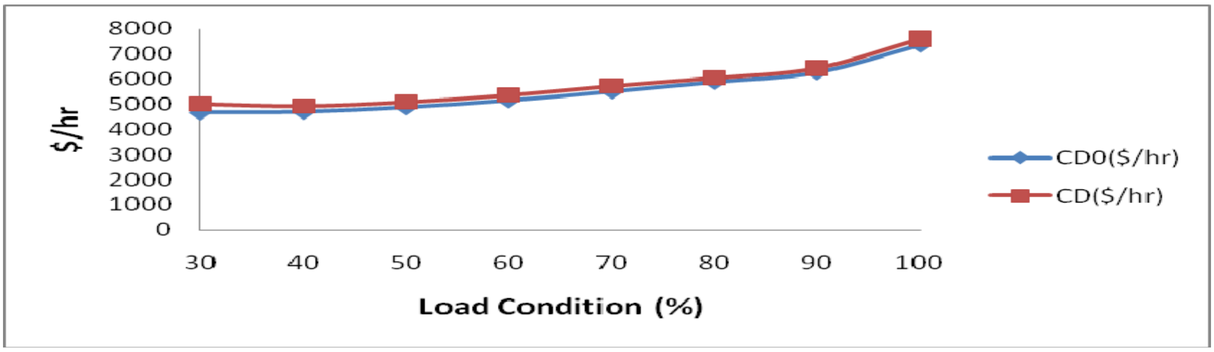

Fig 5.CD, CD_0 of repowered power plants at different load

Although the overall picture of a system can be shown and major directions for improving the system performance can be identified from the above two levels of analysis, the maximum potential or the limit of improvement for individual units and processes are still uncertain, since the exergy loss analysis so far is based on the concept of total exergy loss. In some cases, the suggestions for promising modifications based on the total exergy loss may be misleading, since they do not consider the minimum exergy loss which is required to operate a process.

References

[1] M.Frankle. The standardized repowering solution for 300 MW steam power plants in Russia. Siemens AG 2006.

[2] R.carapellucci, A.Milazzo. Repowering combined cycle power plant by a modified STIG configuration . Energy Conversion and Management 48 (2007) 1590–1600.

[3] Sanjay Y, Singh O, Prasad BN. Energy and exergy analysis of steam cooled reheat gas–steam combined cycle. *Applied Thermal Engineering* 2007; 27: 2779–2790.

[4] Chao Z, Yan W. Exergy cost analysis of a coal fired power plant based on structural theory of thermoeconomics. *Energy Conversion and Management* 2006; 47:817–843.

[5] Modesto M, Nebra SA. Analysis of a repowering proposal to the power generation system of a steel mill plant through the exergetic cost method, *Energy* 2006; 31: 3261–3277.

[6] Cziesla F. Produktkostenminimierung beim Entwurf komplexer Energieumwandlungsanlagen mit Hilfe von wissensbasierten Methoden, no. 438 in Fortschr. -Ber. VDI, Reihe 6, VDI Verlag, D¨usseldorf, 2000.

[7] Cziesla F, Tsatsaronis G. Iterative exergoeconomic evaluation and improvement of thermal power plants using fuzzy inference systems. *Energy Conversion and Management* 2002; 43: 1537–1548.

[8] Uhlenbruck S, Lucas K. Exergoeconomically-aided evolution strategy applied to a combined cycle power plant. *International Journal of Thermal Science* 2004; 43: 289–296.

[9] Bejan A, Tsatsaronis G, Moran M. Thermal design and optimization. New York: Wiley; 1996.

[10] Dobrowolski R, Witkowski A, Leithner R, Simulation and optimization of power plant cycles, in: G. satsaronis, M. Moran F. Cziesla T. Bruckner (Eds.), ECOS 2002, Proceedings of the 15th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems, Berlin, Germany, 2002, pp. 766–772.

[11] Nafey AS, Fath HES, Mabrouk AA. Exergy and thermoeconomic evaluation of MSF process using a new visual package. *Desalination 2006;* 201: 224-240.

[12] Dobrowolski R, Witkowski A, Leithner R. Simulation and optimization of power plant cycles. ECOS 2002, Proceedings of the 15th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems, Berlin, Germany, 2002, pp. 766–772.

[13] Emmerich M, Grotzner M, Schutz M. Design of graph-based evolutionary algorithms: A case study for chemical process networks. Evolutionary Computation 2001; 9 (3): 329–354.

[14] Joint Army-Navy–Air Force Thermochemical Tables. NSRDS-N3537, Washington, DC: National Bureau of Standard Publications; 1985.