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Solar Thermal Power Systems Project
Parabolic Dish Systems Development

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A Program for the Calculation of Paraboloidal-Dish Solar Thermal Power Plant Performance

J.M. Bowyer, Jr.

April 15, 1985

Prepared for
U.S. Department of Energy
Through an Agreement with
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Jet Propulsion Laboratory
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The JPL Solar Thermal Power Systems Project is sponsored by the U.S. Department of Energy and is part of the Solar Thermal Program to develop low-cost solar thermal and electric power plants.

ABSTRACT

A program capable of calculating the design-point and quasi-steady-state annual performance of a paraboloidal-concentrator solar thermal power plant without energy storage has been written for a programmable calculator equipped with suitable printer. The power plant may be located at any site for which a histogram of annual direct normal insolation is available.

Inputs required by the program are aperture area and the design and annual efficiencies of the concentrator; the intercept factor and apparent absorptance of the receiver aperture, and the receiver heat loss; the design efficiency of the power conversion subsystem and a polynomial representation of its normalized part-load efficiency; the efficiency of the electrical generator or alternator; the efficiency of the electric power conditioning and transport subsystem; and the fractional parasitic losses for the plant. (Losses to auxiliaries associated with each individual module are to be deducted when the power conversion subsystem efficiencies are calculated.)

Outputs provided by the program are the system design efficiency, the annualized receiver efficiency, the annualized power conversion subsystem efficiency, the total annual direct normal insolation received per unit area of concentrator aperture, and the system annual efficiency.

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Tables

SECTION I

INTRODUCTION

A program capable of calculating the design-point and quasi-steady-state annual performance of a paraboloidal-concentrator solar thermal power plant operating without energy storage is described in this report. The program has been written for a programmable calculator equipped with a suitable printer, viz., the Texas Instruments TI-59 with PC-100C. For computational purposes, the power plant may be located at any site for which a suitable histogram of annual direct normal insolation is available.

Inputs required by the program are the design and annual efficiencies of the concentrator; the intercept factor and apparent absorptance of the receiver aperture, and the receiver heat loss per unit area of concentrator aperture; the design efficiency of the power conversion subsystem and a polynomial representation of its normalized part-load efficiency; the efficiency of the electrical generator or alternator; the efficiency of the electric power conditioning and transport subsystem; and the fractional parasitic losses for the plant. (Losses to auxiliaries associated with each individual module are to be deducted when the power conversion subsystem efficiencies are calculated.)

Outputs provided by the program are the system design efficiency, the annualized receiver efficiency, the annualized power conversion subsystem efficiency, the total annual direct normal insolation received per unit area of concentrator aperture, and the system annual efficiency. In addition, pertinent performance data for the concentrator, receiver, and power conversion subsystems, and for the entire system are output at each of the twenty-one median values of direct normal insolation included in the histogram (0.025, 0.075, . . ., 0.975, 1.025 kW/m^2).

Input parameters required for the calculation of paraboloidal-dish solar thermal power plant performance, together with supporting explanatory notes, can be entered into a form such as the one presented in Table 1. This form also provides spaces for listing all the design and annual performance data pertinent to a given configuration operating under given design and annual insolation conditions.

The input and output variables and a description of the program and corresponding equations are presented in Section II, Description of the Problem and Its Solution. A flow chart and thoroughly annotated program listing are included in Appendixes A and B, respectively.

A sample problem statement and corresponding solution are presented in Section III, Sample Problem and Solution; input data for the sample problem are included in Appendix C.

Section IV, entitled User Instructions, provides step-by-step instructions for using the program.

Section V provides the concluding remarks.

Table 1. Performance Summary Input Data Form

Technology: ____________________

Time Frame: ____________

Design Direct Normal Insolation: _____ kW/m^2

Geographic Location: ____________________

Annual Direct Normal Insolation: _____ $kWh/m^2/y$

	Performance: Design Point	Performance: Annual
Concentrator		
Design Parameters		
Aperture area (m^2)	______	
Reflectivity	______	
Blocking	(a) ______	
Efficiency	______	
Annual Operating Parameters		
Degradation		(b) ______
Shading		(c) ______
Efficiency		______
Receiver		
Design Parameters		
Aperture area (m^2)	(d) ______	
Temperature of the thermodynamic medium at the receiver outlet (°F)	(e) ______	
Intercept Factor	______	
Conduction loss (kW_t/m^2)	______	
Convection loss (kW_t/m^2)	______	
Reradiation loss (kW_t/m^2)	(f) ______	
Combined losses (kW_t/m^2)	______	
Efficiency	______	
Annual Operating Parameters		
Efficiency		(g) ______
Thermal Transport		
Design Efficiency	(h) ______	
Annual Efficiency		______
Power Conversion Efficiency		
Design Parameters		
Heat Engine Efficiency	______	
Generator Efficiency	______	
Power Conversion System Efficiency	______	
Annual Power Conversion System Efficiency		(i) ______
Power Conditioning and Transport Efficiency	______	______
1 - (Fractional Parasitic Losses)	______	______
System Performance		
Design Parameters		
Receiver Output Thermal Power (kW_t)	______	
Electric Power Output (kW_e)	______	
Efficiency	______	
Annual Performance		
Efficiency		(j) ______

Notes are presented on the following page.

Table 1. (Cont'd): Notes on the Performance Summary Input Data Form

(a) The power conversion assembly package and its supporting struts block insolation that would otherwise fall on the concentrator. This blocking reduces the performance of the concentrator.

(b) Between cleanings, the design reflectivity of the concentrator mirrors is degraded by the gradual accumulation of dust on the first surface of the mirror panels but is virtually completely restored by proper cleaning.

(c) The annual performance of the usual optimal concentrator field is degraded by the shading of some concentrators by others at times considerably removed from solar noon. This is particularly true during the winter.

(d) The apparent absorptance for concentrated insolation of the receiver apertures considered here is assumed to differ negligibly from unity.

(e) The maximum bulk temperature achieved by the thermodynamic medium as it moves through the complete cycle is noted here.

(f) Thermal energy is lost from the receiver through the parallel paths of (1) reradiation through the aperture, (2) direct convection at the aperture, and (3) conduction through the body and/or supports of the receiver followed by convection from the surface of the receiver body. One minus the sum of these losses (expressed as fractions of energy entering the receiver cavity) represents the transfer factor for energy entering the receiver aperture.

(g) Receiver annual efficiency is affected by the insolation histogram employed, even in the case of a non-storage system.

(h) Because the receiver and thermodynamic engine subsystems are closely coupled in a point-focusing thermodynamic power module, the module's thermal transport efficiency differs negligibly from unity. Annual thermal transport efficiency is assumed equal to the design thermal transport efficiency.

(i) Power conversion annual efficiency is affected by the insolation histogram employed, even in the case of a non-storage system.

(j) Annual system efficiency is a function of both receiver and power conversion annual efficiencies and thus is affected by the insolation histogram employed, even in the case of a non-storage system.

SECTION II

DESCRIPTION OF THE PROBLEM AND ITS SOLUTION

A. INPUT VARIABLES (All in Segment No. 1)

Algebraic Variable	Acronym	Definition
I_{DND}	IDND	Design level of direct normal insolation (often assumed to be 0.8 or 1.0 kW/m^2).
η_{CD}	HCD	Design efficiency of the concentrator.
η_C	HC	Annual average efficiency of the concentrator (degraded by mirror soiling and by the mutual shading of grouped concentrators).
Q_{RL}	QRL	Receiver combined thermal loss in kW_t/m^2 of concentrator area projected onto the concentrator aperture plane.
ϕ	FSBS	Intercept factor of the receiver aperture, i.e., the fraction of concentrated solar radiation falling on the aperture plane of the receiver that passes through the aperture.
α	ALPH	Apparent absorptivity of the receiver aperture for the concentrated insolation incident on it.
η_{PD}	HPD	Design efficiency of the engine.
a_n	ANPS	The degree of the polynomial representation must be no greater than 6.
	NOTE:	PPX-59 Professional Program 208008 Polynomial Regression by T. H. Wysmuller has been most useful in evaluating the required polynomial coefficients from graphs of normalized power conversion efficiency as a function of normalized input thermal power.
η_{EGT}	HEGT	Efficiency of the combined electrical generator, and transport and power conditioning subsystems.
η_P	HPAR	Correction factor by which the gross output of the power plant must be multiplied in order to account for losses due to plant auxiliary equipment, office and control room space conditioning, etc.

Algebraic Variable	Acronym	Definition
I_{DN}	IDN	Actual level of direct normal insolation at which performance is to be determined (kW/m^2).
H	HRS	Annual total hours of direct normal insolation at intensity centered at I_{DN} ($\Delta I_{DN} = 0.05\ kW/m^2$).
N	NPOL	Degree of the polynomial representing the normalized power conversion subsystem efficiency. $0 \leq N \leq 6$ (Integer).

B. OUTPUT VARIABLES

1. In Segment No. 1

Algebraic Variable	Acronym	Definition
η_{CD}	HCD	Concentrator design efficiency (an input variable).
η_{RD}	HRD	Receiver design efficiency.
η_{PD}	HPD	Power conversion subsystem design efficiency defined as thermal input to electrical generator output (an input variable).
η_{EP}	HEP	Efficiency of electrical power conditioning and transport including an allowance for module or plant parasitic power requirements.
η_{SD}	HSD	System design efficiency.

2. In Segment No. 2

Algebraic Variable	Acronym	Definition
	At each value of IDN:	
η_C	HC	Concentrator efficiency.
η_{CN}	HCN	Normalized concentrator efficiency, HC/HCD.
Q_C	QC	Concentrator photon power output per unit concentrator area (kW/m^2).
Q_{CN}	QCN	Normalized concentrator photon power output, QC/QCD. (See page 2-6 for the definition of QCD.)
η_R	HR	Receiver efficiency.

Algebraic Variable	Acronym	Definition
η_{RN}	HRN	Normalized receiver efficiency, HR/HRD.
Q_R	QR	Receiver thermal power output per unit concentrator area (kW/m^2).
Q_{RN}	QRN	Normalized receiver thermal power output, QR/QRD.
η_P	HP	Power conversion subsystem efficiency.
η_{PN}	HPN	Normalized power conversion subsystem efficiency, HP/HPD.
Q_P	QP	Power conversion subsystem electrical power output per unit concentrator area (kW/m^2).
Q_{PN}	QPN	Normalized power conversion subsystem electrical power output, QP/QPD.
η_S	HS	System efficiency.
η_{SN}	HSN	Normalized system efficiency, HS/HSD.
Q_S	QS	System electrical power output per unit concentrator area (kW/m^2).
Q_{SN}	QSN	Normalized system electrical power output, QDS/QSD.
	Annual Performance:	
η_{RA}	HRA	Annual average receiver efficiency.
η_{PA}	HPA	Annual average power conversion subsystem efficiency.
ΣE_I	ΣEI	Annual direct normal insolation [$kW/(m^2y)$].
η_{SA}	HSA	Annual average system efficiency.

C. METHOD OF SOLUTION

As indicated in both the abstract and the introduction, the program presented here has been developed to allow calculation of the design-point and quasi-steady-state annual performance of a modular solar thermal electric power plant, each module of which comprises (1) a sun-tracking, point-focusing concentrator and (2) a power conversion assembly that is mounted on the concentrator with the receiver aperture near the focal plane and on the optical axis of the concentrator. In turn, the power conversion assembly comprises a cavity receiver, a thermodynamic engine complete with auxiliaries, and an electrical generator. The electrical control and conditioning equipment directly associated with each modular power conversion assembly may be concentrator-mounted or ground-mounted, or parts of it may be concentrator-mounted and the remainder, ground-mounted. Typically, the power plant in its entirety will require additional power control and conditioning equipment to enable connection to a power grid and to supply auxiliary power to the modules, at least during start-up.

It is again emphasized that the program developed here is valid only for a power plant that has negligible energy storage capacity for either thermal or electric energy.

Another more subtle but ordinarily less important limitation of the program is that the plant power output may exceed its design value if the direct normal insolation exceeds the design value selected for this parameter. More sophisticated programs ordinarily impose the requirement that the design output of the power plant never be exceeded, wasting the excess power if necessary. However, because of TI-59 limitations in available program steps and memory cells, the author has been unable to incorporate this feature into the program presented here. If the direct normal insolation received at a given site seldom exceeds the selected design value or only exceeds it by small amounts, this limitation on the program is negligible. On the other hand, if a design direct normal insolation of 800 W/m^2 were chosen for a plant whose power conversion subsystem could accept the energy collected by the concentrator at a direct normal insolation of 1000 W/m^2 and if this plant were located in the desert Southwest, the difference in annual performance as calculated by this program and by one limiting output to the design maximum would be appreciable.

Figure 1 has been included so as to provide a graphic representation of the energy path through the power plant. Most of the direct normal insolation collected, reflected, and concentrated by the concentrator is directed to the receiver as photon energy; most of the photon energy absorbed by the receiver is transferred as thermal energy to the thermodynamic engine; the thermodynamic engine converts some of the thermal energy to mechanical energy and rejects or loses the remainder; the generator converts most of the mechanical energy to electrical energy with only slight energy dissipation; the module's electrical power control and conditioning transfers the energy to the plant control and conditioning system, again with relatively small losses; finally, the plant control and conditioning system transfers most of this energy to the electrical grid, while most of the remainder is absorbed by plant auxiliaries and the rest is dissipated.

Concentrator performance is determined in the following manner. At design conditions,

$$A_C Q_{CD} = A_C I_{DND} \rho_C F_B \qquad \text{in kW}$$

represents the photon flux transmitted to the receiver aperture plane by the concentrator at design conditions, where A_C represents the concentrator's reflecting surface area projected on the plane of the concentrator aperture, ρ_C represents mirror reflectance, and F_B represents the fraction of A_C that is blocked by the power conversion assembly package and its supporting

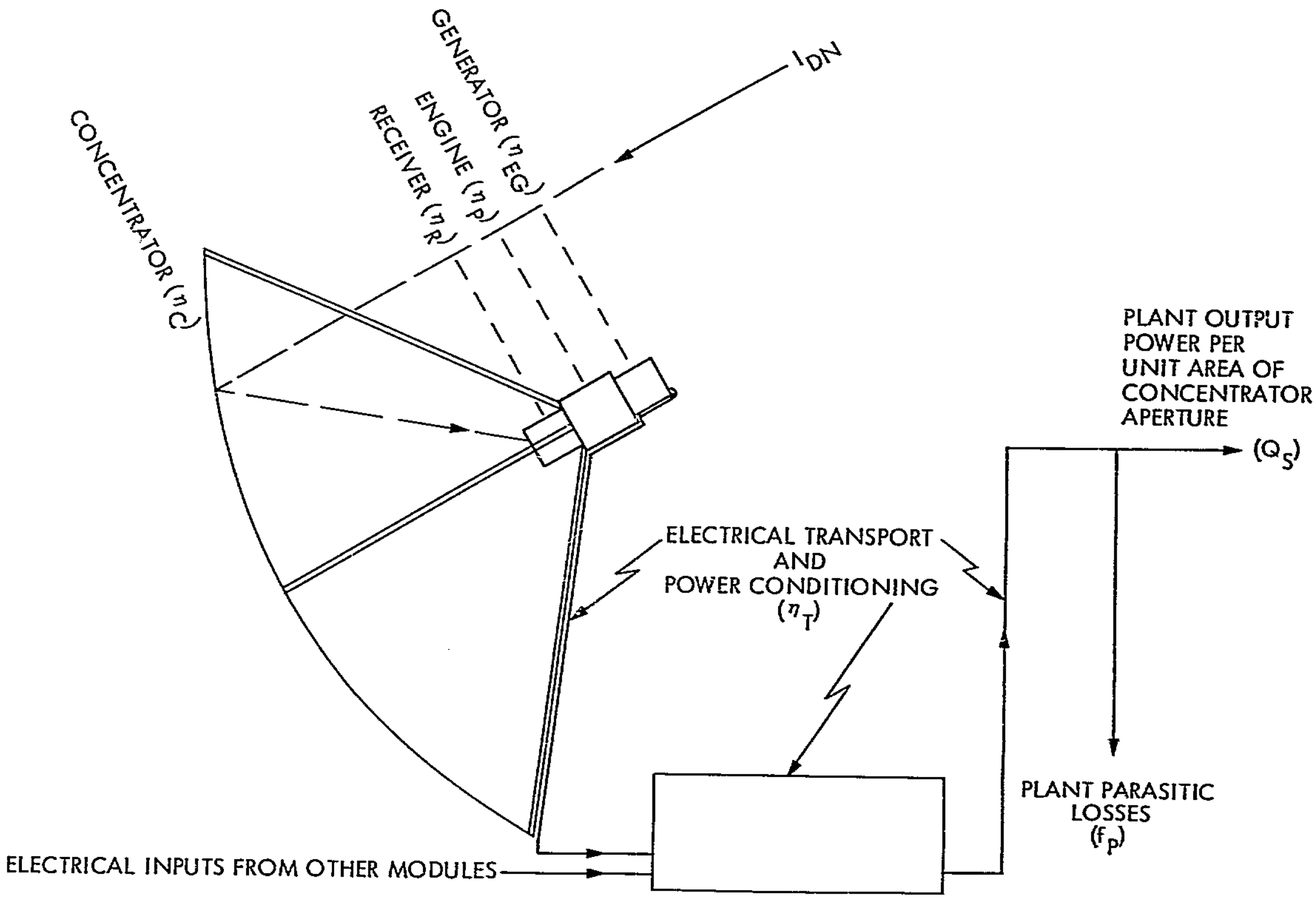

Figure 1. Energy Exchange and Efficiency of Paraboloidal-Dish Solar Thermodynamic Power Module Subsystems

struts. I_{DND} is defined in Section A of this chapter. Under general conditions,

$$A_C Q_C = A_C I_{DN} \rho_C F_B \cdot F_{DG} \cdot F_S \quad ,$$

where F_{DG} represents the average fractional degradation of mirror reflectivity that results from dust accumulation on the first surfaces of the mirrors between cleanings, and F_S represents the average degradation of concentrator field performance for the entire power plant due to the shading of some concentrators by others. Even in an optimally distributed field of concentrators, shading is appreciable near sunrise and sunset and, at latitudes appreciably above or below the equator, is more important in the winter than in the summer. Obvious definitions can be written for the design and general efficiencies of the concentrator as

$$\eta_{CD} = \rho_C F_B$$

and

$$\eta_C = \rho_C F_B F_{DG} F_S \quad ,$$

respectively. Then Q_{CD} and Q_C can be expressed by

$$Q_{CD} = \eta_{CD} I_{DND}$$

and

$$Q_C = \eta_C I_{DN} \quad .$$

Note that Q_{CD}, Q_C, and all other Q's in the following discussion represent energy flux per unit area of concentrator reflective surface projected upon the aperture plane of the concentrator. Defining the Q's in this way allows any one of them along the path of energy transport and conversion to be compared directly with the incident direct normal radiation, I_{DN}. A normalized photon flux from the concentrator, valid for annual average conditions of shading and degradation, can then be defined for an arbitrary I_{DN} as

$$Q_{CN} = Q_C / Q_{CD} \quad .$$

The definition of receiver efficiency employed by the program is more complicated than that for the concentrator. Receiver thermal flux delivered to the thermodynamic engine is defined in the following way:

$$Q_{RD} = \alpha\phi Q_{CD} - Q_{RL} \quad ,$$

where all the parameters and variables on the right side of this equation have already been defined. Defining receiver design efficiency as

$$\eta_{RD} = \frac{Q_{RD}}{Q_{CD}} \quad ;$$

by substitution,

$$\eta_{RD} = \alpha\phi - \frac{Q_{RL}}{Q_{CD}} \quad .$$

At other than design conditions, the receiver thermal flux delivered to the engine is defined as

$$Q_R = \alpha\phi Q_C - Q_{RL} \quad ,$$

and receiver design efficiency can be defined as

$$\eta_R = \frac{Q_R}{Q_C}$$

$$= \alpha\phi - \frac{Q_{RL}}{Q_C} \quad .$$

Then from earlier definitions,

$$\eta_{RD} - \eta_R = - \frac{Q_{RL}}{Q_{CD}} \left(1 - \frac{1}{Q_C/Q_{CD}}\right)$$

and

$$\eta_R = \eta_{RD} + \frac{Q_{RL}}{Q_{CD}} \left(1 - \frac{1}{Q_{CN}}\right) \quad .$$

Finally, a normalized receiver efficiency can be defined as

$$\eta_{RN} = \eta_R/\eta_{RD} \quad .$$

As can be seen from the formulae for η_R, at insolation levels below a certain threshold, receiver thermal efficiency can become negative. The program presented here sets $\eta_{RN} = 0$ whenever $\eta_R < 0$ is calculated; obviously, all subsequent Q's and η's except η_p are set equal to zero for insolation levels below this threshold.

The evaluation of the energy flux through the remainder of the power conversion subassembly is treated in a manner different from that employed in the case of the concentrator or receiver. The full-load efficiency of the engine is considered known from extensive analysis and/or experiment by the manufacturer. The same knowledge is usually available for the generator and the complete power conditioning and transport system. The fractional parasitic losses for the plant are also known from experiment or have been estimated.

In the program presented here, parasitic losses are assumed to be a small constant fraction of the gross plant-produced, conditioned, and transported electrical output; thus, a constant component efficiency reflecting plant parasitic losses can be defined as

$$\eta_{PAR} = 1 - f_{PAR} \quad ,$$

where f_{PAR} represents the normalized fractional parasitic losses just described. The efficiencies of the generator and of the electrical power conditioning and transport subsystem can be entered during the first segment of program execution as normalized fractional constants. Typically, real generator and electrical conditioning and transport subsystems exhibit efficiencies that reflect a relatively small, constant, fractional no-load loss and an additive fractional loss that varies with the fraction load. This same behavior is also exhibited by the typical thermodynamic engine. Therefore, if the user of this program wishes a more accurate representation of the combined efficiency of the engine, generator, and power conditioning and transport subsystems and if combined efficiency as a function of load is known or can be estimated for this combination, a polynomial representation for this efficiency, $\eta_P \cdot \eta_{EGT}$, can be entered during the loading phase (Segment No. 1) of the program in place of $\eta_{PN} = \eta_{PN}\{Q_{RN}\}$, and $\eta_{EGT} = 0$ can be set. Another alternative often employed by the author is to define the normalized efficiency of the engine-generator combination by a least-squares-best-fit polynomial function of normalized thermal flux from the receiver to the engine (converted from the manufacturer's data presenting efficiency as a function of output for this combination) and to assume respective constant values for η_{EGT} and f_{PAR}, the efficiency of the power conditioning and transport subsystem,and the fractional parasitic losses, respectively.

In the sample problem and corresponding solution here, η_{EGT} and η_{PAR} have been defined as constants, and only the efficiency of the engine has been defined as a function of the heat flow into the engine.

The program presented here allows the representation of normalized engine efficiency as a polynomial function of normalized thermal flux to the engine from the receiver. This representation is limited to a polynomial of no more than sixth degree.

Once the normalized thermal flux from the receiver, Q_{RN}, has been determined, the normalized efficiency of the engine, η_{PN}, can be calculated. Then the normalized mechanical output power of the engine, its efficiency, and its dimensional mechanical output power can be calculated:

$$Q_{PN} = \eta_{PN} \cdot Q_{RN} \quad ,$$

$$\eta_P = \eta_{PN} \cdot \eta_{PD} \quad ,$$

and

$$Q_P = \eta_P \cdot Q_R \quad .$$

As was the case with the receiver, at input thermal fluxes to the engine below some threshold, η_P will be negative. When this occurs, the program sets $\eta_{PN} = 0$, and all subsequent Q's and η's in the energy train are also set equal to zero.

If the product of η_{EGT} (the efficiency of the generator and electrical power conditioning and transport subsystem) and η_{PAR} (the normalized fractional correction for plant parasitic electrical power dissipation) is defined as η_{EP}, the electrical power output of the plant can be calculated for design and arbitrary loads as

$$Q_{SD} = \eta_{EP} \cdot Q_{PD}$$

and

$$Q_S = \eta_{EP} \cdot Q_P \quad .$$

For design and arbitrary loads, plant efficiency can be obtained from the simple formulae,

$$\eta_{SD} = Q_{SD}/I_{DND}$$

and

$$\eta_S = Q_S/I_{DN} \quad .$$

A formula for the normalized system efficiency of the plant is

$$\eta_{SN} = \eta_S/\eta_{SD} \quad .$$

The assumption of quasi-steady plant operation allows all transients due to abrupt changes in insolation to be ignored; thus, it becomes unnecessary to employ a dynamic temporal record of direct normal insolation at a particular site in order accurately to simulate annual plant performance. A histogram of annual direct normal insolation at the same site serves just as well under this assumption, and, instead of making thousands of calculations of plant performance to obtain annual plant performance, only a few tens of calculations of plant performance are required. Histograms for a few typical sites during what have been judged to be representative years are presented in Figure 2.

Annual plant performance for a plant is calculated by the program in the following way. At the average I_{DN} corresponding to each incremental ΔI_{DN}, energy fluxes are calculated and multiplied by the number of hours during the year in which that particular I_{DN} was measured:

$$E_I = I_{DN} \cdot H$$

$$E_C = Q_C \cdot H$$

$$E_R = Q_R \cdot H$$

$$E_P = Q_P \cdot H$$

$$E_S = Q_S \cdot H$$

These individual energies are then added to the sum of corresponding energies determined for all the previously employed (smaller) values of average I_{DN}. When all bands of I_{DN} have been considered, summations for the year are then available:

$$\Sigma E_I = \Sigma(I_{DN} \cdot H)$$

$$\Sigma E_C = \Sigma(Q_C \cdot H)$$

$$\Sigma E_R = \Sigma(Q_R \cdot H)$$

$$\Sigma E_P = \Sigma(Q_P \cdot H)$$

$$\Sigma E_S = \Sigma(Q_S \cdot H)$$

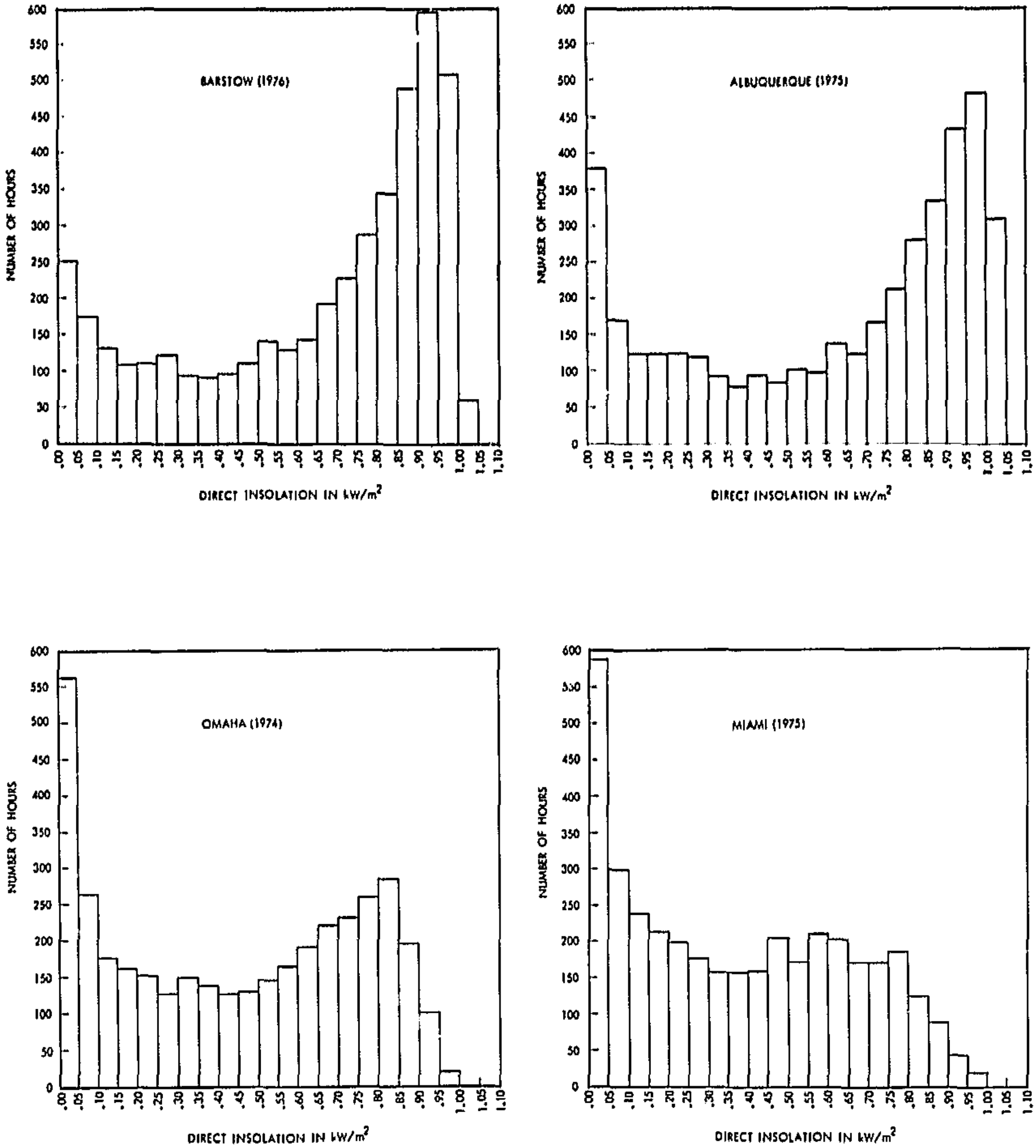

Figure 2. Histograms of the Annual Hourly Average Direct Insolation for Four Selected Sites

Finally, from these annual summations, the annual average efficiencies of the receiver, the engine, and the system can be calculated:

$$\eta_{RA} = \Sigma E_R / \Sigma E_C$$

$$\eta_{PA} = \Sigma E_P / \Sigma E_R$$

$$\eta_{SA} = \Sigma E_S / \Sigma E_I$$

The annual average efficiency of the concentrator was established near the beginning of this section. It is therefore unnecessary to determine

$$\eta_{CA} = \Sigma E_C / \Sigma E_I \quad ,$$

although this equation can be employed as a check.

D. FLOW CHART

The flow chart (Appendix A) of the programmed solution follows standard flow charting conventions and is virtually self-explanatory. Segment No. 1 is stored on the first TI-59 program card and Segment No. 2, on the second. The names of the various subprograms correspond to the various TI-59 keys employed as user-defined subprogram labels in the course of program development. Although an attempt was made to choose each label in a way that would provide a hint as to the function of the corresponding subroutine, the severely limited number of names available probably prevented much success in this respect. The reader must simply remember the names of the various subprograms as the various loops of the program are traced and retraced.

E. ANNOTATED PROGRAM LISTING

While the flow chart presented in Appendix A is easily adapted to any programmable calculator or microcomputer whose capabilities equal or exceed those of the TI-59, the program listing presented in Appendix B can be directly keyed in and executed only on a TI-59. Nevertheless, since a TI-59 and attached printer are still commonly available and widely used in science and engineering, the program listing has been included in this report. To those who are familiar with the TI-59 programmable calculator and the ancillary, no-longer-extant PPX-59 user's group, the form in which the listing is presented will be completely familiar. The comments accompanying the listing closely parallel the remarks presented in the flow chart.

SECTION III

SAMPLE PROBLEM AND SOLUTION

The design and annual performances of a paraboloidal concentrator (dish)/Brayton solar thermal power plant (PDB/STPP) operating without thermal or electrical storage capability at Barstow, California, is considered here. A histogram of the direct normal insolation received at Barstow in 1976 is presented in tabular form as Table 2.

The design value for direct normal insolation is assumed to be 1.0 kW/m^2. Design and annual values of concentrator efficiency are assumed to be 0.94 and 0.88, respectively.

A receiver outlet temperature of 870°C (1600°F) has been specified. The corresponding combined thermal loss, intercept factor, and apparent aperture absorptance for the receiver have been estimated to be 0.07445 kW/m^2 (based on concentrator aperture), 0.99, and 0.92, respectively. The design efficiency of the Brayton engine has been estimated as 0.271, and the normalized part-load characteristics of the engine are presented in Table 3.

Table 2. Tabular Histogram of Direct Normal Insolation Received at Barstow, California, in Calendar Year 1976

Insolation Increment	Hours of Insolation in this Increment
0.00 - 0.05	251
0.05 - 0.10	174
0.10 - 0.15	131
0.15 - 0.20	109
0.20 - 0.25	111
0.25 - 0.30	122
0.30 - 0.35	94
0.35 - 0.40	92
0.40 - 0.45	96
0.45 - 0.50	111
0.50 - 0.55	141
0.55 - 0.60	129
0.60 - 0.65	143
0.65 - 0.70	192
0.70 - 0.75	228
0.75 - 0.80	288
0.80 - 0.85	345
0.85 - 0.90	489
0.90 - 0.95	595
0.95 - 1.00	508
1.00 - 1.05	60

Table 3. Estimated Garrett Turbine Engine Company SAGT-1A Brayton Engine Normalized Part-Load Efficiency As a Function of Normalized Input Thermal Power

Normalized Input Thermal Power	Normalized Part-Load Efficiency
0.295	0.000
0.375	0.515
0.500	0.827
0.625	0.940
0.750	0.989
0.875	1.000
1.000	1.000

The coefficients of the sixth-degree polynomial approximation corresponding to this normalized part-load operating characteristic are as follows:

$$a_0 = -11.484$$

$$a_1 = +93.721$$

$$a_2 = -303.71$$

$$a_3 = +532.70$$

$$a_4 = -526.26$$

$$a_5 = +257.56$$

$$a_6 = -59.527$$

The combined efficiency of mechanical-to-electrical power conversion by the generator, the power conditioning equipment, and the electrical transport network has been estimated to be 0.95, while the correction factor to the gross output of the power plant required to account for losses due to plant auxiliary equipment, etc., has been estimated to be 0.98.

As indicated by the sample problem (Appendix C), the input segment of the program requests the entry of the input data, item by item. Entering the degree of the polynomial (NPOL) and starting the program results in (1) calculation and printing of the design performance parameters corresponding to the PDB/STPP configuration specified by the input parameters and (2) a printed directive to load the second segment of the program into the calculator.

After the second segment is loaded and started, the annual performance of the specified PDB/STPP is calculated. When the calculator stops, the solution is complete. The following results have then been presented: (1) performance data for the concentrator, receiver, engine, and complete system for each median value of direct normal insolation employed in the histogram -- only the results obtained at I_{DN} = 0.025 are labeled -- and (2) the total direct normal insolation received during the year per square meter of concentrator aperture area and the annual average efficiencies of the receiver, thermodynamic engine, and the system in its entirety.

SECTION IV

USER INSTRUCTIONS

While the instructions presented in Appendix D are intended primarily for instruction of the TI-59 user and while the contents of the data registers are uniquely applicable to the TI-59, the general sequence of instructions is certainly applicable to any programmable calculator or microcomputer that might be employed to solve the problem.

SECTION V

CONCLUDING REMARKS

The results obtained for a wide variety of paraboloidal-dish solar thermal power plants operating at various sites have been compared with hour-by-hour calculations made for the same configurations at the same sites. In every case for which the site was located in the sunbelt and for which $I_{DND} = 1.00$ was specified, the results obtained by the method described herein differed negligibly from the hour-by-hour results obtained with a mainframe computer.

For the reader who has access to a TI-59 programmable calculator and attached TI PC-100C printer, loading the program and duplicating the sample problem should be a relatively simple task.

For the reader who wishes to understand the problem and its solution, the task is more difficult. However, the author recently presented the flow chart and the TI-59 program listing that are included here to members of a senior class in mechanical engineering. Within a few days these students had rewritten the program in BASIC and within ten days had duplicated the sample problem results with a Commodore 64 computer. Since that time, these same students have successfully programmed and solved the sample problem (1) on an HP-41C programmable calculator and (2), using FORTRAN, on the university's mainframe computer. Thus, the author is convinced that, by studying this report, an interested reader who is familiar with a sufficiently capable programmable calculator or computer will be able to create a program and solve the sample problem presented herein and any similar problems of interest.

APPENDIX A

FLOW CHART OF THE PROGRAMMED SOLUTION

SEGMENT NO. 1

Load, store, and print

IDND
HCD
HC
QRL
FSBS
ALPH
HPD
HEGT
HPAR

Calculate and store

HEP
QCD

Load, store, and print

ANPS a_0
a_1
:
a_5
a_6 (max.)

Load, store, and print twenty-one values of

HRS

corresponding to calculated and printed values of

IDN

to provide the tabular histogram of annual insolation required in later calculations:

0.025 = IDN
XXX = HRS
.
.
.
1.025 = IDN
ZXZ = HRS

Recall and print

HCD

Calculate, store, and print

HRD

Recall and print:

HPD
HEP

Calculate, store, and print

HSD

Print:

LOAD SECOND CARD

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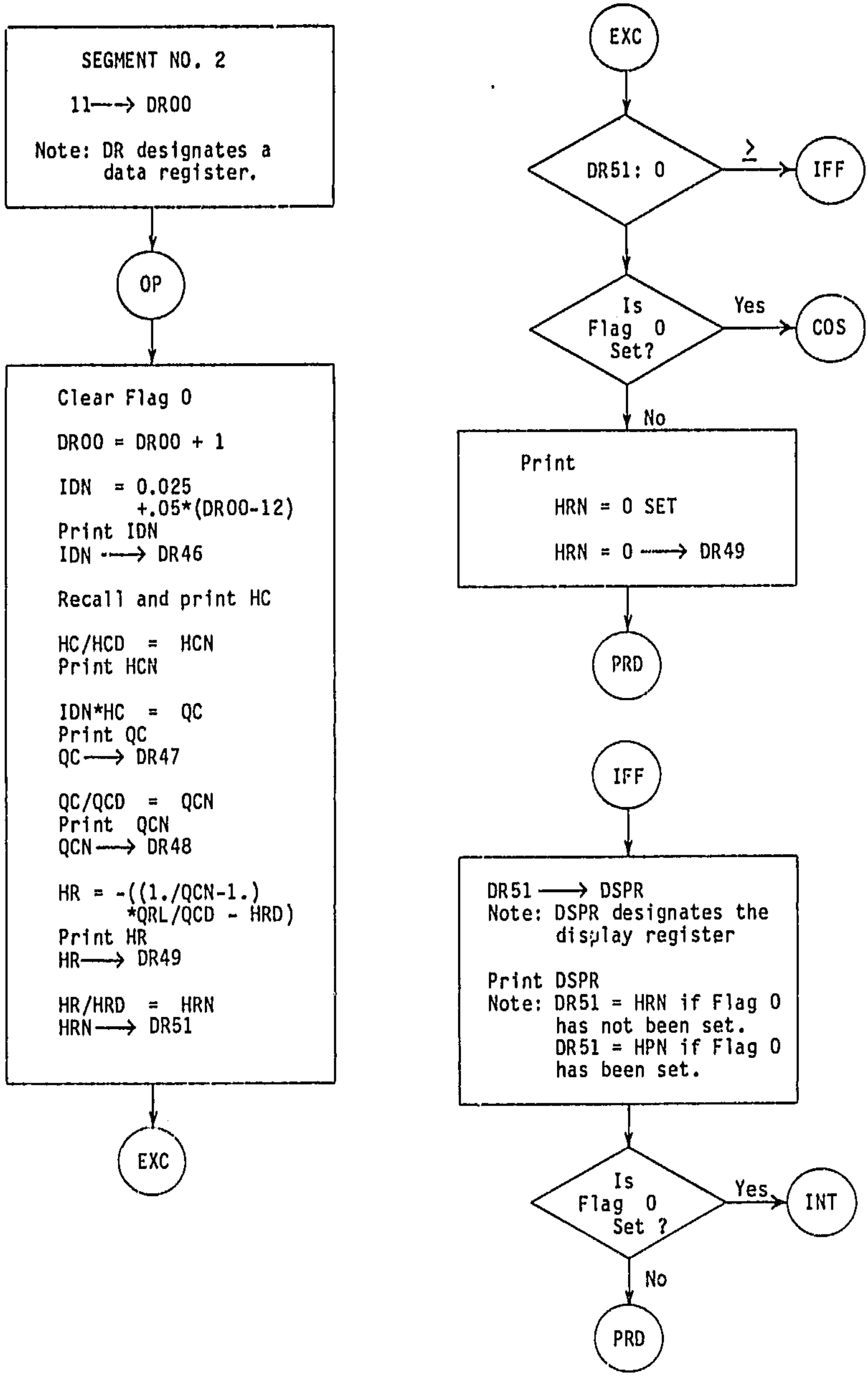
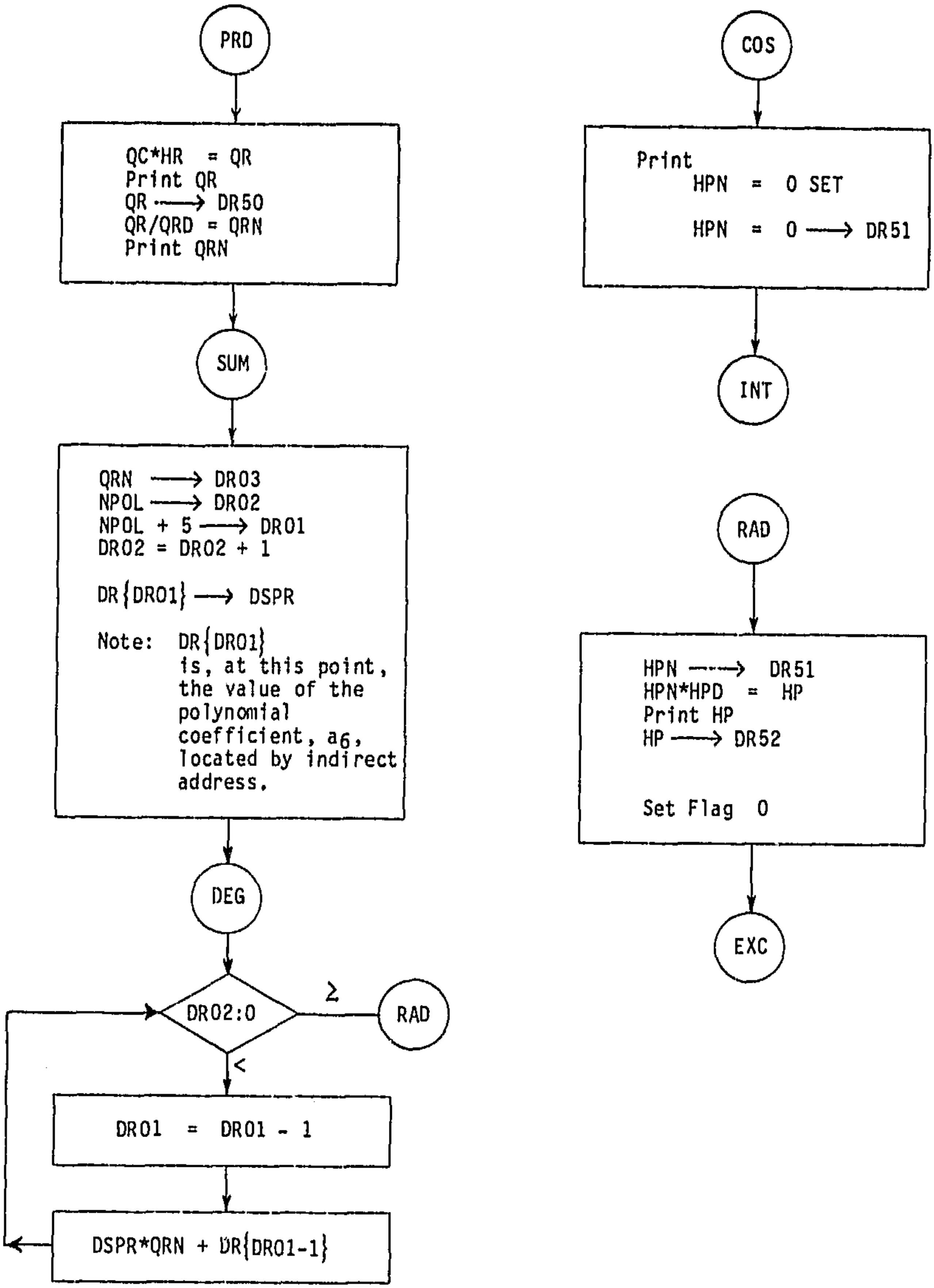
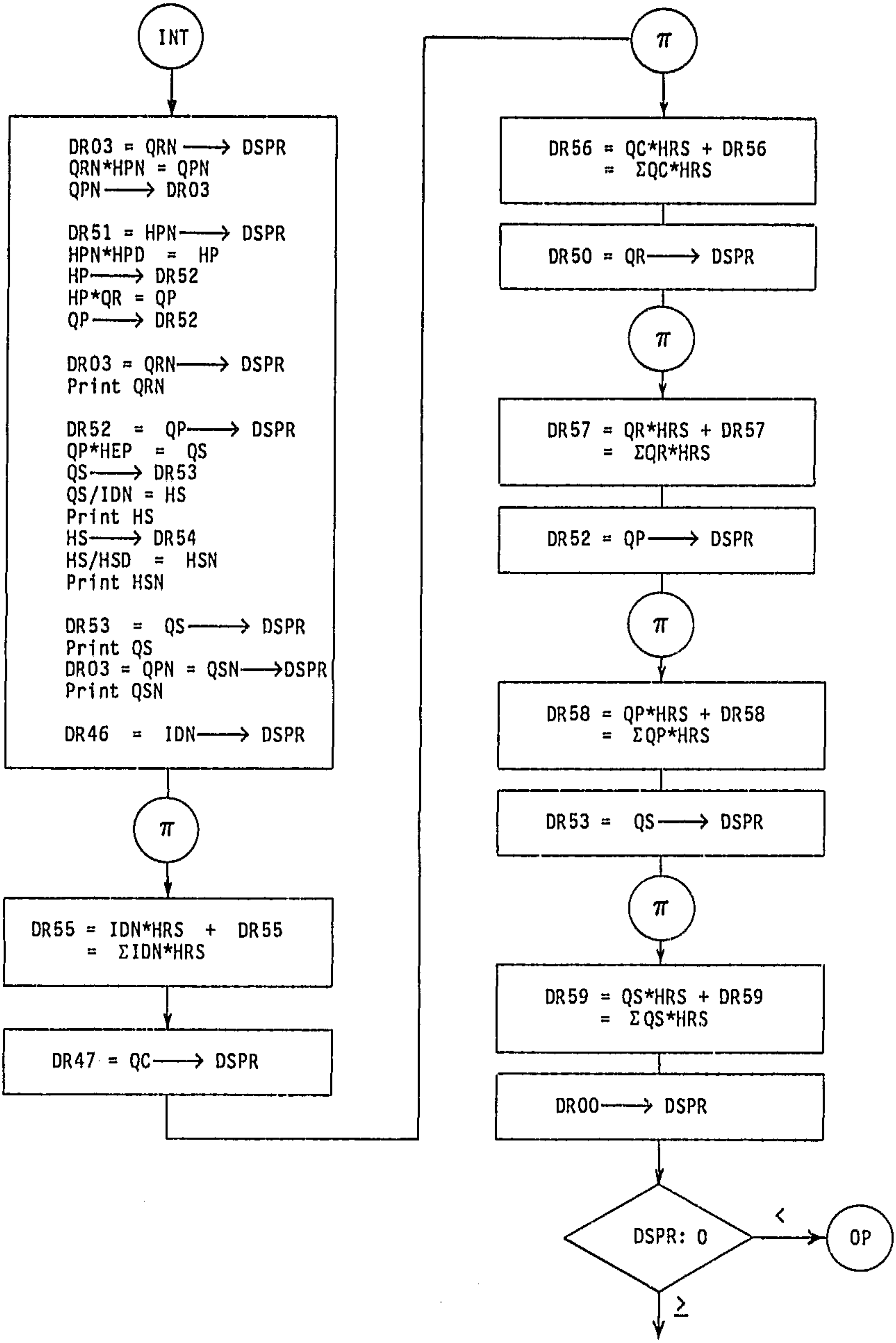
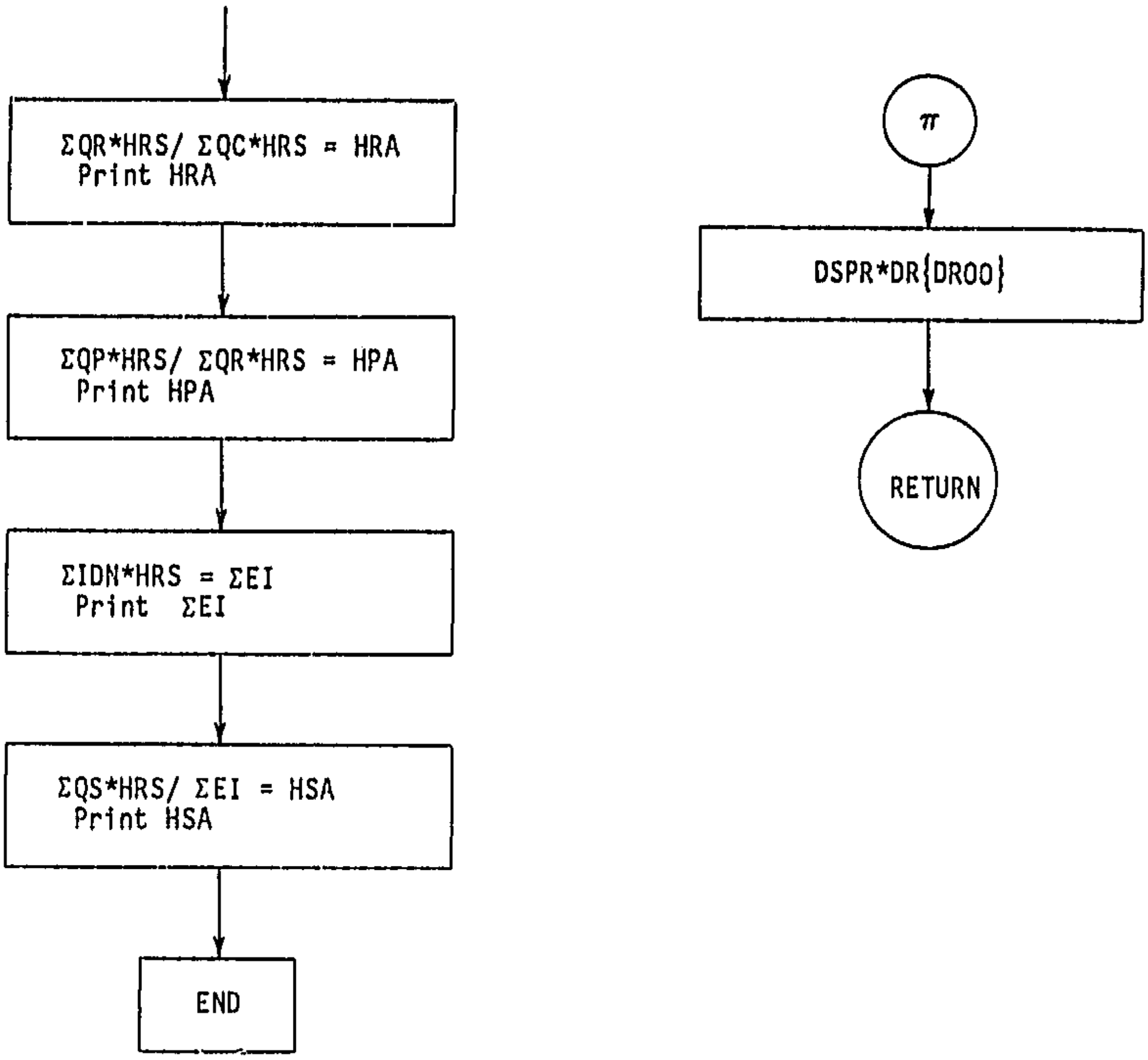

SEGMENT NO. 2
11 ⟶ DR00
Note: DR designates a data register.
OP
Clear Flag 0
DR00 = DR00 + 1
IDN = 0.025 +.05*(DR00-12)
Print IDN
IDN ⟶ DR46
Recall and print HC
HC/HCD = HCN
Print HCN
IDN*HC = QC
Print QC
QC ⟶ DR47
QC/QCD = QCN
Print QCN
QCN ⟶ DR48
HR = -((1./QCN-1.) *QRL/QCD - HRD)
Print HR
HR ⟶ DR49
HR/HRD = HRN
HRN ⟶ DR51
EXC
EXC
DR51: 0
≥
IFF
Is Flag 0 Set?
Yes
COS
No
Print
HRN = 0 SET
HRN = 0 ⟶ DR49
PRD
IFF
DR51 ⟶ DSPR
Note: DSPR designates the display register
Print DSPR
Note: DR51 = HRN if Flag 0 has not been set.
DR51 = HPN if Flag 0 has been set.
Is Flag 0 Set ?
Yes
INT
No
PRD



PRD
QC*HR = QR
Print QR
QR ⟶ DR50
QR/QRD = QRN
Print QRN
SUM
QRN ⟶ DR03
NPOL ⟶ DR02
NPOL + 5 ⟶ DR01
DR02 = DR02 + 1
DR{DR01} ⟶ DSPR
Note: DR{DR01} is, at this point, the value of the polynomial coefficient, a_6, located by indirect address.
DEG
DR02:0
≥
RAD
<
DR01 = DR01 - 1
DSPR*QRN + DR{DR01-1}
COS
Print
HPN = 0 SET
HPN = 0 ⟶ DR51
INT
RAD
HPN ⟶ DR51
HPN*HPD = HP
Print HP
HP ⟶ DR52
Set Flag 0
EXC


INT
DR03 = QRN ⟶ DSPR
QRN*HPN = QPN
QPN ⟶ DR03
DR51 = HPN ⟶ DSPR
HPN*HPD = HP
HP ⟶ DR52
HP*QR = QP
QP ⟶ DR52
DR03 = QRN ⟶ DSPR
Print QRN
DR52 = QP ⟶ DSPR
QP*HEP = QS
QS ⟶ DR53
QS/IDN = HS
Print HS
HS ⟶ DR54
HS/HSD = HSN
Print HSN
DR53 = QS ⟶ DSPR
Print QS
DR03 = QPN = QSN ⟶ DSPR
Print QSN
DR46 = IDN ⟶ DSPR
π
DR55 = IDN*HRS + DR55
= ΣIDN*HRS
DR47 = QC ⟶ DSPR
π
DR56 = QC*HRS + DR56
= ΣQC*HRS
DR50 = QR ⟶ DSPR
π
DR57 = QR*HRS + DR57
= ΣQR*HRS
DR52 = QP ⟶ DSPR
π
DR58 = QP*HRS + DR58
= ΣQP*HRS
DR53 = QS ⟶ DSPR
π
DR59 = QS*HRS + DR59
= ΣQS*HRS
DR00 ⟶ DSPR
DSPR: 0
<
OP
≥


ΣQR*HRS/ ΣQC*HRS = HRA
Print HRA
ΣQP*HRS/ ΣQR*HRS = HPA
Print HPA
ΣIDN*HRS = ΣEI
Print ΣEI
ΣQS*HRS/ ΣEI = HSA
Print HSA
END
π
DSPR*DR{DROO}
RETURN

APPENDIX B

TI-59 PROGRAMMABLE CALCULATOR PROGRAM
SEGMENT NOS. 1 AND 2

Segment No. 1

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
000	03	3		055	90	LST	FSBS → DR39	110	36	36	HCD
001	04	4		056	01	1		111	95	=	= QCD
002	42	STO		057	03	3	A	112	42	STO	
003	00	00	34 → DR00	058	02	2		113	40	40	QCD → DR40
004	71	SBR		059	07	7	L	114	98	ADV	
005	99	PRT		060	03	3		115	04	4	
006	02	2	I	061	03	3	P	116	42	STO	
007	04	4		062	02	2	H	117	00	00	4 → DR00
008	01	1	D	063	03	3	Print	118	05	5	
009	06	6		064	71	SBR	ENTER ALPH	119	42	STO	
010	03	3	N	065	90	LST	ALPH → DR40	120	33	33	5 → DR33
011	01	1		066	02	2	H	121	01	1	
012	01	1	D	067	03	3		122	01	1	
013	06	6		068	03	3		123	42	STO	
014	71	SBR	Print	069	03	3	P	124	34	34	11 → DR34
015	90	LST	ENTER IDND	070	01	1		125	01	1	
016	02	2	IDND → DR35	071	06	6	D	126	03	3	A
017	03	3	H	072	00	0		127	03	3	
018	01	1	C	073	00	0	Print	128	01	1	N
019	05	5		074	71	SBR	ENTER HPD	129	03	3	
020	01	1		075	90	LST	HPD → DR41	130	03	3	P
021	06	6	D	076	02	2	H	131	03	3	
022	00	0		077	03	3		132	06	6	S
023	00	0	Print	078	01	1	E	133	69	OP	Print
024	71	SBR	ENTER HCD	079	07	7		134	02	02	ENTER ANPS
025	90	LST	HCD → DR36	080	02	2	G	135	69	OP	
026	02	2	H	081	02	2		136	05	05	
027	03	3		082	03	3	T	137	76	LBL	
028	01	1	C	083	07	7	Print	138	78	Σ+	
029	05	5		084	71	SBR	ENTER HPAR	139	01	1	DR00 + 1
030	00	0		085	90	LST	HPAR → DR42	140	44	SUM	→ DR00
031	00	0		086	02	2	H	141	00	00	
032	00	0		087	03	3		142	43	RCL	
033	00	0	Print	088	03	3		143	00	00	DR00
034	71	SBR	ENTER HC	089	03	3	P	144	75	-	-
035	90	LST	HC → DR37	090	01	1	A	145	43	RCL	
036	03	3	Q	091	03	3		146	33	33	DR33
037	04	4		092	03	3	R	147	95	=	=n (of a_n)
038	03	3	R	093	05	5		148	99	PRT	Print n
039	05	5		094	69	OP	Print	149	91	R/S	Enter a_n
040	02	2	L	095	02	02	ENTER HPAR	150	72	ST*	Store a_n
041	07	7		096	69	OP		151	00	00	Print a_n
042	00	0		097	05	05		152	99	PRT	Continue
043	00	0	Print	098	91	R/S	Enter HPAR	153	43	RCL	entering
044	71	SBR	ENTER QRL	099	99	PRT	Print HPAR	154	34	34	and storing
045	90	LST	QRL → DR38	100	49	PRD	HPAR *	155	32	X⇌T	a_n through
046	02	2		101	42	42	HEGT → DR42	156	43	RCL	n = 6.
047	01	1	F	102	43	RCL		157	00	00	
048	03	3		103	40	40	ALPH *	158	22	INV	Note: If
049	06	6	S	104	49	PRD	FSBS → DR39	159	77	GE	NPOL=m < 6
050	01	1		105	39	39		160	78	Σ+	store a_n=0
051	04	4	B	106	43	RCL	IDND	161	98	ADV	for n > m.
052	03	3	S	107	35	35		162	01	1	
053	06	6	Print	108	65	×	*	163	02	2	
054	71	SBR	ENTER FSBS	109	43	RCL		164	42	STO	

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LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
165	33	33	12 → DR33	220	04	.04		275	03	3	O
166	03	3		221	01	1		276	02	2	
167	02	2		222	44	SUM	DR00 + 1	277	02	2	L
168	42	STO		223	00	00	→ DR00	278	07	7	
169	34	34	32 → DR34	224	43	RCL		279	69	OP	Print
170	02	2		225	00	00		280	02	02	ENTER NPOL
171	03	3	H	226	75	-		281	69	OP	
172	03	3		227	43	RCL		282	05	05	
173	02	2	O	228	33	33		283	25	CLR	
174	04	4		229	95	=	Calculate	284	91	R/S	Enter NPOL
175	01	1	U	230	65	×	IDN	285	42	STO	
176	03	3		231	93	.		286	04	04	NPOL → DR04
177	05	5	R	232	00	0		287	99	PRT	Print NPOL
178	69	OP		233	05	5		288	98	ADV	
179	02	02		234	85	+		289	69	OP	
180	03	3	S	235	93	.		290	00	00	
181	06	6		236	00	0		291	02	2	
182	00	0		237	02	2		292	03	3	H
183	00	0		238	05	5		293	01	1	
184	01	1		239	95	=		294	05	5	C
185	03	3	A	240	69	OP		295	01	1	
186	03	3		241	06	06	Print IDN	296	06	6	D
187	07	7	T	242	69	OP		297	69	OP	
188	00	0		243	00	00		298	04	04	
189	00	0		244	06	6		299	43	RCL	
190	69	OP		245	04	4	=	300	36	36	
191	03	03		246	02	2		301	69	OP	Print
192	02	2		247	03	3	H	302	06	06	YYXY HCD
193	04	4	I	248	03	3		303	69	OP	
194	01	1		249	05	5	R	304	00	00	
195	06	6	D	250	03	3		305	06	6	=
196	03	3		251	06	6	S	306	04	4	
197	01	1	N	252	69	OP		307	02	2	H
198	00	0		253	04	04		308	03	3	
199	00	0		254	25	CLR		309	03	3	R
200	00	0		255	91	R/S	Enter HRS	310	05	5	
201	00	0		256	69	OP	Print HRS	311	01	1	D
202	69	OP	Print	257	06	06		312	06	6	
203	04	04	ENTER	258	72	ST*	Store HRS	313	69	OP	
204	69	OP	HOURS	259	00	00		314	04	04	
205	05	05	AT	260	43	RCL	Continue	315	43	RCL	ALPH*FSBS
206	76	LBL	IDN	261	34	34	storing	316	39	39	—
207	60	DEG		262	32	X⇌T	HRS	317	75	-	
208	98	ADV		263	43	RCL	corres-	318	43	RCL	QRL
209	69	OP		264	00	00	ponding to	319	38	38	
210	00	00		265	22	INV	IDN until	320	55	÷	÷
211	06	6	=	266	77	GE	the 21	321	43	RCL	
212	04	4		267	60	DEG	bins have	322	40	40	QCD
213	02	2		268	98	ADV	been filled	323	95	=	= HRD
214	04	4	I	269	71	SBR		324	69	OP	Print
215	01	1		270	99	PRT		325	06	06	YYXZ = HRD
216	06	6	D	271	03	3		326	42	STO	
217	03	3		272	01	1	N	327	43	43	HRD → DR43
218	01	1	N	273	03	3		328	65	×	
219	69	OP		274	03	3	P	329	43	RCL	

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LOC	CODE	KEY	COMMENTS
330	40	40	HRD x QCD
331	95	=	= QRD
332	42	STO	
333	44	44	QRD → DR44
334	69	OP	
335	00	00	
336	02	2	H
337	03	3	
338	03	3	P
339	03	3	
340	01	1	D
341	06	6	
342	69	OP	
343	04	04	
344	43	RCL	
345	41	41	
346	69	OP	Print
347	06	06	YYYX HPD
348	69	OP	
349	00	00	
350	06	6	=
351	04	4	
352	02	2	H
353	03	3	
354	01	1	E
355	07	7	
356	03	3	P
357	03	3	
358	69	OP	
359	04	04	
360	43	RCL	
361	42	42	
362	69	OP	Print
363	06	06	YYYY = HEP
364	69	OP	
365	00	00	
366	06	6	=
367	04	4	
368	02	2	H
369	03	3	
370	03	3	S
371	06	6	
372	01	1	D
373	06	6	
374	69	OP	
375	04	04	
376	43	RCL	HCD
377	36	36	
378	65	x	X
379	43	RCL	HRD
380	43	43	
381	65	x	X
382	43	RCL	HPD
383	41	41	
384	65	x	X

LOC	CODE	KEY	COMMENTS
385	43	RCL	HEP
386	42	42	
387	95	=	= HSD
388	42	STO	HSD → DR45
389	45	45	
390	69	OP	Print
391	06	06	YYYZ = HSD
392	98	ADV	
393	71	SBR	
394	99	PRT	
395	03	3	S
396	06	6	
397	01	1	E
398	07	7	
399	01	1	C
400	05	5	
401	03	3	O
402	02	2	
403	69	OP	
404	02	02	
405	03	3	N
406	01	1	
407	01	1	D
408	06	6	
409	00	0	
410	00	0	
411	01	1	C
412	05	5	
413	01	1	A
414	03	3	
415	69	OP	
416	03	03	
417	03	3	R
418	05	5	
419	01	1	D
420	06	6	
421	00	0	
422	00	0	
423	00	0	
424	00	0	
425	00	0	
426	00	0	
427	69	OP	Print
428	04	04	ENTER
429	69	OP	SECOND
430	05	05	CARD
431	91	R/S	← End of
432	76	LBL	Segment
433	99	PRT	No. 1
434	69	OP	
435	00	00	
436	01	1	E
437	07	7	
438	03	3	N
439	01	1	

LOC	CODE	KEY	COMMENTS
440	03	3	T
441	07	7	
442	01	1	E
443	07	7	
444	03	3	R
445	05	5	
446	69	OP	
447	01	01	
448	92	RTN	
449	76	LBL	
450	90	LST	
451	69	OP	
452	02	02	Print
453	69	OP	ENTER----
454	05	05	
455	01	1	
456	44	SUM	DR00 + 1
457	00	00	→ DR00
458	91	R/S	Enter-----
459	72	ST*	Store-----
460	00	00	
461	99	PRT	Print-----
462	98	ADV	
463	04	4	If
464	03	3	DR00 < 43
465	32	X:T	go to
466	43	RCL	Subroutine
467	00	00	PRT;
468	22	INV	otherwise,
469	77	GE	continue.
470	99	PRT	
471	01	1	
472	22	INV	DR00 - 1
473	44	SUM	→ DR00
474	00	00	
475	92	RTN	
476	00	0	
477	00	0	
478	00	0	
479	00	0	

LOC	CODE	KEY	COMMENTS
138	78	Σ+	List of
207	60	DEG	Subroutines
433	99	PRT	
450	90	LST	

Segment No. 2

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
000	01	1		055	43	RCL		110	43	RCL	QRD
001	01	1		056	46	46	IDN	111	44	44	=QRN
002	42	STO		057	65	×	*	112	95	=	
003	00	00	11→DR00	058	43	RCL		113	99	PRT	Print QRN
004	76	LBL		059	37	37	HC	114	98	ADV	
005	69	OP		060	95	=	=QC	115	76	LBL	
006	22	INV	Clear	061	99	PRT	Print QC	116	44	SUM	
007	86	STF	Flag	062	42	STO	QC→DR47	117	42	STO	
008	00	00	0	063	47	47	QC	118	03	03	QRN→DR03
009	98	ADV		064	55	÷	÷	119	53	(	
010	69	OP		065	43	RCL	QCD	120	43	RCL	
011	00	00		066	40	40	=QCN	121	04	04	NPOL
012	06	6		067	95	=	Print QCN	122	42	STO	
013	04	4	=	068	99	PRT	QCN→DR48	123	02	02	NPOL→DR02
014	02	2		069	42	STO		124	85	+	
015	04	4	I	070	48	48		125	05	5	
016	01	1		071	98	ADV		126	54	)	
017	06	6	D	072	35	1/X	1/QCN	127	42	STO	NPOL + 5
018	03	3		073	75	-		128	01	01	→DR01
019	01	1	N	074	01	1	1	129	01	1	DR02 + 1
020	69	OP		075	95	=	=	130	44	SUM	→DR02
021	04	04		076	65	×	(1/QCN-1)	131	02	02	
022	01	1	DR00 + 1	077	43	RCL	*	132	73	RC*	DR{DR01}
023	44	SUM	→DR00	078	38	38	QRL	133	01	01	= a_6→DSPR
024	00	00		079	55	÷	÷	134	76	LBL	If DR02=0
025	93	.		080	43	RCL	QCD	135	60	DEG	go to
026	00	0		081	40	40		136	22	INV	Subroutine
027	02	2		082	75	-	-	137	97	DSZ	RAD;other-
028	05	5		083	43	RCL	HRD	138	02	02	wise, con-
029	85	+		084	43	43		139	70	RAD	tinue.
030	93	.	Calculate	085	95	=	= - HR	140	69	OP	
031	00	0	IDN	086	94	+/-	HR	141	31	31	DR01 - 1
032	05	5		087	99	PRT	Print HR	142	53	(	→DR01
033	65	×		088	42	STO	HR→DR49	143	24	CE	DSPR
034	53	(		089	49	49	HR	144	65	×	*
035	43	RCL		090	55	÷		145	43	RCL	QRN
036	00	00		091	43	RCL	÷ HRD	146	03	03	
037	75	-		092	43	43	=HRN	147	85	+	+
038	01	1		093	95	=		148	73	RC*	DR{DR01}
039	02	2		094	42	STO	HRN→DR51	149	01	01	
040	54	)		095	51	51		150	54	)	
041	95	=		096	61	GTO	Go to	151	61	GTO	Go to
042	69	OP	Print	097	48	EXC	Subroutine	152	60	DEG	Subroutine
043	06	06	X.XXX=IDN	098	76	LBL	EXC	153	76	LBL	DEG
044	98	ADV		099	49	PRD		154	70	RAD	
045	42	STO	IDN→DR46	100	43	RCL		155	42	STO	HPN→DR51
046	46	46		101	47	47	QC	156	51	51	HPN
047	43	RCL		102	65	×	*	157	65	×	*
048	37	37	Print HC	103	43	RCL	HR	158	43	RCL	HPD
049	99	PRT	HC	104	49	49		159	41	41	=HP
050	55	÷	÷	105	95	=	=QR	160	95	=	
051	43	RCL	HCD	106	99	PRT	Print QR	161	99	PRT	Print HP
052	36	36		107	42	STO	QR→DR50	162	42	STO	HP→DR52
053	95	=	=HCN	108	50	50	QR	163	52	52	
054	99	PRT	Print HCN	109	55	÷	÷	164	86	STF	Set

LOC	CODE	KEY	COMMENTS
165	00	00	Flag
166	61	GTO	0
167	48	EXC	Go to
168	76	LBL	Subroutine
169	59	INT	EXC
170	43	RCL	
171	03	03	QRN
172	65	×	*
173	43	RCL	HPN
174	51	51	=QPN
175	95	=	
176	42	STO	QPN→DR03
177	03	03	
178	43	RCL	
179	51	51	HPN
180	65	×	*
181	43	RCL	
182	41	41	HPD
183	95	=	=HP
184	42	STO	HP→DR52
185	52	52	HP
186	65	×	X
187	43	RCL	QR
188	50	50	
189	95	=	=QP
190	99	PRT	Print QP
191	42	STO	
192	52	52	QP→DR52
193	43	RCL	QPN
194	03	03	
195	99	PRT	Print QPN
196	43	RCL	QP
197	52	52	
198	65	×	X
199	43	RCL	
200	42	42	HEP
201	95	=	=QS
202	98	ADV	
203	42	STO	QS→DR53
204	53	53	QS
205	55	÷	÷
206	43	RCL	IDN
207	46	46	
208	95	=	=HS
209	99	PRT	Print HS
210	42	STO	HS→DR54
211	54	54	HS
212	55	÷	÷
213	43	RCL	
214	45	45	HSD
215	95	=	=HSN
216	99	PRT	Print HSN
217	43	RCL	
218	53	53	
219	99	PRT	Print QS

LOC	CODE	KEY	COMMENTS
220	43	RCL	
221	03	03	
222	99	PRT	Print QPN
223	43	RCL	
224	46	46	
225	71	SBR	
226	89	π	
227	44	SUM	ΣIDN*HRS
228	55	55	= ΣEI
229	43	RCL	→DR55
230	47	47	
231	71	SBR	
232	89	π	
233	44	SUM	ΣQC*HRS
234	56	56	→DR56
235	43	RCL	
236	50	50	
237	71	SBR	
238	89	π	
239	44	SUM	ΣQR*HRS
240	57	57	→DR57
241	43	RCL	
242	52	52	
243	71	SBR	
244	89	π	
245	44	SUM	ΣQP*HRS
246	58	58	→DR58
247	43	RCL	
248	53	53	
249	71	SBR	
250	89	π	
251	44	SUM	
252	59	59	ΣQS*HRS
253	03	3	→DR59
254	02	2	
255	32	X⇌T	If
256	43	RCL	DR00 < 32
257	00	00	go to
258	22	INV	Subroutine
259	77	GE	OP;
260	69	OP	otherwise,
261	98	ADV	continue.
262	69	OP	
263	00	00	
264	06	6	
265	04	4	=
266	02	2	
267	03	3	H
268	03	3	
269	05	5	R
270	01	1	
271	03	3	A
272	69	OP	
273	04	04	
274	43	RCL	

LOC	CODE	KEY	COMMENTS
275	57	57	ΣQR*HRS
276	55	÷	÷
277	43	RCL	ΣQC*HRS
278	56	56	
279	95	=	=HRA
280	69	OP	Print
281	06	06	ZZXX=HRA
282	98	ADV	
283	69	OP	
284	00	00	
285	06	6	
286	04	4	=
287	02	2	
288	03	3	H
289	03	3	
290	03	3	P
291	01	1	
292	03	3	A
293	69	OP	
294	04	04	
295	43	RCL	ΣQP*HRS
296	58	58	
297	55	÷	÷
298	43	RCL	ΣQR*HRS
299	57	57	
300	95	=	=HPA
301	69	OP	Print
302	06	06	ZZXY=HPA
303	98	ADV	
304	69	OP	
305	00	00	
306	06	6	
307	04	4	=
308	07	7	
309	07	7	
310	01	1	E
311	07	7	
312	02	2	
313	04	4	I
314	69	OP	
315	04	04	
316	43	RCL	
317	55	55	Print
318	69	OP	ZZXZ = ΣEI
319	06	06	
320	98	ADV	
321	69	OP	
322	00	00	
323	06	6	=
324	04	4	
325	02	2	H
326	03	3	
327	03	3	S
328	06	6	
329	01	1	

LOC	CODE	KEY	COMMENTS
330	03	3	A
331	69	OP	
332	04	04	
333	43	RCL	
334	59	59	ΣQS*HRS
335	55	÷	÷
336	43	RCL	ΣEI
337	55	55	
338	95	=	=HSA
339	69	OP	Print
340	06	06	ZZYX=HSA
341	91	R/S	End of
342	76	LBL	Segment
343	48	EXC	No. 2
344	00	0	If
345	32	X:T	DR51 ≥ 0
346	43	RCL	go to
347	51	51	Subroutine
348	77	GE	IFF; other-
349	87	IFF	wise, con-
350	87	IFF	tinue. If
351	00	00	Flag 0 is
352	39	COS	set, go to
353	69	OP	Subroutine
354	00	00	COS;other-
355	02	2	wise,continue
356	03	3	H
357	03	3	
358	05	5	R -
359	03	3	
360	01	1	N
361	06	6	
362	04	4	=
363	00	0	
364	01	1	0
365	69	OP	
366	01	01	
367	03	3	
368	06	6	S
369	01	1	
370	07	7	E
371	03	3	
372	07	7	T
373	00	0	
374	00	0	
375	69	OP	
376	02	02	Print
377	69	OP	HRN= 0 SET
378	05	05	
379	00	0	
380	42	STO	
381	49	49	0 → DR49
382	61	GTO	Go to
383	49	PRD	Subroutine
384	76	LBL	PRD

LOC	CODE	KEY	COMMENTS
385	87	IFF	
386	43	RCL	DR51
387	51	51	→ DSPR
388	99	PRT	Print DSPR
389	87	IFF	If Flag 0
390	00	00	is set, go
391	59	INT	to
392	61	GTO	Subroutine
393	49	PRD	INT;
394	76	LBL	otherwise
395	39	COS	to to PRD
396	69	OP	
397	00	00	
398	02	2	
399	03	3	H
400	03	3	
401	03	3	P
402	03	3	
403	01	1	N
404	06	6	
405	04	4	=
406	00	0	
407	01	1	0
408	69	OP	
409	01	01	
410	03	3	
411	06	6	S
412	01	1	
413	07	7	E
414	03	3	
415	07	7	T
416	00	0	
417	00	0	
418	69	OP	
419	02	02	
420	69	OP	Print
421	05	05	HPN= 0 SET
422	00	0	
423	42	STO	
424	51	51	0 → DR51
425	61	GTO	Go to
426	59	INT	Subroutine
427	76	LBL	INT
428	89	π	
429	53	(	
430	24	CE	DSPR
431	65	×	*
432	73	RC*	
433	00	00	DR{DR00}
434	54	)	
435	92	RTN	
436	00	0	
437	00	0	
438	00	0	
439	00	0	

LOC	CODE	KEY	COMMENTS
440	00	0	
441	00	0	
442	00	0	
443	00	0	
444	00	0	
445	00	0	
446	00	0	
447	00	0	
448	00	0	
449	00	0	
450	00	0	
451	00	0	
452	00	0	
453	00	0	
454	00	0	
455	00	0	
456	00	0	
457	00	0	
458	00	0	
459	00	0	
460	00	0	
461	00	0	
462	00	0	
463	00	0	
464	00	0	
465	00	0	
466	00	0	
467	00	0	
468	00	0	
469	00	0	
470	00	0	
471	00	0	
472	00	0	
473	00	0	
474	00	0	
475	00	0	
476	00	0	
477	00	0	
478	00	0	
479	00	0	
005	69	OP	List of
099	49	PRD	Subroutines
116	44	SUM	
135	60	DEG	
154	70	RAD	
169	59	INT	
343	48	EXC	
385	87	IFF	
395	39	COS	
428	89	π	

APPENDIX C

THE SAMPLE PROBLEM AND ITS SOLUTION
BY TI-59 PROGRAMMABLE CALCULATOR

Statement of Example

Given (1) the required input data describing a paraboloidal concentrator/Brayton solar thermal power plant operating without thermal or electric storage capability and (2) a histogram of the direct normal insolation received at Barstow, California, in 1976, determine the design and annual performances of the power plant when connected to a conventional electric utility grid.

ENTER	PRESS	OUTPUT/MODE	COMMENT
ENTER IDND 1.			
ENTER HCD 0.94			
ENTER HC 0.88			
ENTER QRL 0.07445			
ENTER FSBS 0.99			
ENTER ALPH 0.92			
ENTER HPD 0.271			
ENTER HEGT 0.95			

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ENTER	PRESS	OUTPUT/MODE	COMMENT
ENTER HPAR			
0.98			
ENTER ANPS			
0.			
-11.484			a_0
1.			
93.721			a_1
2.			
-303.71			a_2
3.			
532.7			a_3
4.			
-526.26			a_4
5.			
275.56			a_5
6.			
-59.527			a_6
ENTER HOURS AT IDN			
0.025 =IDN			
251. =HRS			
0.075 =IDN			
174. =HRS			
0.125 =IDN			
131. =HRS			
0.175 =IDN			
109. =HRS			
0.225 =IDN			
111. =HRS			
0.275 =IDN			
122. =HRS			
0.325 =IDN			
94. =HRS			
0.375 =IDN			
92. =HRS			
0.425 =IDN			
96. =HRS			

ENTER	PRESS	OUTPUT/MODE	COMMENT
0.475	=IDN		
111.	=HRS		
0.525	=IDN		
141.	=HRS		
0.575	=IDN		
129.	=HRS		
0.625	=IDN		
143.	=HRS		
0.675	=IDN		
193.	=HRS		
0.725	=IDN		
228.	=HRS		
0.775	=IDN		
238.	=HRS		
0.825	=IDN		
345.	=HRS		
0.875	=IDN		
489.	=HRS		
0.925	=IDN		
595.	=HRS		
0.975	=IDN		
508.	=HRS		
1.025	=IDN		
60.	=HRS		
ENTER NPOL			
6.			
		0.94 HCD	
		.8315978723 =HRD	
		0.271 HPD	
		0.931 =HEP	
		.1972241963 =HSD	
		ENTER SECOND CARD	

ENTER	PRESS	OUTPUT/MODE	COMMENT
		0.025 =IDN	.000 < IDN ≤ .005
		0.88	HC
		.9361702128	HCN
		0.022	QC
		.0234042553	QCN
		-2.473290909	HR
		HRN=0 SET	HRN
		0.	QR
		0.	QRN
		-3.112164	HP
		HPN=0 SET	HPN
		0.	QP
		0.	QPN
		0.	HS
		0.	HSN
		0.	QS
		0.	QSN
		0.075 =IDN	.005 < IDN ≤ .100
		0.88	Note: Output parameters at each IDN appear in the same order as that shown above for IDN = 0.025
		.9361702128	
		0.066	
		0.070212766	
		-0.217230303	
		HRN=0 SET	
		0.	
		0.	
		-3.112164	Note: Because HEP = HEPD = a constant, QSN = QPN always.
		HPN=0 SET	
		0.	
		0.	
		0.	
		0.	
		0.	
		0.	

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OF POOR QUALITY

ENTER	PRESS	OUTPUT/MODE	COMMENT
		0.125 =IDN	.100 < IDN ≤ .150
		0.88 .9361702128 0.11 .1170212766 .2339818182 .2813641376 0.025738 .0329255906	Note: This is the smallest tabulated value of IDN for which thermal output power from the receiver is positive and, therefore, for which HRN > 0.
		-2.360145651 HPN=0 SET 0. 0. 0. 0. 0. 0.	
		0.425 =IDN	.400 < IDN ≤ .450
		0.88 .9361702128 0.374 .3978723404 .7117358289 .8558653798 0.2661892 .3405251618 .0921677418 .3401023681 .0245340574 .1158134139 .0537440176 .2725021504 .0228412075 .1158134139	Note: This is the smallest tabulated value of IDN for which net power is produced by the power conversion subsystem and, therefore, for which HPN > 0.

ENTER	PRESS	OUTPUT/MODE		COMMENT
		1.025	=IDN	1.000 < IDN ≤ 1.050
		0.88		
		.9361702128		
		0.902		
		.9595744681		
		.8282611973		
		0.995987634		
		0.7470916		
		.9557243041		
		.2708914533		
		.9995994587		
		.2023807293		
		.9553414971		
		.1838209356		
		0.932040485		
		0.188416459		
		.9553414971		
		.7862375972	=HRA	
		.2489081067	=HPA	
		2847.9	=ΣEI	
		0.160333843	=HSA	

APPENDIX D

USER INSTRUCTIONS FOR LOADING AND RUNNING THE TI-59 PROGRAMMABLE CALCULATOR PROGRAM

User Instructions

Program Title: Paraboloidal Concentrator STPP Performance (Seg. #1)

NOTE: To start, press RST; then press R/S

Partition (OP 17)	Parentheses Levels		
479. 59		t Register	☒
Angular Mode (if applicable)	SBR Levels	Absolute Addresses	☐
Library Module ID: 1		Disturbs Pending Operations	☐

USER DEFINED KEYS

None

Note: See OP 08 list following the Segment No. 1 program listing for labels employed in this segment.

DATA REGISTERS

Reg.	Contents
0	Ind. Address Reg.
1	Polynomial pointer
2	" " counter
3	" " x
4	" " N
5	" " a_0
6	" " a_1
7	" " a_2
8	" " a_3
9	" " a_4
10	" " a_5
11	" " a_6
12	Hours @IDN = .025
13	" " " = .075
14	" " " = .125
15	" " " = .175
16	" " " = .225
17	" " " = .275
18	" " " = .325
19	" " " = .375
20	" " " = .425
21	" " " = .475
22	" " " = .525
23	" " " = .575
24	" " " = .625
25	" " " = .675
26	" " " = .725
27	" " " = .775
28	" " " = .825
29	" " " = .875
0	Continued on
1	page D-4
2	
3	
4	

FLAGS 0	1	2	3	4	5	6	7	8	9

STEP	PROCEDURE	ENTER	PRESS	OUTPUT/MODE
1	Start program segment no. 1		RST	
			R/S	ENTER IDND
2	Enter IDND	XXXX	R/S	XXXX
				ENTER HCD
3	Enter HCD	XXXY	R/S	XXXY
				ENTER HC
4	Enter HC	XXXZ	R/S	XXXZ
				ENTER QRL
5	Enter QRL	XXYX	R/S	XXYX
				ENTER FSBS
6	Enter FSBS	XXYY	R/S	XXYY
				ENTER ALPH
7	Enter ALPH	XXYZ	R/S	XXYZ
				ENTER HPD
8	Enter HPD	XXZX	R/S	XXZX
				ENTER ANPS
				0.

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STEP	PROCEDURE	ENTER	PRESS	OUTPUT/MODE
9	Enter a_0	XXZY	R/S	XXZY
				1.
10	Enter a_1	XXZZ	R/S	XXZZ
				2.
11	Enter a_2	XYXX	R/S	XYXX
				3.
12	Enter a_3	XYXY	R/S	XYXY
				4.
13	Enter a_4	XYXZ	R/S	XYXZ
				5.
14	Enter a_5	XYYX	R/S	XYYX
				6.
15	Enter a_6	XYYY	R/S	XYYY
				ENTER HEGT
16	Enter HEGT	XYYZ	R/S	XYYZ
				ENTER HPAR
17	Enter HPAR	XYZX	R/S	XYZX
				ENTER HOURS AT IDN
				0.025 = IDN
18	Enter hours at IDN = 0.025	XYZY	R/S	XYZY = HRS
				0.075 = IDN
19		XYZZ	R/S	XYZZ = HRS
				0.125 = IDN
20		XZXX	R/S	XZXX = HRS
⋮	Note: This process of entering	⋮		⋮ ⋮
⋮	hours continues at each 0.05	⋮		⋮ ⋮
⋮	increment of IDN to IDN = 1.025	⋮		

DATA REGISTERS	
30	Hours @IDN = .925
31	" " " = .975
32	" " " =1.025
33	Ind. Address Min.
34	Ind. Address Max.
35	IDND
36	HCD
37	HC
38	QRL
39	FSBS/104/FSBSxALPH
40	ALPH/112/QCD
41	HPDD
42	HEGT/100/HEGTxHPAR
43	HRD
44	QRD
45	HSD
6	
7	
8	
9	
0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
0	
1	
2	
3	
4	

STEP	PROCEDURE	ENTER	PRESS	OUTPUT/MODE
				: :
:		:		1.025 = IDN
38		YYXX	R/S	YYXX = HRS
				ENTER NPOL
39	Enter NPOL	P	R/S	P
				YYXY HCD
				YYXZ = HRD
				YYYX HPD
				YYYY = HEP
				YYYZ = HSD
				ENTER SECOND CARD

DATA REGISTERS
0
1
2
3
4
5
6
7
8
9
0
1
2
3
4
5
6
7
8
9
0
1
2
3
4
5
6
7
8
9
0
1
2
3
4

User Instructions

Program Title: Paraboloidal Concentrator STPP Performance (Seg. #2)

NOTE: To start, press RST; then press R/S

Partition (OP 17) 479 . 59	Parentheses Levels	t Register	☒
Angular Mode (if applicable)	SBR Levels	Absolute Addresses	☐
Library Module ID 1		Disturbs Pending Operations	☐

USER DEFINED KEYS

None

Note: See OP 08 list following the Segment No. 2 program listing for labels employed in this segment.

DATA REGISTERS

0 Data registers 00
1 through 45 have
2 been loaded by
3 program segment
4 no.1 when segment
5 no.2 is started
46 IDN
47 QC
48 QCN
49 HR
50 QR
51 HRN/154/HPN
52 HP/191/QP
53 QS
54 HS
55 Σ(IDN*HRS)
56 Σ(QC*HRS)
57 Σ(QR*HRS)
58 Σ(QP*HRS)
59 Σ(QO*HRS)
0
1
2
03 117/QRN/176/QPN
4 Note:QRN is stored
5 in 03 at step 117
6 seg. no. 2 QPN
7 is stored in 03 at
8 step 177 of seg.
9 no. 2
0
1
2
3
4

FLAGS 0	1	2	3	4	5	6	7	8	9

STEP	PROCEDURE	ENTER	PRESS	OUTPUT/MODE
40	Enter program segment no. 2		RST	
			R/S	
	Note: Many data are output by this			
	second segment of the program.			
	Refer to the output from the example			
	problem for further details.			

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16. Abstract

A program capable of calculating the design-point and quasi-steady-state annual performance of a paraboloidal-concentrator solar thermal power plant without energy storage has been written for a programmable calculator equipped with suitable printer. The power plant may be located at any site for which a histogram of annual direct normal insolation is available.

Inputs required by the program are aperture area and the design and annual efficiencies of the concentrator; the intercept factor and apparent efficiency of the power conversion subsystem and a polynomial representation of its normalized part-load efficiency; the efficiency of the electrical generator or alternator; the efficiency of the electric power conditioning and transport subsystem; and the fractional parasitic losses for the plant. (Losses to auxiliaries associated with each individual module are to be deducted when the power conversion subsystem efficiencies are calculated.)

Outputs provided by the program are the system design efficiency, the annualized receiver efficiency, the annualized power conversion subsystem efficiency, the total annual direct normal insolation received per unit area of concentrator aperture, and the system annual efficiency.

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