PROGRAM DESCRIPTION I

Program Title M/M/S QUEUE CHARACTERISTICS

Contributor's Name William P. Hannah

Address 9373 Willow Oak Rd.

City Salinas **State/Country** CA **Zip Code** 93907

Program Description, Equations, Variables

SUMMARY:

Selected steady state characteristics are calculated for the multiple server queue with Poisson arrivals and exponential service rates (M/M/S). Calculated characteristics are: traffic intensity, expected queue and system lengths, expected times in queue and system, probability of idle servers, probability of waiting for service, and probability that system length is between any two given numbers. Highly readable printer output is produced.

A no-print option is programmed, and instructions are provided to delete the lengthy printing portions of the program in order to save program storage space for users desiring the display only option.

(Continued on Page 2)

Necessary Accessories 2 Memory Modules; printer optional. No modules if program is reduced (instructions provided) to eliminate print portions (82162A printer).

Operating Limits and Warnings

1. Limiting condition given for certain input parameters.
2. Local alpha labels A-D are used without intended keyboard access.
3. CLRG used.

Reference(s) Wagner, Harvey M; Principles of Management Science, Second Edition, Prentice-Hall, 1975. pp 506-522.

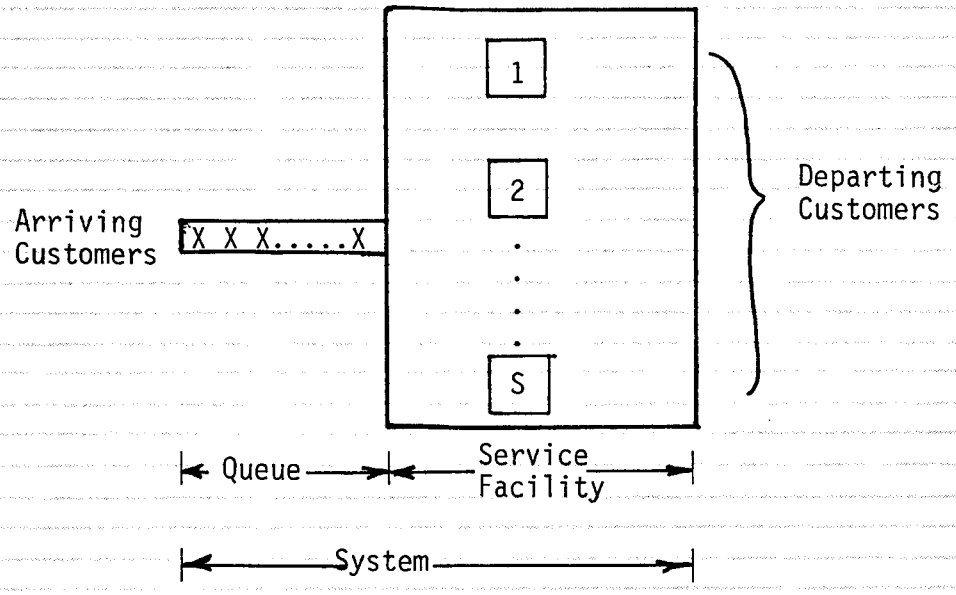
M/M/S is Kendall notation for exponential arrival/service times with S servers.

(CONTINUATION PAGE)

Program Description, Equations, Variables - Continued:

MODEL DESCRIPTION:

This program will calculate selected steady state system and queue characteristics for the single queue, multiple server model with Poisson arrivals and exponential service times (M/M/S queue). The basic elements of the queueing system are:



INPUT PARAMETERS:

λ = Exponential arrival rate of customers Customers/Time

μ = Exponential service rate of each server Customers/Time

s = Number of servers

STEADY STATE EQUATION:

Let random variable LS = length of the system (no. customers in the system). Then the probability that the length of the system = n is:

$$(1) \quad P(LS=n) = \begin{cases} \left(\frac{\lambda}{\mu}\right)^n P_o & \text{for } o \leq n \leq s \\ \frac{\left(\frac{\lambda}{\mu}\right)^n}{S!\, S^{n-s}} P_o & \text{for } n > s \end{cases}$$

STEADY STATE CHARACTERISTICS:

Two factors are calculated in the initial part of the program to simplify subsequent calculations. The factors are:

Interarrival times are distributed exponentially $P(t) = \lambda e^{-\lambda t}$. The mean interarrival time is thus $1/\lambda$
Service times are assumed to be distributed similarly

(CONTINUATION PAGE)

STEADY STATE CHARACTERISTICS - Continued:

(2) $\frac{\lambda}{\mu}$ (≡ traffic intensity for a single server)

(3) $$K = \frac{\mu\left(\frac{\lambda}{\mu}\right)^s}{(s-1)!(\mu s-\lambda)^2}$$

Base parameters calculated are as follows:

(4) r = "Rho" = $\frac{\lambda}{s\mu} < 1$ (≡ traffic intensity for the system)

(5) Probability that the servers are idle:

$$P_o = P(LS=0) = \left[\sum_{i=0}^{s-1}\frac{\left(\frac{\lambda}{\mu}\right)^i}{i!} + K(\mu s-\lambda)\right]^{-1}$$

Queue Characteristics (Output)

(6) $E[LQ] = \lambda K P_o$ Expected length of queue

(7) $E[TQ] = KP_o$ Expected time in queue (waiting time of an arrival)

(8) $P(LQ \geq S) = KP_o(\mu s-\lambda)$ Probability of having to wait for service

(9) $E[LS] = \lambda KP_o + \frac{\lambda}{\mu}$ Expected length of system

(10) $E[TS] = KP_o + \frac{1}{\mu}$ Expected time a customer spends in the system

(11) $P(n_1 \leq LS \leq n_2) = P(LS \leq n_2) - P(LS \leq n_1)$, calculated per equation (1).

Probability that the length of the system is between two values n_1 & n_2 inclusive.

PROGRAM OPTIONS:

The program claculates the intermediate parameters and final characteristics in the sequence of equations (2)-(11) above. The program uses HP-IL printer capabilities to produce a highly readable format, to include upper/lower case and standard statistical notation. The program stops only for prompted inputs; all results are automatically printed.

A display only option is available for those not desiring printed output; it is not necessary to have the HP-1L module and printer connected if this option is desired.

For users desiring to save space (full program is 497 lines, 1002 bytes), the printing segments can be deleted and the resulting program (still with display) is

(CONTINUATION PAGE)

PROGRAM OPTIONS - Continued:

reduced to 186 lines (321 bytes). Run time is not significantly changed. To reduce the program, the following lines should be deleted: 4-13, 22-111, 163-208, 221, 228-229, 234-249, 254-255, 260-275, 286-287, 292-312, 321-322, 327-342, 350-351, 356-371, 376-393, 396, 443-444, and 449-496. These program lines are indicated on the Program Listing by vertical lines to the left of the step numbers.

PROGRAM DESCRIPTION II

Sample Problem (Sketch if Desired)

(1) Customers are served, first come first served, from a single queue by 6 servers. The customers arrive at the rate of 15 per hour, and each server's average service rate is 3 per hour. Assuming Poisson arrivals and exponential service times, find the selected system and queue characteristics. Also, find the proportion of time there are 9 people or less in the queue and/or being served.

SOLUTION: Print mode is MAN

Input	Function	Display	Comments
	XEQ Size 015		Minimum size.
	XEQ "QUEUE"	Printer: Y/N?	Printer option prompt.
Y	R/S	Inputs:	Select printer; input prompt.
			Printer Output:
15	ENTER	15.000	λ input
3	ENTER	3.000	μ input
6	R/S		s input
			Printer Output:

Printer Output:

```
QUEUE

Inputs:
```

```
λ =  15.000
μ =  3.000
s =  6.000

Base Parameters:
r = 0.833
Po = 0.005

Solutions:
E[LQ] = 2.938
E[TQ] = 0.196
P(LQ≥S) = 0.588

E[LS] = 7.938
E[TS] = 0.529
N2, N1?
```

Sample Problem (Sketch if Desired)

(1) Continued

SOLUTION:

Input	Function	Display	Comments
		N2, N1?	Prompt to compute P(N1≤LS≤N2)
9	ENTER	9.000	
0	R/S	0.000	Printer Output:

```
N1=0., N2=9.
P(N1≤LS≤N2) = 0.717
```

Sample Problem (Sketch if Desired)

(2) Execute problem #(1) without using the printer option.

Inputs:

λ = 15/hour

μ = 3/hour

s = 6

N2 = 9, N1 = 0

SOLUTION:

Input	Function	Display	Comments
	XEQ Size 013		
	XEQ "QUEUE"	PRINTER: Y/N?	Printer option prompt
N	R/S	INPUTS?	Input prompt
15	ENTER	15.000	λ input
3	ENTER	3.000	μ input
6	R/S	RHO = .833	s input; traffic intensity r output
		PO = 0.005	P_0
	R/S	LQ = 2.938	E[LQ]
	R/S	TQ = 0.196	E[TQ]
	R/S	P:LQ.GE.S=0.588	P(LQ≥S)
	R/S	LS = 7.938	E[LS]
	R/S	TS = 0.529	E[TS]
	R/S	9.000 INPUTS: N2, N1	Input prompt
9	ENTER	9.000	N2 input
0	R/S	P:N1.LS.N2=0.717	N1 input; output is P(N1≤LS≤N2)

SIZE: (HP-41C) 015

STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
1	Enter program; set printer to MAN			
2	Execute and initialize program		XEQ "QUEUE"	PRINTER: Y/N?
3	Select printer option Yes(Y); go to step 8 for option No (N)	Y	R/S	Printer and display prompt for inputs.
4	Input parameters as follows:			
	• λ (arrival rate)	λ	ENTER	λ
	• μ (service rate)	μ	ENTER	μ
	• s (no. servers)	s	R/S	Printer response: Input: λ,μ,s Outputs: E[LQ] E[TQ],P(LQ≥S), E[LS],E[TS]; Further input prompt: N2, N1?
	Note: $\frac{\lambda}{\mu s} < 1$ condition must be met			
5	Input parameters* as follows:			
	• N2 (upper limit)	N2	ENTER	N2
	• N1 (lower limit)	N1	R/S	Printer response: N2, N1; P(N1≤LS≤N2)
	*(for P(N1≤LS≤N2))			
6	For new P(N1≤LS≤N2) problem, prompt for new N2, N1 and return to step 5.		XEQ "PN1N2"	INPUTS: N2,N1
7	For new queue problem, return to step 2.			

USER INSTRUCTIONS

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SIZE: (HP-41C) 015

STEP	INSTRUCTIONS	INPUT	FUNCTION	DISPLAY
8	Select printer option No (N)	N	R/S	INPUTS?
9	Input parameters as follows:			
	• λ	λ	ENTER	
	• μ	μ	ENTER	
	• s	s	R/S	RHO = X.XXX
				PO = 0.XXX
10	Continue to calculate E[LQ]		R/S	LQ = X.XXX
	characteristics: E[TQ]		R/S	TQ = X.XXX
	P(LQ≥S)		R/S	P:LQ.GE.S=0.XXX
	E[LS]		R/S	LS = X.XXX
	E[TS]		R/S	TS = X.XXX
11	Prompt for N2, N1		R/S	INPUTS: N2,N1
12	Input: • N2	N2	ENTER	N2
	• N1	N1	R/S	P:N1.LS.N2=0.XXX
13	For new P(N1≤LS≤N2) problem, prompt			
	for new N2, N1 and return to step 12.		XEQ "PN1N2"	INPUTS: N2, N1
13	For new queue problem, return to step 2.			

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STEP/ LINE	KEY ENTRY	KEY CODE (67/97 only)	COMMENTS
	01◆LBL "QUE		
	UE"		
	02 CLRG		
	03 FIX 3		
	04 CF 21		
	05 "PRINTER		
	: Y/N?"		
	06 AON		
	07 PROMPT		Prompt for printer use
	08 AOFF		
	09 ASTO Y		
	10 "Y"		
	11 ASTO X		
	12 X=Y?		
	13 GTO a		
	14 "INPUTS?		Begin display only mode
	"		
	15 PROMPT		Prompt for λ, μ, s
	16 STO 02		
	17 RDN		
	18 STO 01		
	19 RDN		
	20 STO 00		
	21 R↑		
	22 GTO b		
	23◆LBL a		
	24 SF 21		
	25 0		
	26 ENTER↑		
	27 0		
	28 BLDSPEC		Build ≤ Character
	29 4		
	30 BLDSPEC		
	31 44		
	32 BLDSPEC		
	33 42		
	34 BLDSPEC		
	35 41		
	36 BLDSPEC		
	37 40		
	38 BLDSPEC		
	39 0		
	40 BLDSPEC		
	41 STO 13		
	42 0		
	43 ENTER↑		
	44 0		
	45 BLDSPEC		Build ≥ Character
	46 40		
	47 BLDSPEC		
	48 41		
	49 BLDSPEC		
	50 42		
	51 BLDSPEC		
	52 44		
	53 BLDSPEC		
	54 4		
	55 BLDSPEC		
	56 0		
	57 BLDSPEC		
	58 STO 14		
	59 CLX		
	60 31		
	61 XEQ "DV"		Print header banner
	62 ADV		
	63 "QUEUE"		
	64 FMT		
	65 SF 12		
	66 ACA		
	67 CF 12		
	68 PRBUF		Print title
	69 ADV		
	70 "I"		
	71 ACA		
	72 "NPUTS:"		
	73 SF 13		
	74 ACA		
	75 CF 13		
	76 PRBUF		
	77 "INPUTS:		
	"		
	78 PROMPT		Prompt for λ, μ, s and print
	79 STO 02		
	80 RDN		
	81 STO 01		
	82 RDN		
	83 STO 00		
	84 FMT		
	85 11		
	86 ACCHR		
	87 " = "		
	88 ACA		
	89 RCL 00		
	90 ACX		
	91 PRBUF		
	92 FMT		
	93 12		
	94 ACCHR		
	95 " = "		
	96 ACA		
	97 RCL 01		
	98 ACX		
	99 PRBUF		
	100 FMT		

Note: Refer to "HP-41C OWNER'S HANDBOOK AND PROGRAMMING GUIDE" for specific information on keystrokes. The Function Index is found at the very back of the Handbook. Refer to Appendix E in 67 or 97 "OWNER'S HANDBOOK AND PROGRAMMING GUIDE" for exact keystrokes.

PROGRAM LISTING

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STEP/ LINE	KEY ENTRY	KEY CODE (67/97 only)	COMMENTS
101	115		
102	ACCHR		
103	" = "		
104	ACA		
105	RCL 02		
106	ACX		
107	PRBUF		
108	ADV		
109	RCL 00		
110	RCL 01		
111	◆LBL b		
112	/		
113	STO 03		λ/μ stored
114	RCL 02		
115	Y↑X		Begin to calculate K
116	RCL 01		
117	*		
118	RCL 02		
119	ENTER↑		
120	ENTER↑		
121	1		
122	-		
123	FACT		
124	X<>Y		
125	RCL 01		
126	*		
127	RCL 00		
128	-		
129	X↑2		
130	*		
131	/		
132	STO 04		K stored in R04
133	0		
134	STO 05		Begin to calculate P_0
135	RCL 02		
136	1		
137	-		
138	.001		
139	*		
140	STO 08		
141	◆LBL 01		
142	RCL 03		
143	RCL 08		
144	INT		
145	Y↑X		
146	LASTX		
147	FACT		
148	/		
149	ST+ 05		
150	ISG 08		
151	GTO 01		
152	RCL 04		
153	RCL 01		
154	RCL 02		
155	*		
156	RCL 00		
157	-		
158	*		
159	RCL 05		
160	+		
161	1/X		
162	STO 05		P_0 stored in R05
163	FC? 21		
164	GTO c		
165	"B"		
166	ACA		
167	SF 13		
168	"ASE"		
169	ACA		
170	CF 13		
171	" P"		
172	ACA		
173	SF 13		
174	"ARAMETE		
RS"			
175	ACA		
176	CF 13		
177	":"		
178	ACA		
179	PRBUF		
180	RCL 03		
181	RCL 02		
182	/		
183	"R = "		
184	ARCL X		
185	SF 13		
186	FMT		
187	ACA		
188	CF 13		
189	PRBUF		
190	"P"		
191	FMT		
192	ACA		
193	"O = "		
194	ARCL 05		
195	SF 13		
196	ACA		
197	CF 13		
198	PRBUF		
199	ADV		
200	"S"		

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STEP/ LINE	KEY ENTRY	KEY CODE (67/97 only)	COMMENTS
201	ACA		
202	"OLUTION S:"		
203	SF 13		
204	ACA		
205	CF 13		
206	PRBUF		
207	GTO d		
208	◆LBL c		
209	"RHO = "		Display r, P_O
210	RCL 03		
211	RCL 02		
212	/		
213	ARCL X		
214	TONE 9		
215	AVIEW		
216	PSE		
217	"PO = "		
218	ARCL 05		
219	AVIEW		
220	RTN		
221	◆LBL d		
222	◆LBL "LQ"		Routine to calculate E[LQ]
223	RCL 00		
224	RCL 04		
225	RCL 05		
226	*		
227	*		
228	FS? 21		
229	GTO 06		
230	"LQ = "		
231	ARCL X		
232	AVIEW		
233	RTN		
234	GTO 07		
235	◆LBL 06		
236	"E"		
237	ACA		
238	91		
239	ACCHR		
240	"LQ"		
241	ACA		
242	93		
243	ACCHR		
244	" = "		
245	ARCL Z		
246	ACA		
247	FMT		
248	PRBUF		
249	◆LBL 07		
250	◆LBL "TQ"		Routine to calculate E[TQ]
251	RCL 04		
252	RCL 05		
253	*		$K*P_O$
254	FS? 21		
255	GTO 08		
256	"TQ = "		
257	ARCL X		
258	AVIEW		
259	RTN		
260	GTO 09		
261	◆LBL 08		
262	"E"		
263	ACA		
264	91		
265	ACCHR		
266	"TQ"		
267	ACA		
268	93		
269	ACCHR		
270	" = "		
271	ARCL Z		
272	ACA		
273	FMT		
274	PRBUF		
275	◆LBL 09		
276	◆LBL "LQS"		Routine to calculate E[LQS]
277	RCL 01		
278	RCL 02		
279	*		
280	RCL 00		
281	−		
282	RCL 04		
283	RCL 05		
284	*		
285	*		
286	FS? 21		
287	GTO 10		
288	"P:LQ.GE .S="		
289	ARCL X		
290	AVIEW		
291	RTN		
292	GTO 11		
293	◆LBL 10		
294	"P"		
295	ACA		
296	40		
297	ACCHR		
298	"LQ"		
299	ACA		
300	RCL 14		

Note: Refer to "HP-41C OWNER'S HANDBOOK AND PROGRAMMING GUIDE" for specific information on keystrokes. The Function Index is found at the very back of the Handbook. Refer to Appendix E in 67 or 97 "OWNER'S HANDBOOK AND PROGRAMMING GUIDE" for exact keystrokes.

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STEP/ LINE	KEY ENTRY	KEY CODE (67/97 only)	COMMENTS
301	ACSPEC		
302	"S"		
303	ACA		
304	41		
305	ACCHR		
306	" = "		
307	ARCL T		
308	ACA		
309	FMT		
310	PRBUF		
311	ADV		
312	◆LBL 11		
313	◆LBL "LS"		Routine to calculate E[LS]
314	RCL 00		
315	RCL 04		
316	RCL 05		
317	*		
318	*		
319	RCL 03		
320	+		
321	FS? 21		
322	GTO 12		
323	"LS = "		
324	ARCL X		
325	AVIEW		
326	RTN		
327	GTO 13		
328	◆LBL 12		
329	"E"		
330	ACA		
331	91		
332	ACCHR		
333	"LS"		
334	ACA		
335	93		
336	ACCHR		
337	" = "		
338	ARCL Z		
339	ACA		
340	FMT		
341	PRBUF		
342	◆LBL 13		
343	◆LBL "TS"		Routine to calculate E[TS]
344	RCL 04		
345	RCL 05		
346	*		
347	RCL 01		
348	1/X		
349	+		
350	FS? 21		
351	GTO 14		
352	"TS = "		
353	ARCL X		
354	AVIEW		
355	RTN		
356	GTO A		
357	◆LBL 14		
358	"E"		
359	ACA		
360	91		
361	ACCHR		
362	"TS"		
363	ACA		
364	93		
365	ACCHR		
366	" = "		
367	ARCL Z		
368	ACA		
369	FMT		
370	PRBUF		
371	◆LBL A		
372	◆LBL "PN1 N2"		Routine to calculate P(N1≤n≤n2)
373	0		
374	STO 10		
375	STO 11		
376	FC? 21		
377	GTO B		
378	"N2, N1? "		
379	ACA		
380	FMT		
381	PRBUF		
382	PROMPT		
383	"N1="		
384	FIX 0		
385	ARCL X		
386	"⊢, N2="		
387	ARCL Y		
388	FIX 3		
389	ACA		
390	FMT		
391	PRBUF		
392	GTO C		
393	◆LBL B		
394	"INPUTS: N2, N1"		
395	PROMPT		
396	◆LBL C		
397	STO 06		n1 loop counter
398	X<>Y		
399	STO 07		n2 loop counter
400	.001		

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STEP/ LINE	KEY ENTRY	KEY CODE (67/97 only)	COMMENTS
401	*		
402	STO 09		
403	◆LBL 02		
404	RCL 02		
405	RCL 09		
406	INT		
407	STO 12		
408	X>Y?		$n_j > s$?
409	GTO 03		
410	FACT		
411	GTO 04		
412	◆LBL 03		
413	X<>Y		
414	-		
415	LASTX		
416	STO Z		
417	X<>Y		
418	Y↑X		
419	X<>Y		
420	FACT		
421	*		$s!s^{n-s}$
422	◆LBL 04		
423	RCL 03		
424	RCL 12		
425	Y↑X		
426	RCL 05		
427	*		
428	X<>Y		
429	/		
430	ST+ 11		
431	RCL 12		
432	RCL 06		
433	X<=Y?		$n_1 \leq n_j$?
434	GTO 05		
435	RCL Z		
436	ST+ 10		
437	◆LBL 05		
438	ISG 09		
439	GTO 02		
440	RCL 11		
441	RCL 10		
442	-		$P(n_1 \leq n \leq n_2)$
443	FS? 21		
444	GTO D		
445	"P:N1.LS .N2="		
446	ARCL X		
447	AVIEW		
448	RTN		
449	◆LBL D		
450	"P"		
451	ACA		
452	40		
453	ACCHR		
454	"N1"		
455	ACA		
456	RCL 13		
457	ACSPEC		
458	"LS"		
459	ACA		
460	ACSPEC		
461	"N2"		
462	ACA		
463	41		
464	ACCHR		
465	" = "		
466	CLX		
467	ARCL T		
468	ACA		
469	FMT		
470	PRBUF		
471	ADV		
472	31		
473	XEQ "DV"		
474	ADV		
475	ADV		
476	ADV		
477	ADV		
478	ADV		
479	RTN		
480	◆LBL "DV"		Subroutine for banner divider
481	ENTER↑		
482	BLDSPEC		
483	CLA		
484	ARCL X		
485	ARCL X		
486	ARCL X		
487	ASTO X		
488	ARCL X		
489	ASTO X		
490	ARCL X		
491	FC? 12		
492	ARCL X		
493	FC? 12		
494	ARCL X		
495	PRA		
496	CLX		
497	.END.		

Note: Refer to "HP-41C OWNER'S HANDBOOK AND PROGRAMMING GUIDE" for specific information on keystrokes. The Function Index is found at the very back of the Handbook. Refer to Appendix E in 67 or 97 "OWNER'S HANDBOOK AND PROGRAMMING GUIDE" for exact keystrokes.

REGISTERS, STATUS, FLAGS, ASSIGNMENTS

DATA REGISTERS

00	λ
01	μ
02	s
03	λ/μ
04	K
05	P_o
06	N1
07	N2
08	P_o loop counter
09	N loop counter (for N1→N2)
10	$\sum_{N=0}^{N1-1} P(LS=N)$
11	$\sum_{N=0}^{N2} P(LS=N)$
12	Scratch for Ni
13	$\leq$ character
14	$\geq$ character

STATUS

SIZE 015 TOT. REG. 144 USER MODE

ENG FIX 3 SCI ON OFF X

DEG RAD GRAD

FLAGS

#	INIT S/C	SET INDICATES	CLEAR INDICATES
12	C	Double wide print	
13	C	Lowercase print	
21	C	Printer enable	

Note: 12, 13 are set as required by program, 21 is set by user when prompted for print option. 21 is assumed to match 55.

ASSIGNMENTS None

FUNCTION	KEY	FUNCTION	KEY

PROGRAM REGISTERS NEEDED: 144

ROW 1 (1 : 4)

ROW 2 (4 : 5)

ROW 3 (5 : 13)

ROW 4 (13 : 17)

ROW 5 (18 : 26)

ROW 6 (27 : 34)

ROW 7 (34 : 41)

ROW 8 (42 : 49)

ROW 9 (50 : 57)

ROW 10 (57 : 63)

ROW 11 (63 : 68)

ROW 12 (69 : 73)

ROW 13 (73 : 77)

ROW 14 (77 : 86)

ROW 15 (86 : 92)

ROW 16 (92 : 98)

ROW 17 (98 : 103)

ROW 18 (103 : 111)

ROW 19 (112 : 124)

ROW 20 (125 : 137)

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