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MILESTONE REPORT
TCTP APPLICATION TO THE
SSME HYDROGEN SYSTEM ANALYSIS

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1.0 INTRODUCTION

The Transient Cryogen Transfer Computer Program (TCTP) was initially developed by the Boeing Company for NASA under Contract NAS8-5608 and documented in Reference 1. TCTP was further developed and verified for LOX systems by analyses of Skylab S-IB stage loading data from John F. Kennedy Space Center (KSC) launches (Reference 2). The program was then used to analyze planned space shuttle LOX loading systems at both the National Space and Technology Laboratories (NSTL) and KSC (References 3 and 4). Under the effort reported in this milestone report, TCTP was extended to include hydrogen as the working fluid and a study was made to determine the feasibility of incorporating TCTP into the SSME dynamic model.

The four tasks performed during this study were: (1) Develop and incorporate program modifications for SSME hydrogen system analysis. (2) Provide support for execution of the SSME dynamic analysis. (3) Determine the feasibility of incorporating TCTP into the SSME dynamic model. (4) Document the program application. Tasks (1) and (2) are documented in Sections 2.0 and 3.2, respectively. Task (3) is documented in Section 4.0, while this milestone report represents completion of Task (4). In addition to information published in this milestone report, the computer program user's guide information will be updated in the final report for Contract NAS8-30745 (Reference 5).

2.0 PROGRAM MODIFICATIONS FOR SSME HYDROGEN SYSTEM ANALYSIS

Modification to the basic TCTP (Reference 2) was required in two major areas in order to perform an analysis of the SSME hydrogen system. First, the program required modification to simulate parallel flow (flow which emanates from and terminates into the main flow line) and branch flow (flow which emanates from the main flow line and terminates into a plenum external to the main system). The original TCTP philosophy allowed only one flow path in the simulation during a computation step. This flow path originated at a system supply node (normally a pump) and terminated into a plenum with variable pressure at the system exit. Flows which originated from a system node and either discharged into a plenum or followed a path parallel to the system and discharged into another system node could be simulated only by incorporating a constant density flow rate-pressure drop function. TCTP was restructured to accurately simulate both parallel and branch flow legs, including transient heat transfer and local phase and density changes for leg nodes. This effort is described in Section 2.1.

A second major area of modification was required in the incorporation of hydrogen thermophysical properties into TCTP. Oxygen was the original working fluid used in the development and verification of the program. However, schemes used to initialize and calculate state variables such as density and internal energy as well as other thermophysical properties for oxygen were found to be inaccurate for hydrogen, particularly at or near critical conditions. New algorithms were developed to compute these required data. The hydrogen properties algorithms are documented in Section 2.2.

2.1 PARALLEL AND BRANCH FLOW SIMULATION

The Space Shuttle Main Engine hydrogen system contains multiple flow paths which cannot be modeled accurately by a single flow path simulation such as the one originally devised for TCTP. Flow splits and transient thermodynamic characteristics in all flow paths downstream of the flow split points cannot be accurately determined using

2.1 (Continued)

the techniques available in the original TCTP. Therefore, TCTP was restructured for the SSME configuration. Since no concise SSME configuration data were made available until late in this study, a generalized model for system description had to be generated to process the configuration data when it became available. The philosophy used to develop this model was to incorporate the nodal math model of the original TCTP and to make the restructured TCTP an extension of the original single flow path model. Iteration/convergence techniques of the original model were used where ever possible.

The following definitions are basic to the TCTP parallel and branch flow simulation in the restructured model:

Main Flow Leg - An arbitrarily chosen flow path through a system. This path must start at the system supply point and terminate at a plenum which is outside the system. The pressure in the plenum may be time variant.

Parallel Flow Leg - A flow path which emanates from a point in the main flow leg, and terminates into a different point in the main flow leg.

Branch Flow Leg - A flow path which emanates from a point in the main flow leg and terminates into a plenum. The pressure in the plenum may be time variant but the plenum must be external to the system.

Mixing Region - Junction point of main leg and parallel and/or branch legs. The mixing region is modeled as a point with no volume or mass storage capability. Mixing regions are always located at the downstream (away from supply node) end of a main flow leg node.

2.1 (Continued)

The following ground rules were adopted in developing the leg flow simulation of the restructured model:

1. The maximum allowable number of legs will be six; one main leg and any combination of five parallel and/or branch legs which are consistent with ground rules.

2. All branch and parallel flow legs will emanate from the main flow leg; parallel legs will terminate into the main leg.

3. No nested parallel legs; each parallel leg must be terminated into the main flow leg before another parallel leg may be initiated.

4. Branch and parallel legs may be initiated at any node in the main flow leg with the exception of the system supply node and the system exit node.

5. Positive flow direction will be consistent with original TCTP convention, from supply to exit is the positive direction.

6. Mixing regions will be considered as points with no mass storage capability. Instantaneous mixing in the mixing regions will be assumed.

The computational sequence for the restructured model is shown in logic block form in Figure 2.1. Where as the original program worked main leg nodes sequentially from system supply to system exit, the restructured program breaks this sequence to consider branch and parallel leg entrances as well as parallel leg exits when they are encountered. Note that the logic flow in Figure 2.1 does not contain a loop for a system supply pressure/flowrate model. This model may be located in either the SSME dynamic model or in the TCTP portion of the simulation, once the two programs are linked.

2.1 (Continued)

TCTP input procedures were modified to allow automatic processing of parallel and branch leg simulation data. These input data include leg entrance and exit node numbers, initial flow splits at entrances (and exits for parallel legs), initial enthalpy and density values at leg entrances (and exits for parallel legs), and identification of the first node in a leg. Complete documentation of the required input parameters for parallel and branch legs is given in Reference 5.

2.1.1 Parallel Flow Test Case

After program code was completed for parallel and branch flow simulation, the program was tested using a NSTL LOX loading system configuration with an equivalent parallel leg included in the system. This NSTL configuration was documented in Reference 3 and is shown schematically in Figure 2-2. The section of the system which was simulated by an equivalent parallel leg is circled and represents nodes 30 and 40 of the NSTL replenish system configuration of the reference. The original and parallel systems are shown schematically in Figure 2-3. The node descriptions for the original nodes and the equivalent parallel nodes are given in Table 2-I.

Results for the first 16 seconds of tank head flow were compared to verify the parallel flow code in TCTP. It was noted that results did not compare one-for-one. Differences were attributed to inability to derive a truly equivalent parallel system description and to convergence tolerances of trial-and-error iterations. No attempt was made to force the results to a one-for-one match since the purpose of the test case was to verify the program computational procedures rather than analyze that particular system with a parallel flow path.

2.1.2 Branch Flow Test Case

Branch flow computational procedures were verified by simulating the by-pass line from the pump to the storage tank in the KSC shuttle

2.1.2 (Continued)

configuration. The KSC configuration is shown in Figure 2-4 with the by-pass line circled. Analysis of this facility was accomplished using the original version of TCTP,as documented in Reference 2 and updated in Reference 5,with a functional simulation of the by-pass line included. This analysis is documented in Reference 4.

The first 32 seconds of the KSC simulation were executed with the by-pass simulated as a branch leg consisting of four nodes (the leg nodal data description is given in Table 2-II). Results of the two simulations are compared in Table 2-III. Results of this simulation served to verify the branch leg flow procedures of TCTP.

2.2 HYDROGEN PROPERTIES

Prior to the SSME hydrogen system study, TCTP had been executed with oxygen as the working fluid. In order to analyze the hydrogen system, it was necessary to incorporate hydrogen thermophysical properties into the program.

TCTP was originally designed to accept any boiling fluid as working media. Incorporated into the TCTP design were provisions for input of vapor density as a function of pressure and temperature, saturation temperature as a function of pressure, vapor saturation internal energy as a function of temperature, and liquid saturation internal energy as a function of temperature. These data were tabulated from National Bureau of Standards (NBS) tabulations given in Reference 6 and installed in the TCTP input data deck and program block data section.

An investigation was made of the change of internal energy with respect to temperature and pressure over the anticipated range of hydrogen properties for the SSME hydrogen system start transient. Internal energy as a function of temperature and pressure may be expressed as:

2.2 (Continued)

$$du = \left(\frac{\partial u}{\partial T}\right)_P dT + \left(\frac{\partial u}{\partial P}\right)_T dP.$$

For liquids at relatively low pressures and for gases which are approximately ideal, the change in internal energy with respect to temperature is essentially constant and the change in internal energy with respect to pressure is negligible or zero. Therefore

$$du \cong C\, dT.$$

Oxygen internal energy, over the ranges previously analyzed with TCTP, obeys this simplified equation. However, for the anticipated range of hydrogen properties for the SSME start transient, neither of the partial derivatives, $\left(\frac{\partial u}{\partial P}\right)_T$ or $\left(\frac{\partial u}{\partial T}\right)_P$, are constant or negligible. Variation of these partial derivatives is especially large near the critical point. The change of internal energy with respect to temperature at constant pressure is given in Tables 2-IV and 2-V. The change of internal energy with respect to pressure at constant temperature is given in Tables 2-VI and 2-VII. These data were determined from hydrogen data given in Reference 6.

TCTP was modified to incorporate the internal energy partial derivatives as a part of the program block data section and a method was derived to compute initial values of internal energy at all expected values of temperature and pressure. Initial values of internal energy are calculated by

$$U_I = \int_{T_R}^{T_I} \left(\frac{\partial u}{\partial T}\right)_P dT + \int_{P_R}^{P_I} \left(\frac{\partial u}{\partial P}\right)_T dP + U_R$$

2.2 (Continued)

where U_I is the initial value of internal energy

T_I is the initial temperature

p_I is the initial pressure

T_R is the reference temperature for U_R
T_R = saturation temperature for P_R

P_R is the reference pressure for U_R
$P_R = P_I$ for $P_I \leq P_{CRITICAL}$
$P_R = P_{CRITICAL}$ for $P_I > P_{CRITICAL}$

U_R is the reference internal energy at T_R and P_R

A test case for initial internal energy calculations was executed using the TCTP code. Results of this test case are compared with data from Reference 6 in Table 2-VIII.

Time step computations of single phase hydrogen internal energy assume that the partial derivatives $(\frac{\partial u}{\partial P})_T$ and $(\frac{\partial u}{\partial T})_P$ are constant over the time step. These derivatives are evaluated at the node initial conditions for single phase flow and at saturation conditions for initially two-phase flow. Table 2-IX presents a comparison of data from Reference 6 with program calculated values of internal energy at initial conditions and after five time slices in the simulation.

Liquid densities vary with temperature and pressure. TCTP was modified to calculate hydrogen liquid densities as a function of temperature and pressure by incorporating subroutine FULDEN. FULDEN contains a surface curve fit for liquid density and was originally developed by Rocketdyne for the Saturn program. The version of FULDEN installed in TCTP was taken from the Saturn V propulsion performance prediction program MARK IX (Reference 7). Check cases were executed using FULDEN alone. Results were acceptable when compared with data from Reference 6. Densities derived from FULDEN and interpolation of tabular data by TCTP are compared with reference values in Table 2-VIII.

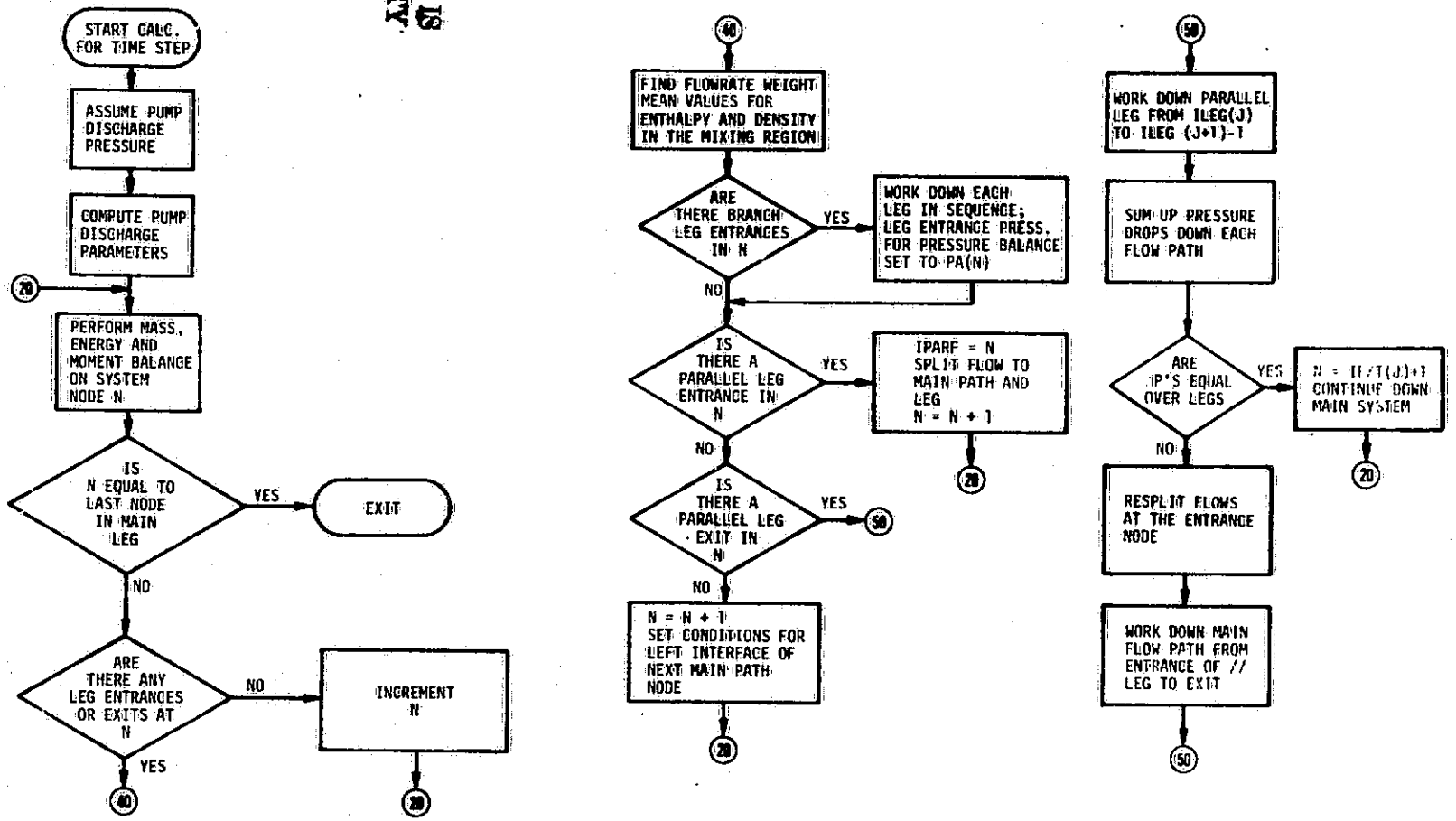

FIGURE 2-1 TCTP COMPUTATIONAL SEQUENCE WITH PARALLEL AND BRANCH FLOW

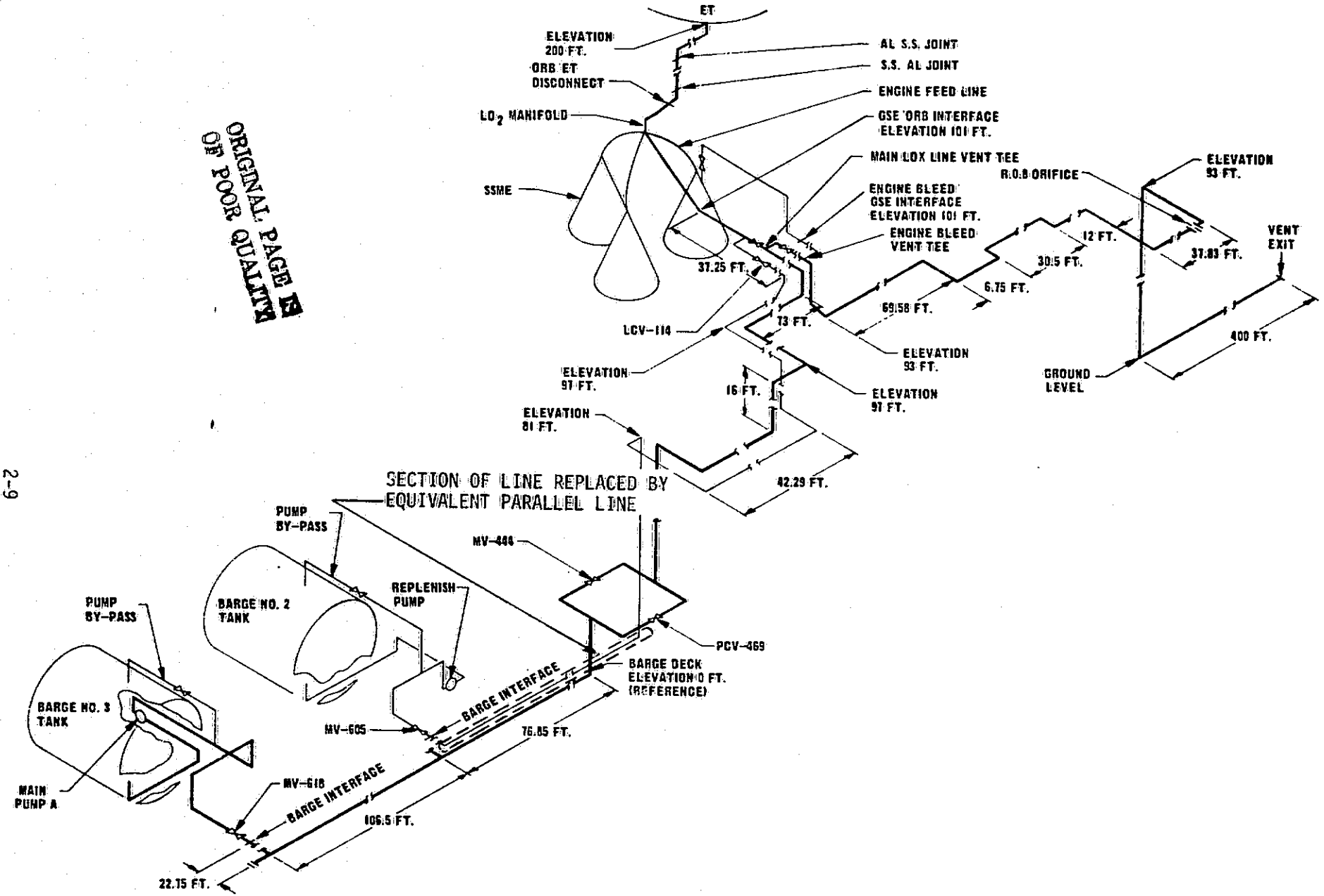

FIGURE 2-2 NSTL LOX LOADING/MPTA SYSTEM

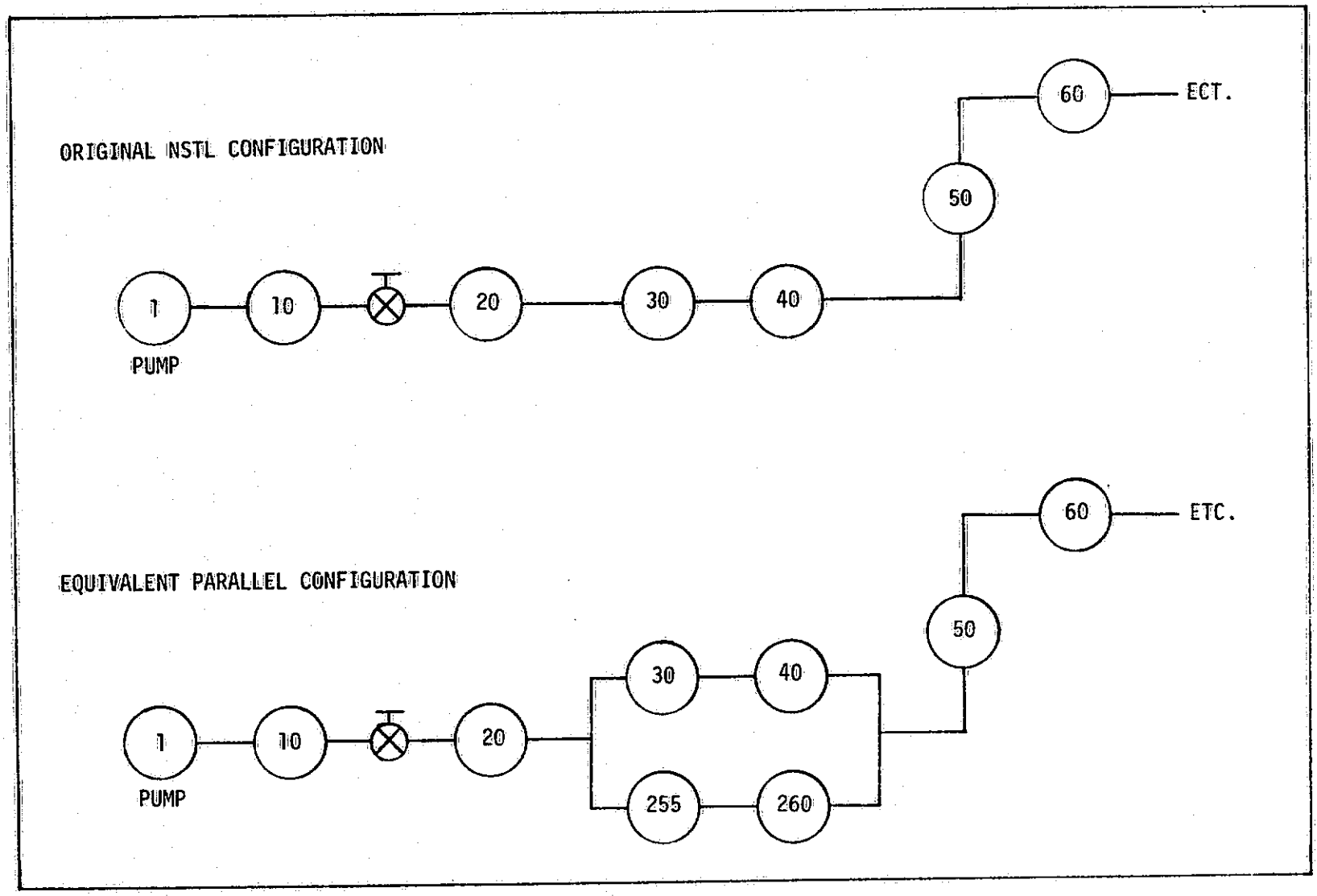

FIGURE 2-3 ORIGINAL AND PARALLEL SYSTEMS FOR PARALLEL FLOW TEST CASE

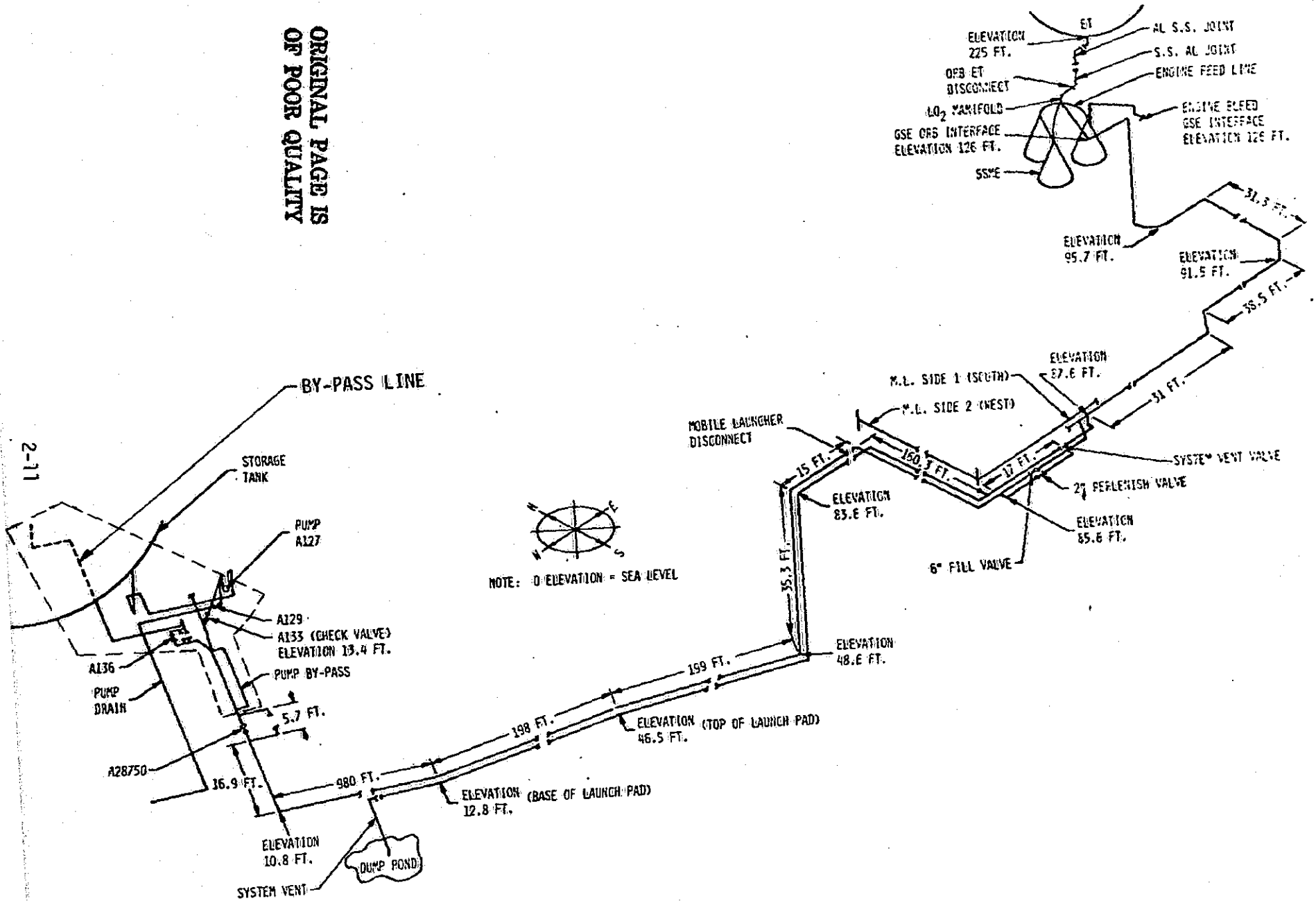

FIGURE 2-4 KSC/SHUTTLE LOX LOADING SYSTEM

TABLE 2-I TEST CASE NODAL DATA FOR PARALLEL FLOW

NODE	LENGTH (FT)	INTERNAL DIAMETER (FT)	NODE EXIT ELEVATION (FT)	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
30	55.0	0.3612	-1.22	1650.54	220.57
40	30.0	0.3612	0.80	377.02	120.30
30*	27.5	0.3612	-1.22	6602.16	110.28
40*	15.0	0.3612	0.80	1508.08	60.15
255*	27.5	0.3612	-1.22	6602.16	110.28
260*	15.0	0.3612	0.80	1508.08	60.15

*EQUIVALENT PARALLEL NODE

TABLE 2-II TEST CASE NODAL DATA FOR BRANCH FLOW

NODE	LENGTH (FT)	INTERNAL DIAMETER (FT)	NODE EXIT ELEVATION (FT)	EQUIVALENT (L/D)	DUCT WALL MASS (LB_M)
262	25.85	0.5339	0.0	150.42	200.72
264	8.58	0.2778	0.0	3344.64	26.60
266	19.09	0.5339	-2.42	1383.50	148.23
268	36.17	1.0365	3.00	1516.87	776.90

TABLE 2-III COMPARISON OF FUNCTIONAL AND BRANCH FLOW SIMULATIONS OF KSC BY-PASS FLOWS

	FUNCTIONAL SIMULATION			BRANCH FLOW SIMULATION		
TIME	FLOWRATE NODE 10	FLOWRATE NODE 20	FLOWRATE BY-PASS	FLOWRATE NODE 10	FLOWRATE NODE 20	FLOWRATE BY-PASS
0.0	228.5	148.0	80.5	228.5	148.0	80.5
4.0	205.6	132.8	72.8	211.3	140.1	71.2
8.0	201.7	128.8	72.9	208.5	137.8	70.8
12.0	201.1	128.0	73.1	208.3	137.5	70.8
16.0	200.7	127.5	73.2	207.9	137.0	70.9
20.0	200.2	126.9	73.3	207.5	136.4	71.1
24.0	200.1	126.6	73.5	207.3	136.2	71.1
28.0	199.5	125.9	73.6	206.8	135.4	71.4
32.0	199.1	125.4	73.7	206.3	134.9	71.4

T \ P	1.0	14.696	50	100	150	187.51	200	250	300	400	600	800	1200	2000
25	1.503													
36.483	1.489	1.712												
45.406	1.485	1.596	2.247											
52.072	1.484	1.557	1.871	3.264										
56.645	1.483	1.541	1.754	2.432	6.725									
59.357	1.483	1.570	1.725	2.258	4.231	33.107	14.277	6.205	4.950	3.949	3.179	3.820	2.441	2.085
62.0	1.482	1.529	1.686	2.069	3.008	6.110	14.942	12.680	6.923	4.584	3.428	2.974	2.536	2.150
66.0	1.482	1.522	1.649	1.921	2.421	3.177	3.602	7.627	9.694	5.738	3.788	3.183	2.656	2.228
70.0	1.483	1.516	1.615	1.806	2.096	2.429	2.515	3.450	4.964	6.114	4.241	3.445	2.802	2.319
75.0	1.485	1.514	1.601	1.760	1.985	2.223	2.320	2.842	3.654	5.111	4.346	3.563	2.877	2.364
80.0	1.488	1.513	1.585	1.711	1.875	2.033	2.093	2.386	2.768	3.750	4.204	3.640	2.964	2.433
90.0	1.500	1.519	1.571	1.658	1.760	1.849	1.881	2.025	2.192	2.575	3.285	3.399	3.021	2.529
100	1.523	1.538	1.578	1.642	1.714	1.714	1.795	1.886	1.986	2.211	2.653	2.931	2.932	2.588
110	1.562	1.574	1.605	1.654	1.707	1.707	1.764	1.826	1.891	2.034	2.329	2.566	2.736	2.577
120	1.617	1.627	1.652	1.691	1.732	1.732	1.775	1.821	1.869	1.969	2.181	2.367	2.572	2.577
130	1.690	1.698	1.719	1.750	1.782	1.782	1.817	1.852	1.889	1.965	2.124	2.270	2.468	2.537
150	1.879	1.884	1.899	1.921	1.944	1.961	1.967	1.990	2.014	2.063	2.161	2.258	2.417	2.549
200	2.430	2.433	2.440	2.451	2.462	2.471	2.474	2.486	2.496	2.520	2.567	2.614	2.700	2.812
250	2.813	2.815	2.819	2.826	2.833	2.838	2.839	2.846	2.853	2.867	2.894	2.921	2.974	3.059
270	2.887	2.889	2.893	2.899	2.90[illegible]	2.909	2.910	2.916	2.922	2.933	2.957	2.980	3.025	3.100
290	2.918	2.920	2.923	2.928	2.[illegible]33	2.937	2.938	2.944	2.949	2.959	2.979	2.999	3.038	3.104
300	2.920	2.922	2.925	2.930	2.935	2.938	2.939	2.944	2.949	2.958	2.977	2.996	3.032	3.086
400	2.771	2.772	2.774	2.777	2.779	2.781	2.782	2.785	2.787	2.793	2.803	2.813	2.832	2.868
500	2.604	2.604	2.605	2.607	2.609	2.610	2.610	2.612	2.613	2.616	2.623	2.629	2.640	2.662

TABLE 2-IV CHANGE OF HYDROGEN INTERNAL ENERGY WITH RESPECT TO TEMPERATURE AT CONSTANT PRESSURE, $(\frac{\partial u}{\partial T})_P$ for $T > T_{CRIT}$ OR QUALITY = 1

T \ P	14.696	50	100	150	187.51	200	250	300	400	600	800	1200	2000
25	1.619	1.577	1.560	1.546	1.545	1.544	1.543	1.542	1.517	1.465	1.463	1.409	1.381
36.483	2.33	2.311	2.255	2.205	2.170	2.159	2.118	2.080	1.959	1.900	1.813	1.677	1.500
41.299		2.68	2.594	2.516	2.464	2.448	2.388	2.334	2.240	2.095	1.984	1.823	1.614
45.406		3.150	3.046	2.914	2.828	2.802	2.709	2.629	2.495	2.300	2.160	1.965	1.731
52.072			5.028	4.297	3.947	3.855	3.564	3.352	3.055	2.698	2.479	2.209	1.918
56.645				8.715	6.927	6.256	4.917	4.292	3.634	3.031	2.720	2.377	2.041
59.357					33.107	14.277	6.205	4.950	3.949	3.179	2.820	2.441	2.085

TABLE 2-V CHANGE OF HYDROGEN INTERNAL ENERGY WITH RESPECT TO TEMPERATURE AT CONSTANT PRESSURE, $(\frac{\partial u}{\partial T})_p$ FOR $T < T_{CRIT}$ AND QUALITY = 0

P \ T	32	44	52	56	58	59.357	60	62	66	70	80	100	150	200	500
1.000	.3020	.4007	.3184	.2869	.2733	.1655	.2603	.2486	.2270	.2087	.1713	.1211	.0584	.0355	.0000
6.446	.4390	.2467	.2022	.1827	.1671	.1667	.2343	.2216	.2056	.1857	.1539	.1106	.0599	.0350	.0029
42.334		.3989	.2485	.2128	.2000	.1910	.1869	.1764	.1589	.1433	.1188	.0872	.0518	.0354	.0101
99.392			.5401	.3282	.2817	.2782	.2485	.2243	.1900	.1664	.1291	.0906	.0524	.0355	.0103
142.027				.9466	.5438	.4877	.3753	.3021	.2288	.1895	.1257	.0929	.0524	.0355	.0102
150.0					.5934	.5596	.3990	.3166	.2360	.1938	.1358	.0933	.0524	.0355	.0102
167.848					1.923	1.191	.8034	.4150	.2643	.2075	.1420	.0942	.0524	.0355	.0102
184.36						4.794	1.178	.5060	.2904	.2201	.1477	.0950	.0525	.0354	.0101
187.51						4.434	1.249	.5234	.2954	.2255	.1488	.0952	.0525	.0354	.0101
193.775						.9970	3.225	.5981	.3098	.2285	.1505	.0957	.0525	.0355	.0101
200						.8940	2.455	.6892	.3247	.2344	.1520	.0959	.0524	.0355	.0100
220						.3053	.3615	1.427	.3880	.2564	.1573	.0968	.0524	.0355	.0101
230						.2268	.2648	1.400	.4274	.2700	.1600	.0973	.0524	.0355	.0101
240						.1857	.2193	.7767	.4719	.2834	.1628	.0978	.0524	.0355	.0101
250						.1586	.1836	.4868	.5217	.2977	.1657	.0983	.0524	.0355	.0100
280						.1136	.1267	.2283	.6088	.3439	.1743	.0996	.0523	.0354	.0100
300						.1021	.1068	.1731	.5051	.3692	.1792	.1004	.0523	.0354	.0100
400						.0586	.0618	.0798	.1438	.2403	.1954	.1033	.0518	.0353	.00984
600						.0334	.0349	.0407	.0558	.0765	.1297	.1001	.0503	.0349	.00954
800						.0235	.0243	.02733	.0347	.0439	.0716	.0849	.0483	.0342	.00927
1200						.0145	.0148	.01623	.0191	.0231	.0338	.0513	.0420	.0317	.00872
2000						.00731	.00747	.00811	.00943	.0109	.0148	.0227	.0284	.0248	.00774

TABLE 2-VI CHANGE OF HYDROGEN INTERNAL ENERGY WITH RESPECT TO PRESSURE AT CONSTANT TEMPERATURE, $-\left(\frac{\partial u}{\partial P}\right)_T$ FOR $T > T_{CRIT}$ OR QUALITY = 1

P \ T	32	44	52	56	58	59.357
6.446	.00977					
42.334	.00939	.0276				
99.329	.00876	.0243	.0782			
142.027	.00835	.0224	.0615	.2128		
150.0	.00827	.0220	.0583	.1430		
167.848	.00809	.0213	.0542	.1077	.6544	
187.51	.00790	.0205	.0496	.1077	.2432	4.434
193.76	.00785	.0203	.0485	.1022	.2140	.9970
200	.00779	.0201	.0473	.0967	.1848	.8940
220	.00762	.0193	.0439	.0837	.1383	.3053
230	.00753	.0190	.0425	.0790	.1239	.2268
250	.00737	.0184	.0400	.0700	.1033	.1586
300	.00698	.0170	.0348	.0555	.0746	.1021
400	.00627	.0147	.0276	.0401	.0492	.0586
600	.00510	.0116	.0197	.0260	.0300	.0334
800	.00417	.00932	.0151	.0191	.0215	.0235
1200	.00278	.00642	.00996	.0122	.0134	.0145
2000	.00113	.00327	.00518	.00628	.00686	.00731

TABLE 2-VII CHANGE OF HYDROGEN INTERNAL ENERGY WITH RESPECT TO PRESSURE AT CONSTANT TEMPERATURE, $-\left(\frac{\partial u}{\partial P}\right)_T$ FOR $T < T_{CRIT}$ AND QUALITY = 0

TABLE 2-VIII HYDROGEN PROPERTIES INITIALIZATION CHECKOUT

P_F*	T_F*	T_S	T_S Ref+	U_F	U_F Ref+	DENSITY	DENSITY Ref+
15.0	34.0	36.592	36.608	-117.518	-116.346	4.5170	4.5156
25.0	34.0	39.878	39.975	-116.702	-116.459	4.5223	4.5210
500.0	34.0	59.357**	59.357	-127.327	-124.041	4.7330	4.7339
14.7	36.0	36.484	36.483	-113.082	-111.964	4.4395	4.4386
40.0	42.0	43.412	43.536	- 98.091	- 97.247	4.1836	4.1858
1600.0	46.0	59.357**	59.357	-109.811	-104.848	4.7959	4.7963
25.0	350.0	39.878	39.975	759.714	761.268	0.01348	0.01342
25.0	500.0	39.878	39.975	1169.064	1170.647	0.0096	0.0094
15.0	40.0	36.592	36.608	54.677	54.719	0.07788	0.07626
1600.0	500.0	59.357**	59.357	1152.092	1156.058	0.5712	0.5616
15.0	460.0	36.592	36.608	1062.776	1065.545	0.0062	0.0061
1400.0	220.0	59.357**	59.357	346.155	347.972	1.1139	1.1222
200.0	240.0	59.357**	59.357	432.521	438.374	0.1567	0.1555

*INPUT DATA

+DATA FROM REFERENCE 6

**$T_S = T_{CRITICAL}$ FOR $P_F \geq P_{CRITICAL}$

TABLE 2-IX TCTP INTERNAL ENERGY VALUES

	INITIAL CONDITIONS				CONDITIONS AFTER 5 TIME STEPS			
NODE	PRESSURE	TEMPERATURE	U_I	U^+_{IREF}	PRESSURE	TEMPERATURE	U_F	U^+_{FREF}
1	42.36	38.66	-107.082	-106.041	43.5689	38.660	-106.092	-106.061
10	42.36	38.66	-107.082	-106.041	43.5697	38.782	-106.803	-105.757
20	14.70	520.00	1220.310	1222.597	15.1862	36.610	- 76.310	2 PHASE
30	14.70	520.00	1220.310	1222.597	15.0186	266.141	536.303	517.685
40	14.70	520.00	1220.310	1222.597	14.9574	451.269	1041.333	1042.181
50	14.70	520.00	1220.310	1222.597	14.9341	507.876	1188.740	1191.167
60	14.70	520.00	1220.310	1222.597	14.9110	518.865	1217.355	1219.653
70	14.70	520.00	1220.310	1222.597	14.9016	520.412	1221.838	1223.654
80	14.70	520.00	1220.310	1222.597	14.8862	520.495	1221.598	1223.868
90	14.70	520.00	1220.310	1222.597	14.8718	520.451	1221.485	1223.755
100	14.70	520.00	1220.310	1222.597	14.8641	520.784	1222.352	1224.461
110	14.70	520.00	1220.310	1222.597	14.8592	520.868	1222.569	1224.483
120	14.70	520.00	1220.310	1222.597	14.8437	343.954	750.502	744.070
130	14.70	520.00	1220.310	1222.597	14.7000	517.417	1213.584	1215.901
150	14.70	520.00	1220.310	1222.597	15.0386	308.420	648.383	640.732
160	14.70	520.00	1220.310	1222.597	14.9134	477.528	1109.713	1111.998
170	14.70	520.00	1220.310	1222.597	14.8953	512.666	1201.213	1203.584
180	14.70	520.00	1220.310	1222.597	14.9253	135.970	206.459	205.477
190	14.70	520.00	1220.310	1222.597	14.8592	214.812	383.450	376.537
200	14.70	520.00	1220.310	1222.597	14.7567	471.801	1101.476	1096.751
210	14.70	520.00	1220.310	1222.597	14.7000	474.537	1105.285	1103.987

+DOUBLE LINEAR INTERPOLATION OF REFERENCE 6 DATA

3.0 STUDY OF THE SSME DYNAMIC MODEL

The SSME dynamic model structure and analytical methods were studied to insure that no unresolvable program inconsistancies exist between TCTP and the dynamic model, to provide support for the SSME dynamic analysis, to establish TCTP/dynamic model linkage and interface points and to insure availability of TCTP boundary conditions from the dynamic model. Compatibility of the TCTP and the SSME dynamic model is discussed in Section 3.1. Support provided for the SSME dynamic analysis is discussed in Section 3.2. TCTP/dynamic model linkage and interface points as well as TCTP boundary condition availability are discussed in Section 3.3.

3.1 TCTP/DYNAMIC MODEL COMPATIBILITY

The basic SSME dynamic model structure was studied initially and the input and output schemes were analyzed. Primary emphasis was then applied to the dynamic model fuel system simulation subprogram FUELF and the subprograms called by FUELF. No unresolvable inconsistencies between the dynamic model and TCTP were found and the two programs were judged compatible. A potential problem does exist in deriving one boundary condition from available dynamic model data. This boundary condition is discussed in detail in Section 3.3.

It was noted that only one basic difference exists in physical units employed by each of the programs. TCTP employs length in feet, while the dynamic model employs length in inches. However, this difference can be accounted for in a linked program containing both TCTP and the dynamic model by use of pre-processor and post-processor routines to transform the required parameters.

3.2 SSME DYNAMIC ANALYSIS SUPPORT

This study did not reach the point of integration of the TCTP and SSME Dynamic Model. Therefore, no support was required for the SSME dynamic analysis during the effort reported here.

3.3 BOUNDARY CONDITIONS AND INTERFACE POINTS

A primary goal of this study was incorporation of TCTP into the SSME dynamic model. Although this goal was not accomplished under the present contract, methodology and requirements for linkage of the two programs were derived. Methodology and requirements for linkage of the two programs are discussed in this section.

In order to accomplish the incorporation of TCTP into the dynamic model, TCTP would be substituted for the hydrogen system subroutine FUELF during a specified interval of the simulated engine buildup. With this one for one substitution, the program interface point would be the main routine of the dynamic model. Data normally supplied to other portions of the dynamic model by FUELF would be supplied by TCTP. Logic would be inserted into the dynamic model main routine to switch from TCTP to FUELF at a specified time during the simulation. At the end of the TCTP simulation, FUELF would be initialized by insertion of final TCTP values for thermophysical properties into the dynamic model common storage and execution of the initialization portion of FUELF. This initialization procedure would be similar to executing the non-zero start (restart) capability already available in the dynamic model.

Pre-processor and post-processor routines would be required to make the two programs compatible. These routines would perform data transformation and data storage functions at every time slice during the simulation. The pre-processor routine would transform the required data, derived in other portions of the dynamic model, into a form which is usable in TCTP and then store these data for TCTP use. The post-processor routine would transform the required data, derived in TCTP, into a form which is usable in the remainder of the dynamic model, perform any auxilliary computations required for continuity of simulation, and store these data for dynamic model use. Preliminary cross reference lists which define variables to be included in pre-processor and post-processor routines were derived during this effort.

3.3 (Continued)

Review of the SSME dynamic model code and the engine physical configuration indicates that boundary points for the TCTP simulation of the SSME hydrogen system should be established at the following:

High pressure fuel pump discharge
Fuel preburner combustion chamber
Oxygen preburner combustion chamber
Low pressure fuel turbine inlet

The high pressure fuel pump discharge represents the system supply node for TCTP simulation. Boundary conditions required at this point are pump discharge flowrate and temperature. These boundary data may be derived from a pump model located in either the TCTP routine or in another portion of the dynamic model. The boundary conditions pump model should be located for the most efficient use of computer run time.

The fuel and oxygen preburner combustion chambers provide boundary conditions for the main system leg and one branch leg in the TCTP simulation. The required boundary condition at these points are pressures. Dynamic model variables PFP and POP represent the combustion chamber pressures for the fuel and oxygen preburners. These variables provided the required boundary conditions for TCTP simulation.

The inlet of the low pressure fuel turbine provides a boundary for the remaining hydrogen system branch leg. The required boundary condition at this point is pressure. This pressure is calculated in FUELF as a function of the main chamber cooling circuit discharge pressure P(6). Since the turbine inlet pressure is computed from what would necessarily be an internal node for TCTP, a change in the SSME dynamic model computation procedure would be required in order to provide the necessary boundary condition for TCTP. Under this changed procedure, turbine inlet pressure would be calculated as a function of downstream pressure

3.3 (Continued)

and the previous time step value of flowrate. This technique is similar to current POP and PFP computations and appears viable.

4.0 SSME HYDROGEN SYSTEM ANALYSIS

Feasibility of incorporating TCTP into the SSME dynamic model is contingent upon the ability of TCTP to simulate the SSME hydrogen system performance. In order to demonstrate the feasibility of applying TCTP to the SSME hydrogen system, a checkout case was executed on a typical SSME data set. The basis for this typical SSME data set was a system description derived from the system physical characteristics and ISTB test sixteen. Pump discharge flowrates and temperatures derived from test sixteen data, were input directly into TCTP as functions of time. Other test sixteen data were used directly for outlet boundary conditions.

The checkout case input data and results are presented in this section. The SSME hydrogen system description is given in Section 4.1. The heat transfer model used in the checkout case is discussed in Section 4.2. Boundary conditions used for the checkout are given in Section 4.3. Results of the simulation are given in Section 4.4.

4.1 SSME HYDROGEN SYSTEM DESCRIPTION

Information provided by Teledyne Brown Engineering Company (Reference 8) was used to derive TCTP physical description input data. The information provided by Brown included the physical dimensions (lengths, diameters, volumes) of the system components, component materials, material specific heats, and component equivalent masses. A schematic representation of the hydrogen system is given in Figure 4-1. As shown in Figure 4-1, one main leg, one parallel leg and two branch legs were required to describe the system.

Twenty-one nodes were used to partition the system, fourteen nodes in the main leg and a minimum of two nodes in each of the other three legs. Node physical descriptions are given in Table 4-I. For situations in which several small ducts were parallel flow paths internal to a node (MCC and nozzle cooling jackets) or manifolds and ducts were lumped, a single equivalent area was chosen for the node. Equivalent

4.1 (Continued)

lengths and diameters were then computed from appropriate volumes and this equivalent area.

Equivalent length to diameter ratios for each node were developed from resistances given in the SSME Model, Engine Data Reduction and Prediction Computer Program description (Reference 9) and output for ISTB case 145 (60 % power level, Reference 10). The program description and output were provided by NASA/MSFC. Resistances for the SSME along with steady state pressure drops, flow splits and densities are given in Table 4-II. Resistance was converted to equivalent length to diameter ratios by applying the following equation:

$$(L/D)_e = 27.951\ A_e^2\ R$$

where $(L/D)_e$ = equivalent length to diameter ratio

A_e = node equivalent area in IN^2

R = node resistance in $LB_M SEC^2/LB_F IN^2 FT^3$

This equation implicitly assumes a fully developed turbulent flow friction factor of 0.016.

4.2 SSME HEAT TRANSFER MODEL

Heat transfer data for input to TCTP are summarized in Table 4-III. Verified analytical or experimental heat transfer input data were not available for the feasibility study of TCTP application to the SSME hydrogen system analysis. Therefore, for the feasibility study, the following assumptions were made to provide heat transfer input data:

1. An ambient temperature of 520°R and an external film coefficient of 10 $BTU/FT^2 \cdot HR \cdot °R$ were assumed for the entire system during the start transient. These assumptions resulted in an external steady

4.2 (Continued)

state heat load of 1.34 BTU/FT^2·SEC for the insulated portions of the system. Insulation on that portion of the system from the pump discharge to the main fuel valve inlet reduces the external steady state heat load to 0.0295 BTU/FT^2·SEC.

2. The effective mass to be chilled down was assumed for the massive components such as valves, distributors and mixers, with relatively small internal heat transfer surface areas. The actual surface areas and wall thicknesses were used to determine the component mass for other components such as ducts and tubes.

3. Constant values of wall specific heat were assumed. A specific heat of 0.075 BTU/LB_M·°R was assumed for the inlet portions of the system with relatively low expected temperatures. A value of 0.085 BTU/LB_M·°R was used for the main chamber coolant inlet duct, manifold, and cooling tubes to the throat. For the remainder of the system expected to reach relatively high temperatures, a specific heat of 0.09 BTU/LB_M·°R was used. A relatively simple program modification to input specific heat as a function of wall temperature could be incorporated at a later date when better external heat transfer data are available.

4.3 BOUNDARY CONDITIONS

Boundary conditions for the TCTP checkout case were derived from ISTB engine test data, test number sixteen. The following measurements were used to generate the required data:

MEASUREMENT	DESCRIPTION
PID 310	High Pressure Fuel Pump Discharge Pressure
PID 313	Low Pressure Fuel Turbine Inlet Pressure
PID 317	Oxygen Preburner Fuel Manifold Pressure
PID 318	Fuel Preburner Fuel Manifold Pressure

4.3 (Continued)

MEASUREMENT	DESCRIPTION
PID 424	High Pressure Fuel Pump Discharge Temperature
PID 481	Fuel Flowmeter Count
PID 492	High Pressure Fuel Pump Speed

The derived boundary conditions serve to simulate conditions at the SSME dynamic model interfaces for the feasibility study.

Due to a lower than measurable flow rate, a flow rate schedule was assumed during the first 0.7 second of the simulation. During the 0.0 to 0.24 second time period the main fuel valve (MFV) apparently leaks a very small flowrate into the system. At 0.24 second the main port starts to open and flowrate increases until system pressure losses become sufficient to reduce the flow to a value which was assumed constant. This assumed flow profile is shown in Figure 4-2.

4.4 SIMULATION RESULTS

The checkout case using a typical SSME data set was executed on TCTP. Stable program operation was observed for the first 0.31 seconds of simulation (20 time slices). System pressure profiles closely match test data from test sixteen. However, temperatures calculated during the simulation characteristically fall off more quickly than test data. Noting that sensor lag may influence some of the apparent error, these results indicate two things: first, the assumed flowrates during the leak portion of valve opening are high, and second, the volumes, heat transfer rates and wall masses of some of the components in the system physical description are low. Typical pressure and temperature profile comparison of calculated and test data are shown in Figure 4-3.

Program convergence problems were encountered after 0.31 second. This problem occurred in the branch leg iteration and can be alleviated by restructuring the iteration scheme to insure convergence. However the current contract schedule precludes further program development and checkout.

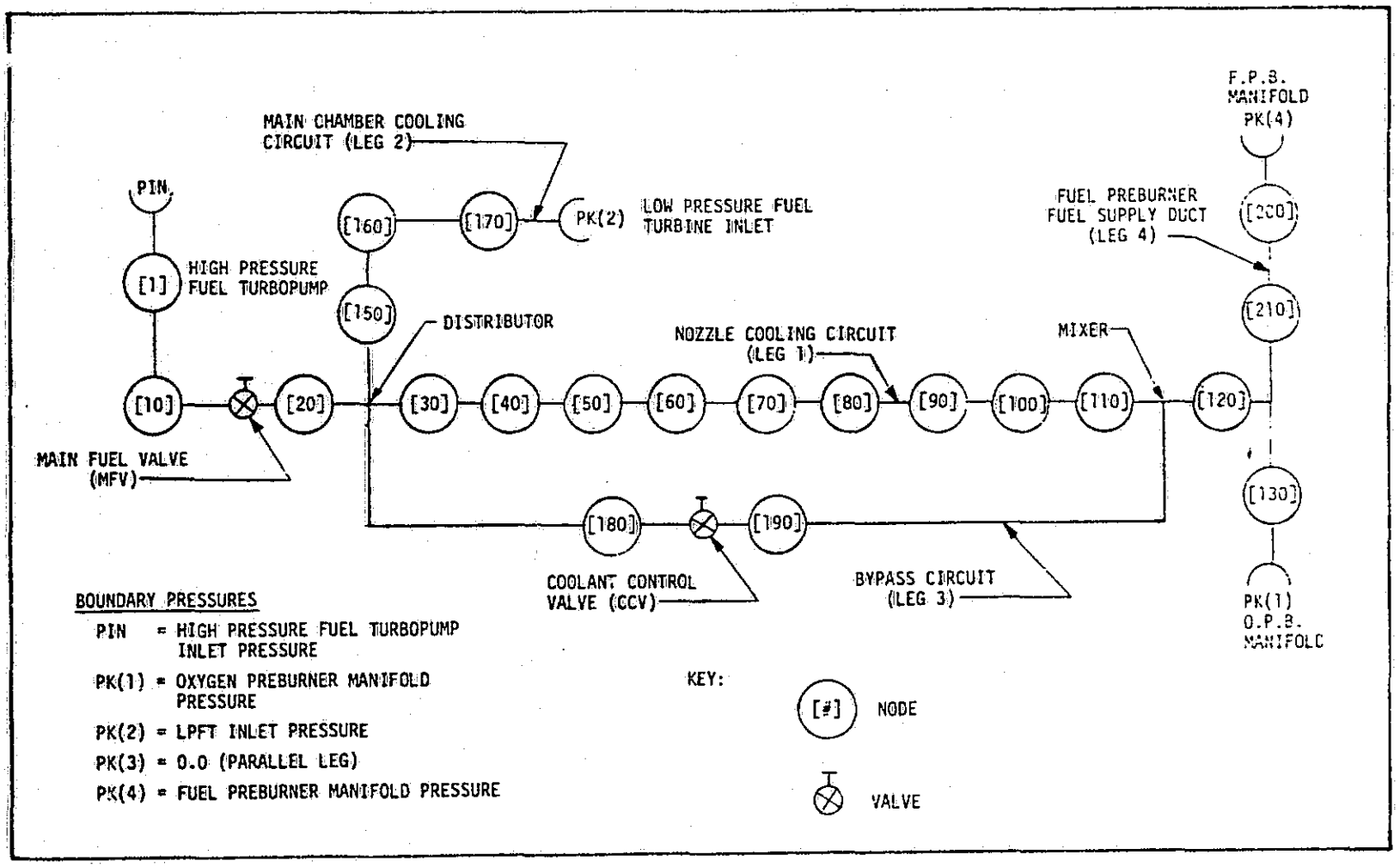

FIGURE 4-1 SSME HYDROGEN SYSTEM SCHEMATIC WITH TCTP NODES IDENTIFIED

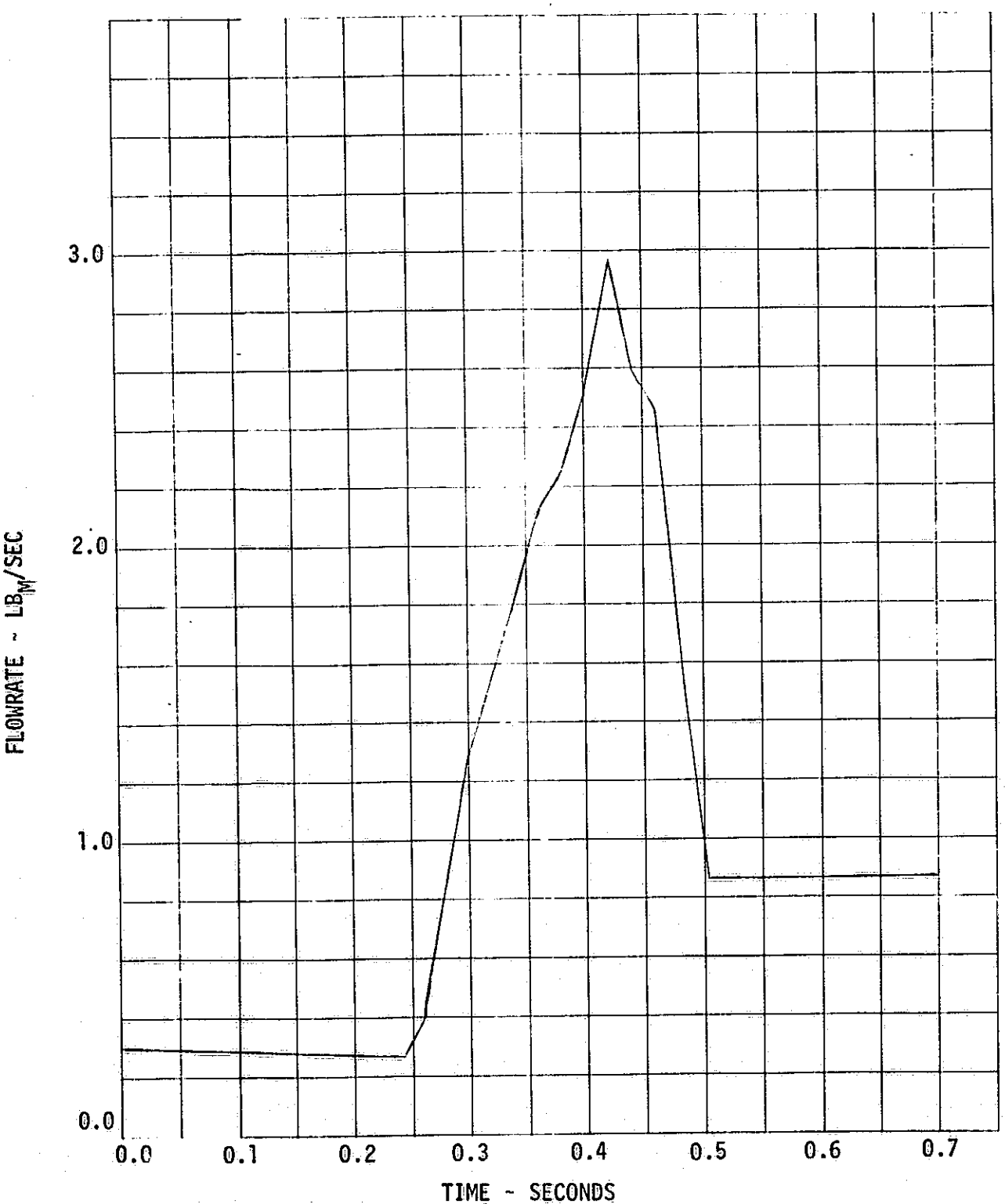

FIGURE 4-2 ASSUMED PUMP DISCHARGE FLOWRATE DURING MFV TRANSIENT

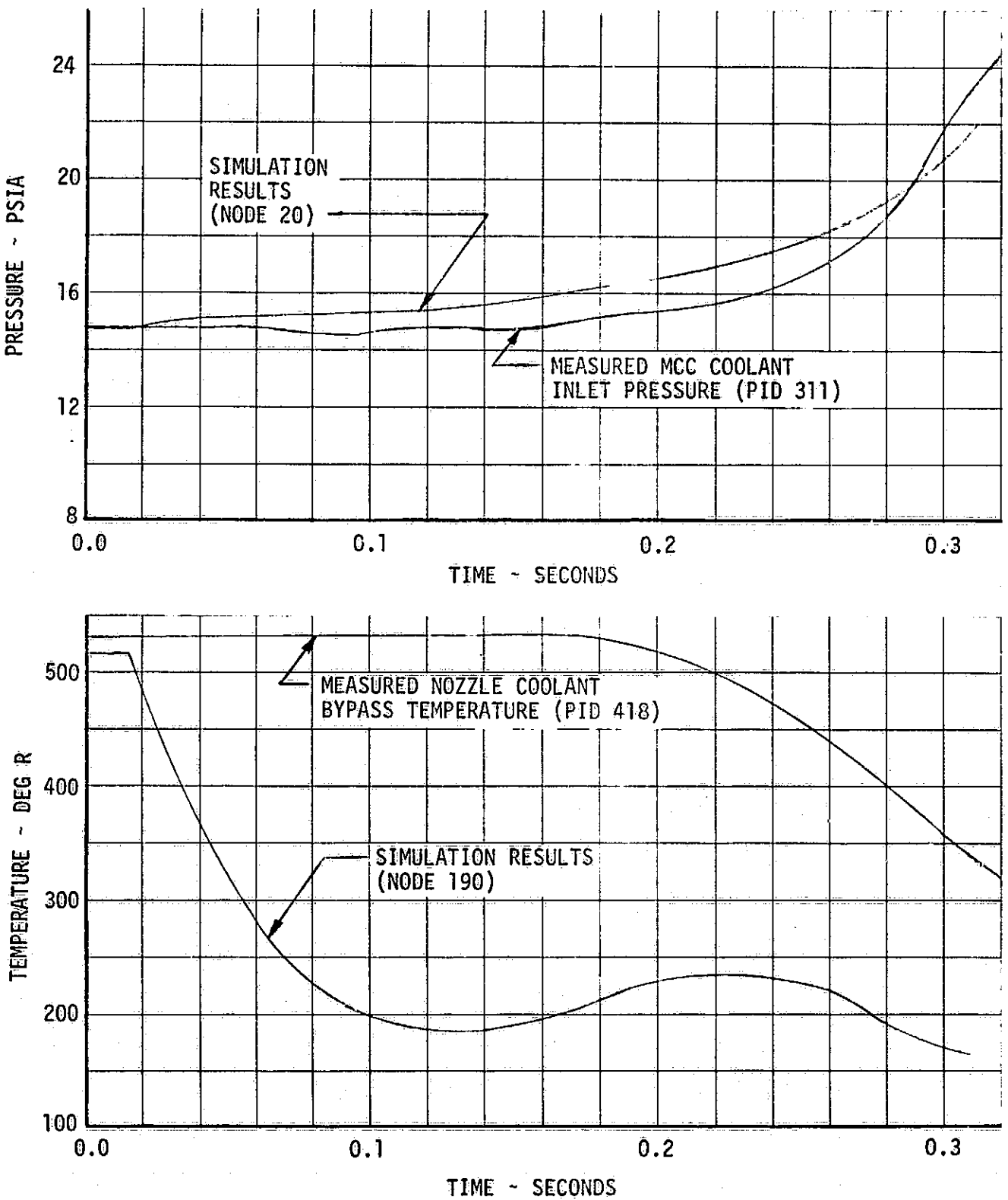

FIGURE 4-3 COMPARISON OF TYPICAL SIMULATION RESULTS WITH TEST 16 DATA

TABLE 4-I SSME HYDROGEN SYSTEM NODAL INPUT DATA FOR FEASIBILITY STUDY

NODE NO.	DESCRIPTION	LENGTH* (FT)	INTERNAL DIA. (EQUIV-FT)	INCLUDED COMPONENTS	EQUIV. $(L/D)_e$**	WALL MASS (LB_M)	WALL C_p ($BTU/LB \cdot {}^\circ R$)
10†	HPFTP DISCHARGE TO MFV INLET	2.96	0.2833	3 BENDS (75°,61°,& 90°) 2.96 FT. LINE	51.60	41.44	0.075
20	MFV TO FLOW DISTRIBUTOR	0.7923	0.2729	MFV & MFV DISCHARGE DUCT	229.21	8.6	0.075
30	FLOW DISTRIBUTOR TO NOZZLE INLET MANIFOLD	9.009	0.1875	NOZZLE COOLING INLET DUCT (1/2 EQUIV. TUBE)	47.97	16.266	0.075
40	FLOW DISTRIBUTOR TO NOZZLE INLET MANIFOLD	9.009	0.1875	NOZZLE COOLING INLET DUCT (1/2 EQUIV. TUBE)	47.97	16.266	0.075
50	NOZZLE INLET MANIFOLD	8.43	0.2083	1/2 INLET MANIFOLD	24.72	65.76	0.090
60	NOZZLE INLET MANIFOLD	8.43	0.2083	1/2 INLET MANIFOLD	24.72	65.76	0.090
70	NOZZLE COOLING TUBES	2.5435	0.38702	1/3 EQUIV. TUBE	962.54	32.37	0.090
80	NOZZLE COOLING TUBES	2.5435	0.38702	1/3 EQUIV. TUBE	962.54	32.37	0.090
90	NOZZLE COOLING TUBES	2.5435	0.38702	1/3 EQUIV. TUBE	962.54	32.37	0.090
100	1/2 NOZZLE COOLING TUBE DISCHARGE TO MIXER	3.6979	0.25	1/2 (OUTLET MANIFOLD & DISCHARGE DUCT)	52.595	53.11	0.090
110	(1/2 NOZZLE COOLING TUBE DISCHARGE TO MIXER) PLUS MIXER	4.0665	0.25	1/2 (OUTLET MANIFOLD & DISCHARGE DUCT) + MIXER	56.89	55.52	0.909
120	PREBURNER SUPPLY DUCT	1.539	0.30	18.5"-3.6" LINE FROM MIXER TO TEE	20.56	6.0	0.090

†INSULATED NODE K = 0.01667 BTU/(HR·FT·°R), ΔX = 0.074 FT.

*EQUIVALENT LENGTH = $V/A_{eq.}$; $A_{eq.} = \pi(D_e)2/4$; $(L/D)_e \equiv K_e/f = K_e/0.016$

**$(L/D)_e \equiv (K_e/f) = K_e/0.016$; $K_e \equiv \Delta P_f/(\rho V^2/288 \cdot gc)$

TABLE 4-I SSME HYDROGEN SYSTEM NODAL INPUT DATA FOR FEASIBILITY STUDY (Cont'd)

NODE NO.	DESCRIPTION	LENGTH* (FT)	INTERNAL DIA. (EQUIV.,FT)	INCLUDED COMPONENTS	EQUIV. $(L/D)_e$**	WALL MASS (LB_M)	WALL C_p (BTU/LB·°R)
130	OXIDIZER P.B. INLET DUCT & MANIFOLD	4.43	0.1667	23.5"-2" LINE & MANIFOLD	54.62	10.87	0.090
150	DIST. TO AFT MANIFOLD, AFT MANIFOLD AND LOWER PORTION OF MCC COOLING JACKET TUBES	11.0793	0.12485	DIST. TO MANIFOLD LINE, AFT MANIFOLD AND COOLING TUBES TO THROAT	309.1154	25.654	0.090
160	UPPER PORTION OF MCC COOLING JACKET TUBES, FORWARD MANIFOLD AND DISCHARGE DUCT	8.449	0.16667	COOLING TUBE FROM THROAT TO DISCHARGE, FORWARD MANIFOLD AND DISCHARGE DUCT TO FLANGE ON LPFT INLET LINE	1801.32	63.54	0.090
170	DISCHARGE DUCT TO LPFT INLET	5.8788	0.16667	LINE, FLANGES, 3 FLEX JOINTS	65.6835	78.04	0.085
180	DISTRIBUTOR TO CCV INLET	6.2959	0.20375	LINE AND ENTRANCE LOSSES	28.1642	14.78	0.075
190	CCV TO MIXER TUBE OUTLETS	1.98244	0.191266	CCV EXIT, 90 BEND, 7 MIXER TUBES	35.1530	11.21	0.075
200	FUEL PREBURNER INLET DUCT	1.866	0.3167	16"-3.6" LINE 8"-3.8" LINE	42.42	7.87	0.090
210	FUEL PREBURNER MANIFOLD	1.227	0.3167	LINE	42.42	11.97	0.090

*EQUIVALENT LENGTH = $V/A_{eq.}$; $A_{eq.} = \pi(D_e)2/4$; $(L/D)_e \equiv K_e/f = K_e/0.016$

**$(L/D)_e \equiv (K_e/f) = K_e/0.016$; $K_e \equiv \Delta P_c/(\rho V^2/288 \cdot gc)$

TABLE 4-II

STEADY-STATE PRESSURE DROPS AND RESISTANCES FROM CASE 145 (60% POWER LEVEL)

DESCRIPTION	PRESSURE VAR. NAME	STORAGE ARRAY LOC.	CASE 145 VALUE (PSIA)	FLOW-RATE (LBM/SEC)	DENSITY (LBM/FT)	RESISTANCE SEC^2/IN^2FT^3	VAR. NAME	STORAGE ARRAY LOC.
HIGH PRESSURE FUEL PUMP TO DISTRIBUTOR								
High Pressure Pump Discharge	P2FP2	486	3723.13	86.99	4.782	---	---	---
ΔP to MFV Inlet	DP1	254	-35.44	86.99	4.782	0.0224	R1	129
MFV Inlet	P1MFV	458	3687.69	86.99	4.785	---	---	---
ΔP Across MFV	DP3	256	-177.11	86.99	4.743*	0.1110	R3	131
MFV Discharge	P2MFV	515	3510.58	86.99	4.700	---	---	---
ΔP MFV Discharge Duct	DP30	283	-5.75	86.99	4.700	0.00357*	*	---
MFV Discharge Duct Exit	P7	537	3504.83	86.99	4.700	---	---	---
CCV BY-PASS CIRCUIT TO MIXER								
Circuit Inlet=MFV Discharge Duct Exit	P7	537	3504.83	86.99	4.700	---	---	---
ΔP CCV Inlet Duct	DP9	262	-7.66	28.07	4.700	0.04571	R9	137
CCV Inlet	P20	505	3497.17	28.07	4.696	---	---	---
ΔP CCV	DP37	290	-367.98	28.07	4.603*	2.15	R37	165
CCV Discharge	P37	523	3129.19	28.07	4.510	---	---	---
ΔP CCV Outlet Duct	DP38	291	-3.64	28.07	4.510	0.02081	R38	166
Mixer Inlet from By-Pass Side	PMIX1	447	3125.55	28.07	4.510	---	---	---
ΔP Mixer from By-Pass Side	*	320/291	-9.20	28.07	4.510	0.05266*	*	---
Mixer Discharge	PEXTCJ	417	3116.35	67.92	1.587	---	---	---
NOZZLE COOLING CIRCUIT TO MIXER								
Circuit Inlet=MFV Discharge Duct Exit	P7	537	3504.83	86.99	4.700	---	---	---
ΔP Nozzle Cooling Jacket Inlet Duct	*	288/231	-80.03	39.86	4.700	0.2508	R35	163
Cooling Jacket Inlet	P35	521	3424.80	39.86	4.700	---	---	---
ΔP Nozzle Cooling Jacket	DPJ	241	-197.55	39.86	2.900*	0.36058*	*	---
Nozzle Cooling Jacket Discharge	PJ1	438	3227.25	39.86	1.101	---	---	---
ΔP Cooling Jacket Discharge Duct	*	---	-106.36	39.86	1.101	0.07532	R5	133
Mixer Inlet from Nozzle Side	PMIX2	448	3120.89	39.86	1.101	---	---	---
ΔP Mixer from Nozzle Side	*	---	-4.44	39.86	1.101	0.0037068*	*	---
Mixer Discharge	PEXTCJ	417	3116.45	67.92	1.587	---	---	---

*CALCULATED VALUE

TABLE 4-II

STEADY-STATE PRESSURE DROPS AND RESISTANCES FROM CASE 145 (60% POWER LEVEL) (Cont'd)

DESCRIPTION	PRESSURE VAR. NAME	STORAGE ARRAY LOC.	CASE 145 VALUE (PSIA)	FLOW-RATE (LBM/SEC)	DENSITY (LBM/FT)	RESISTANCE SEC^2/IN^2FT^3	VAR. NAME	STORAGE ARRAY LOC.
MIXER TO OXIDIZER PREBURNER								
Mixer Discharge	PEXTCJ	417	3116.35	67.92	1.587	---	---	---
ΔP Preburner Supply Duct	*	---	-20.68	67.92	1.587	0.0071	R52	180
Preburner Supply Duct Discharge	P9	539	3095.67	67.92	1.587	---	---	---
ΔP Supply Disch. to P.B. Duct Disch.	DP41	294	-44.94	21.48	1.587	0.153	R41	169
Ox. P.B. Fuel Manifold Inlet	P41	528	3050.73	21.48	1.587	---	---	---
ΔP Ox. P.B. Fuel Manifold	DP13	266	-13.32	20.92	1.587	0.0450	R13	141
Ox. P.B. Fuel Manifold	P13	477	3037.41	20.92	1.587	---	---	---
MIXER TO FUEL PREBURNER								
Mixer Discharge	PEXTCJ	417	3116.35	67.92	1.587	---	---	---
ΔP Preburner Supply Duct	*	---	-20.68	67.92	1.587	0.0071	R52	180
Preburner Supply Duct Discharge	P9	539	3095.67	67.92	1.587	---	---	---
ΔP Supply Disch. to P.B. Duct Disch.	DP39	292	-16.15	46.44	1.587	0.01180	R39	167
Fuel P.B. Fuel Manifold Inlet	P39	525	3079.52	46.44	1.587	---	---	---
ΔP Fuel P.B. Fuel Manifold	DP17	270	-16.22	45.89	1.587	0.01180	R17	145
Fuel P.B. Fuel Manifold	P17	481	3063.30	45.89	1.587	---	---	---
MCC COOLING CIRCUIT TO LPFT INLET								
Circuit Inlet=MFV Discharge Duct Exit	P7	537	3504.83	86.99	4.700	---	---	---
ΔP MCC Cooling Jacket Inlet Duct	DP33	286	-35.58	18.38	4.700	0.4951	R33	161
MCC Cooling Jacket Inlet	P33	519	3469.25	18.38	4.700	---	---	---
ΔP MCC Cooling Jacket	DPJ2	242	-793.10	18.38	2.733*	6.4172*	*	---
MCC Cooling Jacket Discharge	PJ2	439	2676.15	18.38	0.767+	---	---	---
ΔP Jacket Discharge to Flange	*	---	-49.98	18.38	0.767+	0.1125	R28	156
LPFT Inlet Duct Inlet	P28	513	2626.17	18.38	0.767+	---	---	---
ΔP LPFT Inlet Duct	DP25	278	-108.76	18.38	0.767+	0.2381	R25	153
LPFT Inlet Pressure	P1FT1	461	2517.41	18.38	0.767+	---	---	---

*CALCULATED VALUE
+ASSUMED VALUE

TABLE 4-III STEADY STATE HEAT TRANSFER DATA FOR THE SSME HYDROGEN SYSTEM

NODE NO.	DESCRIPTION	Q_{EXT} BTU/ (FT^2HR)	WALL AREA FT^2	HEAT TRANSFER RATE BTU/HR
1	PUMP DISCHARGE NODE	0.0	0.0	0.0
10	HPFTP DISCHARGE TO MFV INLET	0.029	2.634	0.076
20	MFV TO FLOW DISTRIBUTOR	1.342	0.840	1.127
30	$\frac{1}{2}$(FLOW DISTRIBUTION TO NOZZLE INLET MANIFOLD)		5.776	7.751
40	$\frac{1}{2}$(FLOW DISTRIBUTION TO NOZZLE INLET MANIFOLD)		5.776	7.751
50	$\frac{1}{2}$(NOZZLE INLET MANIFOLD)		6.621	8.885
60	$\frac{1}{2}$(NOZZLE INLET MANIFOLD)		6.621	8.885
70	$\frac{1}{3}$(NOZZLE COOLING TUBES)		101.630	136.387
80	$\frac{1}{3}$(NOZZLE COOLING TUBES)		101.630	136.387
90	$\frac{1}{3}$(NOZZLE COOLING TUBES)		101.630	136.387
100	$\frac{1}{2}$(NOZZLE COOLING TUBE DISCHARGE TO MIXER)		2.904	3.897
110	$\frac{1}{2}$(NOZZLE COOLING TUBE DISCHARGE TO MIXER) + MIXER		3.330	4.469
120	PREBURNER SUPPLY DUCT		1.450	1.946
130	OXIDIZER P.B. INLET DUCT AND MANIFOLD		2.320	3.113
150	FLOW DISTRIBUTION TO MCC THROAT		4.346	5.832
160	MCC THROAT TO MCC COOLING JACKET DISCH. DUCT		4.424	5.937
170	MCC COOLING JACKET DISCH. DUCT TO LPFT INLET		3.078	4.131
180	FLOW DISTRIBUTION TO CCV INLET		4.030	5.408
190	CCV TO MIXER TUBE OUTLETS		1.520	2.040
200	FUEL P.B. INLET DUCT		1.857	2.492
210	FUEL P.B. MANIFOLD	1.342	1.221	1.639
TOTAL		---	362.882	484.540

5.0 CONCLUSIONS AND RECOMMENDATIONS

Results of the TCTP checkout runs to date indicate that application of the TCTP to the SSME hydrogen system is feasible, and that such an application could be used to predict transient one or two-phase flow rate splits in a system with multiple flow paths. Application of the TCTP could also be used to resolve unknown heat transfer parameters by varying these parameters until the overall system transient thermodynamic performance is simulated.

Additional program development would be required in the following areas to develop a fully operational and verified subprogram suitable for incorporation into the SSME dynamic model.

(1) Improvement of iterative convergence logic.

(2) Incorporation of variable wall specific heat.

(3) Further definition and refinement of program interfaces.

(4) Program refinement and verification by comparisons with measured test data.

(5) Optimization of computational time increment to be used in conjunction with the SSME dynamic model.

It is recommended that further program development be pursued and that an improved system definition and heat transfer model be derived during ensuing studies. Detailed analyses of the first 0.7 second of the buildup transient are also recommended. These analyses are needed to derive good system initial conditions for the pump flow transient during buildup.

6.0 REFERENCES

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2. Boeing Letter Report 5-9030-HT-158, "Cryogen Transfer Computer Program Development and Verification," dated September 3, 1974.

3. Boeing Letter Report 2-1056-HT-082, "National Space and Technology Laboratories (NSTL) LOX Loading Facility Analyses," dated May 8, 1975.

4. Boeing Letter Report 2-1056-HT-164, "Kennedy Space Center (KSC) LOX Loading Facility Analyses," dated December 1, 1975.

5. Boeing Document D180-19190-1, "Shuttle LOX Loading Transient Study Final Report," dated December 1, 1975.

6. NBS Technical Note 617, "Thermophysical Properties of Parahydrogen from the Freezing Liquid Line to 5000 R for Pressures to 10,000 Psia," dated April, 1972.

7. Boeing Document, D5-17776-2, "S-II Stage Propulsion Performance Digital Simulation Computer Program (MARK IX)," dated November 29, 1968.

8. Data Coordination Meetings: D. Blount, D. Weiss (Teledyne Brown Engineering Company) J. Richards, V. Glasgow (Boeing Aerospace Company) June 18, 1975; September 12, 1975 and October 28, 1975.

9. Rocketdyne Document RSS-8598, "SSME Model, Engine Data Reduction and Prediction," dated November 1, 1974.

10. ISTB Steady State Power Balance Program, Revision D, Case 145, 60% Thrust, dated April 30, 1975. Received from J. Monk (NASA/MSFC), May 6, 1975.