R

Report No. ACNP-6008

AUG 8 1960

MASTER

PATHFINDER ATOMIC POWER PLANT

IBM-704 PROGRAM FOR REACTOR CONTAINMENT

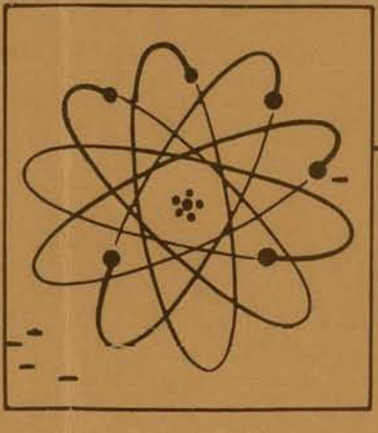
Pressure Suppression Analysis

July 15, 1960

Submitted to
U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
Milwaukee 1, Wisconsin



Ref: AEC Contract No. AT(11-1)-589

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor Allis-Chalmers Manufacturing Company, nor any person acting on behalf of the Commission or Allis-Chalmers Manufacturing Company:

A. Makes any warranty or representation to others, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities to others with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, 'person acting on behalf of the Commission or Allis-Chalmers Manufacturing Company' includes any employe or contractor of the Commission, or Allis-Chalmers Manufacturing Company or employe of such contractor, to the extent that such employe or contractor of the Commission, or Allis-Chalmers Manufacturing Company or employe of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission or Allis-Chalmers Manufacturing Company or his employment with such contractor.

ACNP – 6008

MASTER

ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
MILWAUKEE 1, WISCONSIN

PATHFINDER ATOMIC POWER PLANT

IBM-704 PROGRAM FOR REACTOR CONTAINMENT

Pressure Suppression Analysis

July 15, 1960

This report covers work performed under Allis-Chalmers Manufacturing Company's Purchase Order No. WA-491284-NSP, a part of the research and development program under AEC Contract No. AT(11-1)-589 with Northern States Power Company.

by

E. E. Mason

W. M. Chmielewski

internuclear company 7 N. Brentwood Blvd. • Clayton 5, Missouri
Phone: PArkview 7-2668

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

IBM-704 PROGRAM FOR
REACTOR CONTAINMENT
PRESSURE SUPPRESSION ANALYSIS

DISTRIBUTION

USAEC, Chicago Operations Office - P.O. Box 59, Lemont Ill.	8
USAEC, Division of Reactor Development - Washington 25, D.C.	8
USAEC, TISE, Oak Ridge, Tennessee OFFSET MASTER, PLUS	20
Northern States Power Company & CUAPA	35
Allis-Chalmers Manufacturing Company	39
TOTAL COPIES	110

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

A research and development program to investigate the feasibility of eliminating vapor closure for the Pathfinder reactor was conducted. The investigation was undertaken as part of the research and development program for the 66-mwe Pathfinder Atomic Power Plant, which will be owned and operated by Northern States Power Company of Minneapolis. The plant is being built near Sioux Falls, South Dakota and is scheduled for initial operation in June 1962. Contributing toward the research and development program are the Atomic Energy Commission and Central Utilities Atomic Power Associates, a group of ten midwestern public utility companies. Allis-Chalmers Manufacturing Company is prime contractor for design and construction of the plant.

The major inquiry under the feasibility study involved an analysis of the complex transient conditions occurring in the reactor cavity, the pump rooms, and the entire reactor building following a primary system rupture. To solve the simultaneous non-linear set of equations evolving from the heat, mass, and force balances in the system, an I.B.M. 704 digital computer program was developed. The program has a very general input and can therefore be used with other containment designs. Input parameters include: Initial pressures in reactor and throughout the containment building, heat capacity of vessel, decay heat, feedwater flow rate, enthalpy of feedwater, and volume of primary coolant system.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

The Pathfinder Nuclear Power Plant(1) consists of a heterogeneous light water cooled and moderated forced circulation direct cycle boiling water nuclear reactor and a light water moderated integral nuclear superheater.

An early reference design utilizes a cylindrical containment vessel as depicted by Figures 1.A and 1.B.

Early in the Pathfinder research, development, and design program the desirability of pressure suppression containment was recognized. Such containment is designed so that in the unlikely event of primary system rupture the steam released would be condensed in quenching pools and on the walls of the reactor cavity and pump rooms.

Previous exploratory calculations by Pioneer Service and Engineering Company(5) and Allis Chalmers(4) indicated that compartmentalized building design combined with provisions for quenching steam with shield pool water might reduce to a nominal value the pressure in the reactor building resulting from a primary loop rupture. Under purchase order WA491284-NSP Internuclear Company was retained to study further the feasibility of elimination of containment of a nuclear power plant and to develop adequate engineering calculations and concepts necessary to support such a study.

A preliminary analysis of the transient conditions which might occur in the reactor cavity, the pump rooms and the entire reactor building during the first few minutes after rupture showed that simultaneous time dependent solutions of a number of partial differential equations would be required to adequately study the feasibility of reducing containment.

Further investigation of the problem indicated that the mechanisms by which steam from a primary loop rupture would be condensed on compartment walls, building walls, and in the shield pool are not well understood nor is adequate empirical data as a function of turbulence, velocity degree of superheat, and pool depth available.

In order to accomplish an integrated and supported study it was deemed desirable to first develop the capability to analyze several possible geometric configurations under several possible mechanisms of steam condensation in quenching pools and on building walls. The number of possible permutations and combinations together with the desirability of observing the time dependence of the pressure in the various compartments and in the reactor building indicated the need for an electronic computer code.

Development of such a code has progressed to the point that its feasibility is unquestioned and its usefulness has been established.

The analytical tools are now available to predict transient pressures in the various compartments of any reactor building and in the free volume of the building itself.

In Section 3.0 recommendations are presented for a program designed to establish beyond a doubt the safety and reliability of pressure suppression containment.

The consulting advice and assistance of B. John Garrick of Holmes and Narver Company is gratefully acknowledged, as is the assistance of Dale Mohr, K. H. Gruenwald, and R. W. Klecker of Allis Chalmers Mfg. Company.

Figure 1.A

Structural Concept of Steel Cylinder Reactor Building

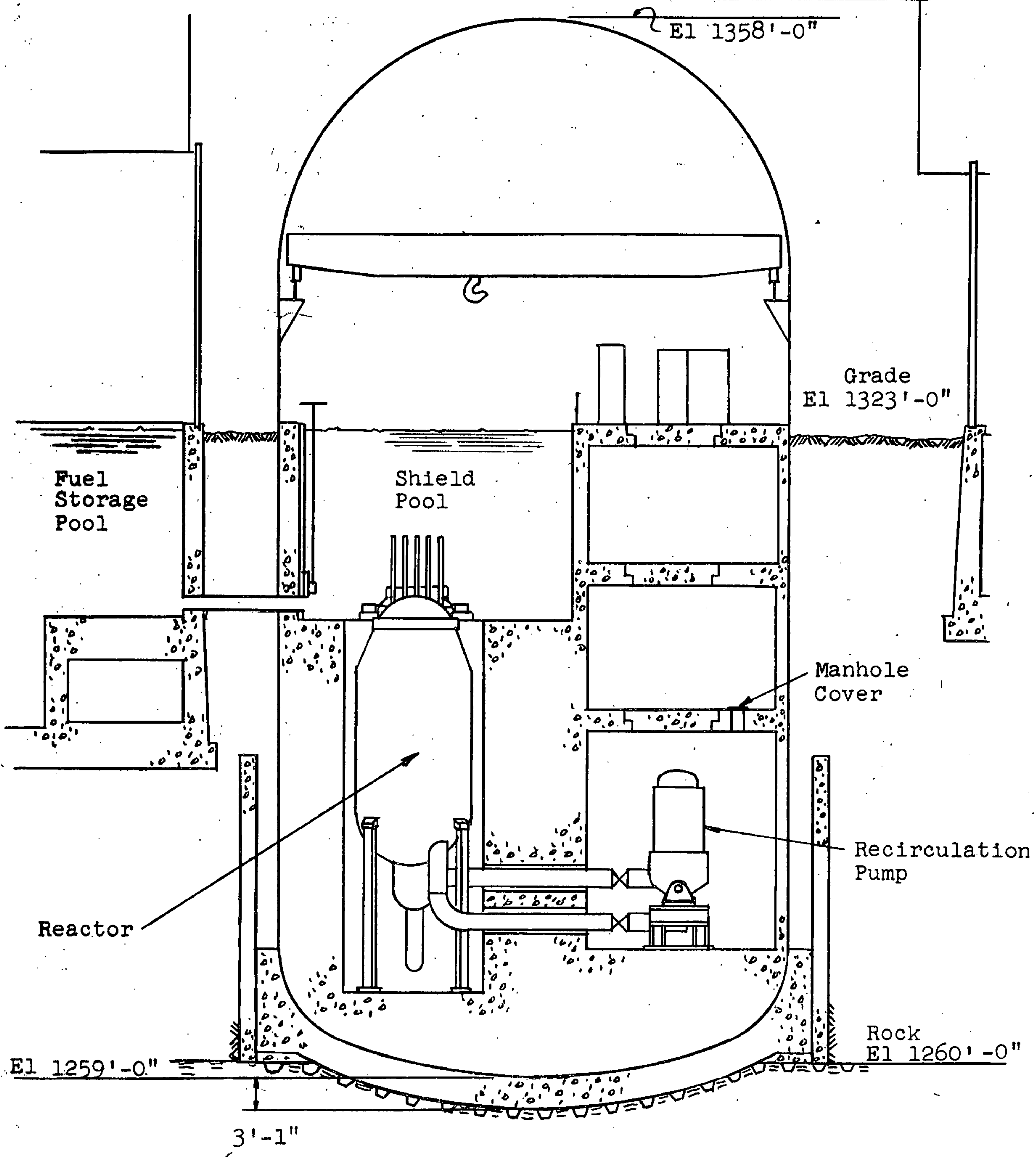
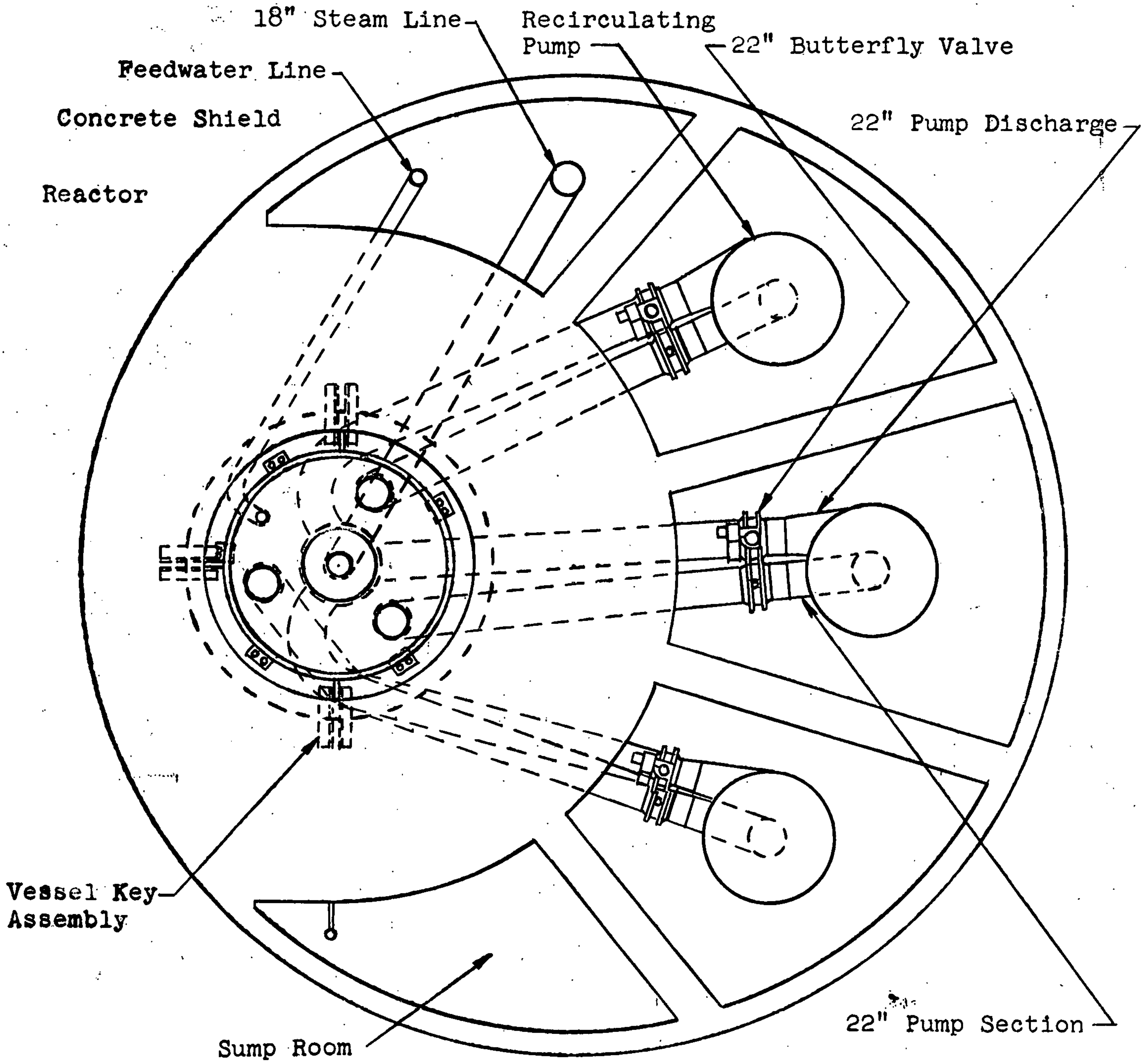


Figure 1.B

Plan View of Reactor Containment Building



2.0 SUMMARY AND RESULTS

Using methods developed by Ketchum(2), the largest hole that results from a ductile rupture of the primary system of the reference design has been shown to be 4.1 inches in equivalent diameter.(3) In such a breach of the primary system, the stored energy of a rapidly released coolant will lead to a pressure rise peaking in a short time and then decaying through heat transfer to the contained air and structure.

Thermodynamic treatment for expansion into a containment structure of a compressed liquid vapor system has been given by J. C. Heap(3). Results, relating pressure in the containment structure to containment volume required per pound of saturated liquid, are shown by Figure 2.A. Applying these results to the reference design Pathfinder Plant the maximum pressure buildup due to coolant expansion is ~80 psi. (Containment free volume 112,000 ft^3, coolant mass in vessel 89,800 lbs.)*

In calculations by Allis Chalmers and Pioneer Service and Engineering Company(4,5) the maximum pressure rise is shown to be about 15 psi for a 6 inch rupture. (Results are shown in Figure 2.C). In these calculations the condensation on the walls is shown to quench the steam and thereby greatly reduce the pressure buildup from the approximately 80 psi theoretical pressure rise with no condensation.

To corroborate and extend these results, and IBM-704 program, described in Appendices A1.0 and A2.0 was written to determine the pressure buildup due to a break in the primary loop. In the program the method of analysis approximates the actual time solution of the partial differential equations by a set of finite difference equations which are solved in a series of time steps. The assumption is made that the time steps are small enough so that the quantities involved do not change appreciably during the time step. These equations are solved explicitly for water volumes at each time increment and system pressures are determined implicitly as time dependent variables. Thermodynamic equilibrium is assumed at any time after the rupture. This is essentially true for a small rupture causing extended blowdown.

The pressure transient program was successfully run up to a time of 44 seconds following rupture. Results are shown plotted in Figures 2.D, 2.E, and 2.F. The pressure versus time in the reactor and building compartments are shown by Figures 2.D and 2.E. The coolant flow out of the rupture in the primary system is plotted versus time in Figure 2.F. The pressures in the reactor building compartments after 22 seconds when the dampers close and at 44 seconds are as follows:

---

* Private Communication, D. Mohr, 3 April, 1959.

Table 2.a

Pressure Buildup in Reactor Building

	22 seconds	44 seconds
Reactor pressure vessel	460.0 psia	427 psia
Reactor cavity	15.7 psia	29 psia
Pump rooms*	15.4 psia	28 psia
Steam chase	15.3 psia	28 psia
Main area	15.3 psia	28 psia

* The three pump rooms are treated identically in the program and combined into one equivalent room.

After 22 seconds, the core in the reactor is uncovered. Consequently, in the program, as in the actual building, the dampers in the intake and exhaust ducts are assumed to close. Also, steam flow to the turbine is shut off.

In the calculation of the above pressures, machine stops occured at time of 22 and 44 seconds after a rupture of the primary system. These machine stops resulted from pressure estimations out of the range of the steam tables that are an integral part of the program. After the 22 second machine stop insertion of a small time step and a lower limit on the pressure estimation resulted in successful pressure calculations to a time of 44 seconds. A minor program correction of a maximum limit of the pressure estimation will result in successful operation of the code throughout the time period of interest.

Figure 2.A

Expansion of One Pound of Saturated Water into a Containment Shell of Dry Air Initially at 14.7 psia and 60°F

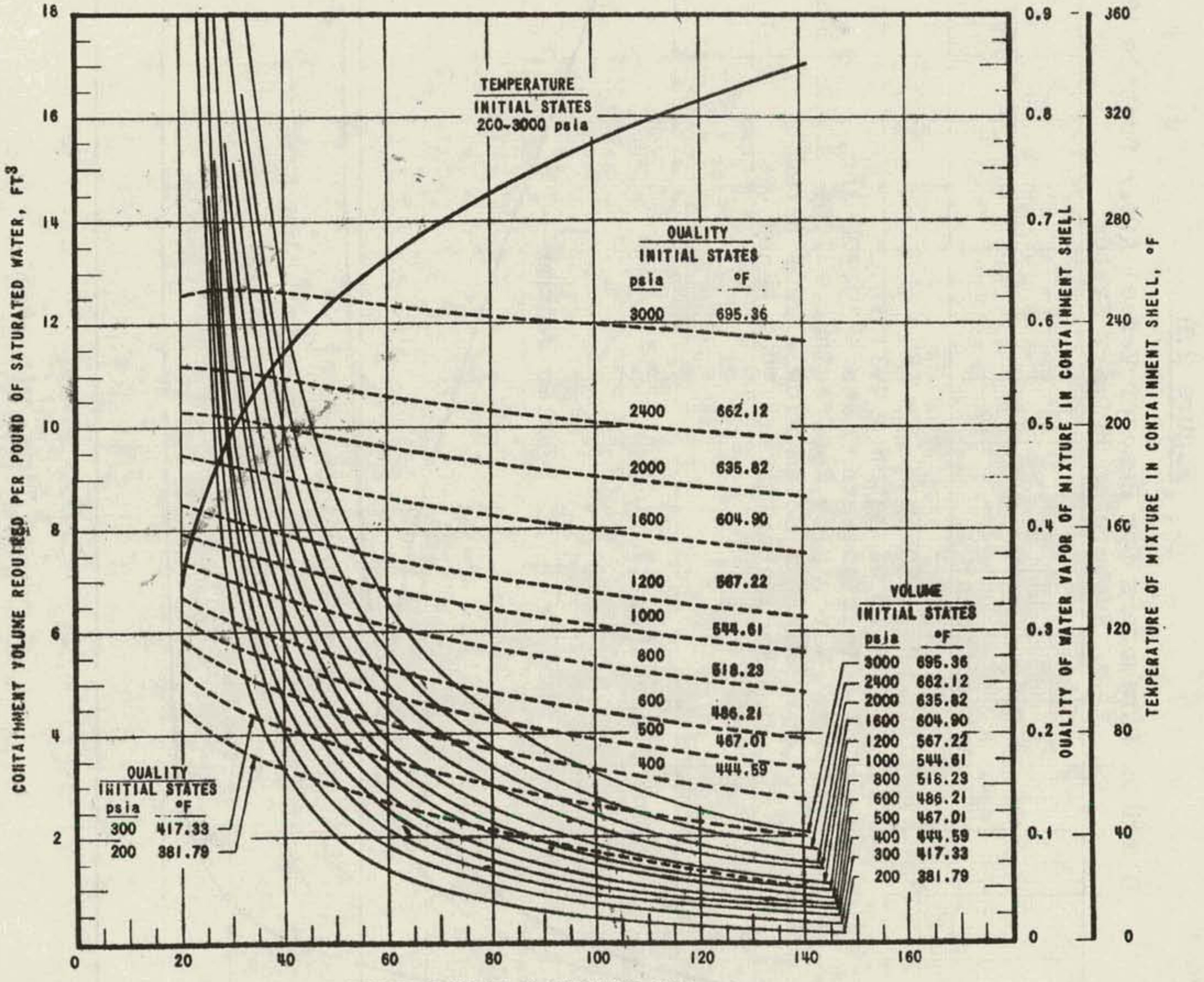


Figure 2.B

Blowdown Parameters for Reactor Vessel After Ductile Water Line Rupture in Primary System

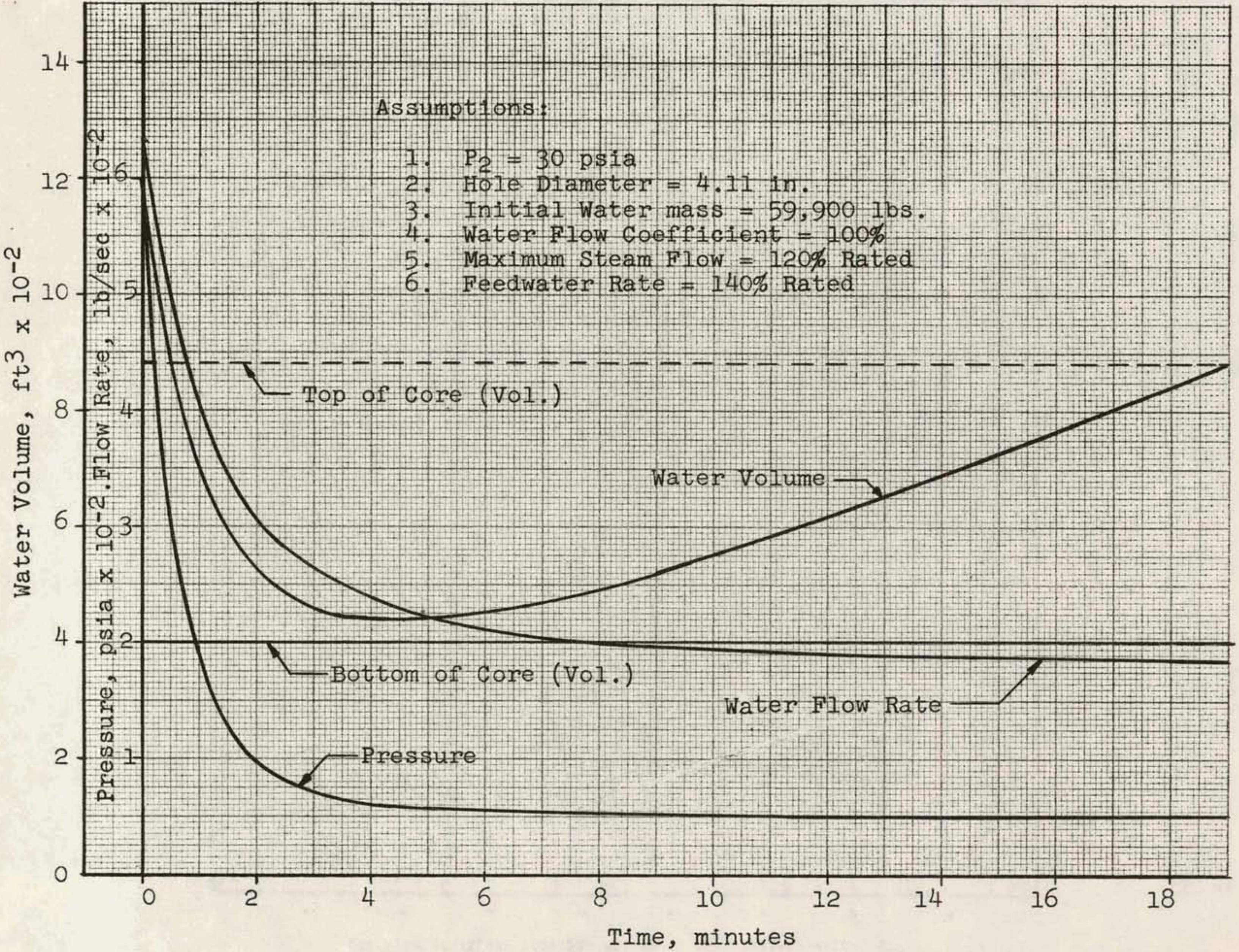
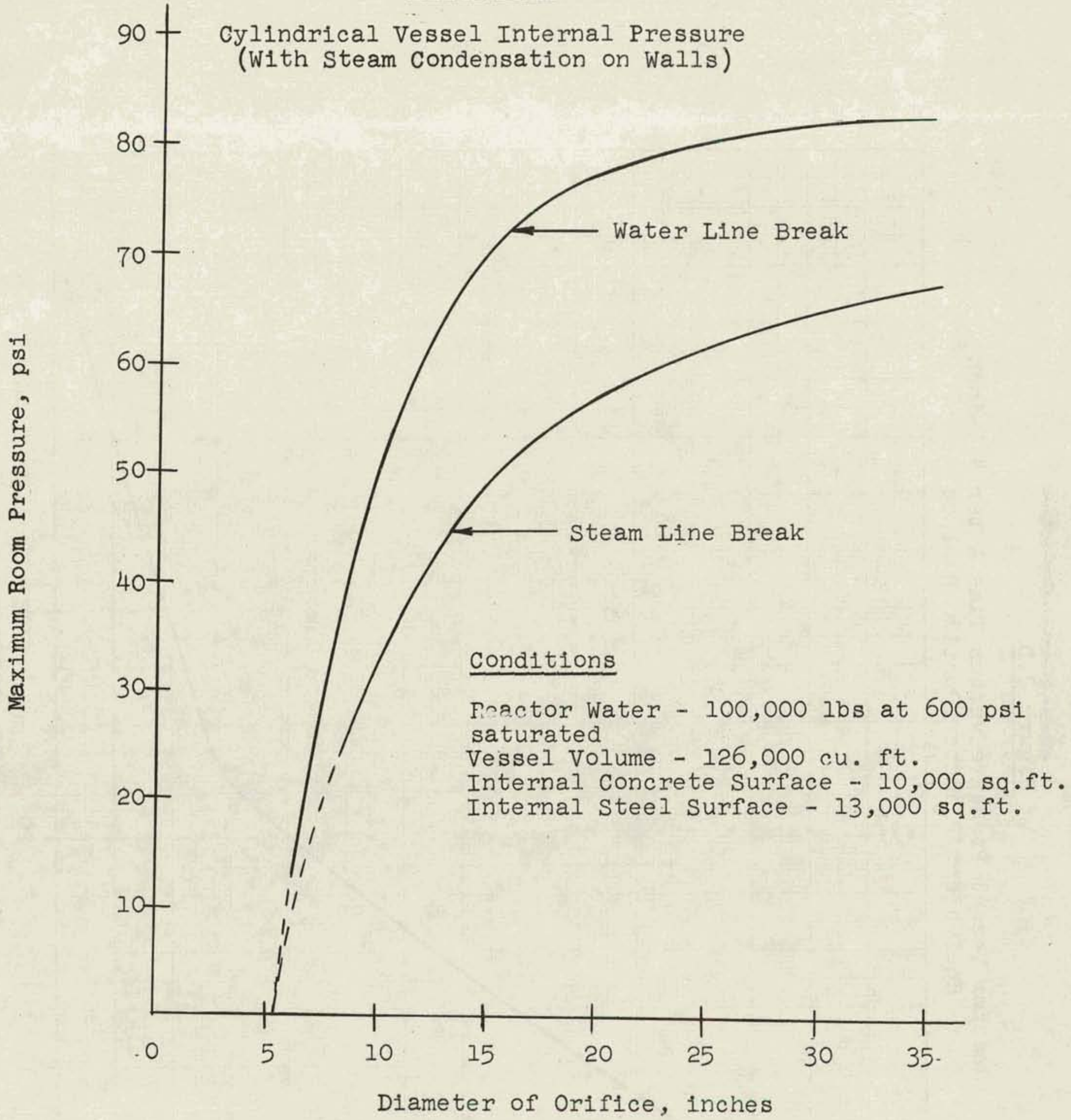


Figure 2.C



Cylindrical Vessel Internal Pressure
(With Steam Condensation on Walls)

Conditions

Reactor Water - 100,000 lbs at 600 psi saturated
Vessel Volume - 126,000 cu. ft.
Internal Concrete Surface - 10,000 sq.ft.
Internal Steel Surface - 13,000 sq.ft.

Figure 2.D

Reactor Vessel Pressure versus Time After 4.1-inch Equivalent Diameter Ductile Rupture

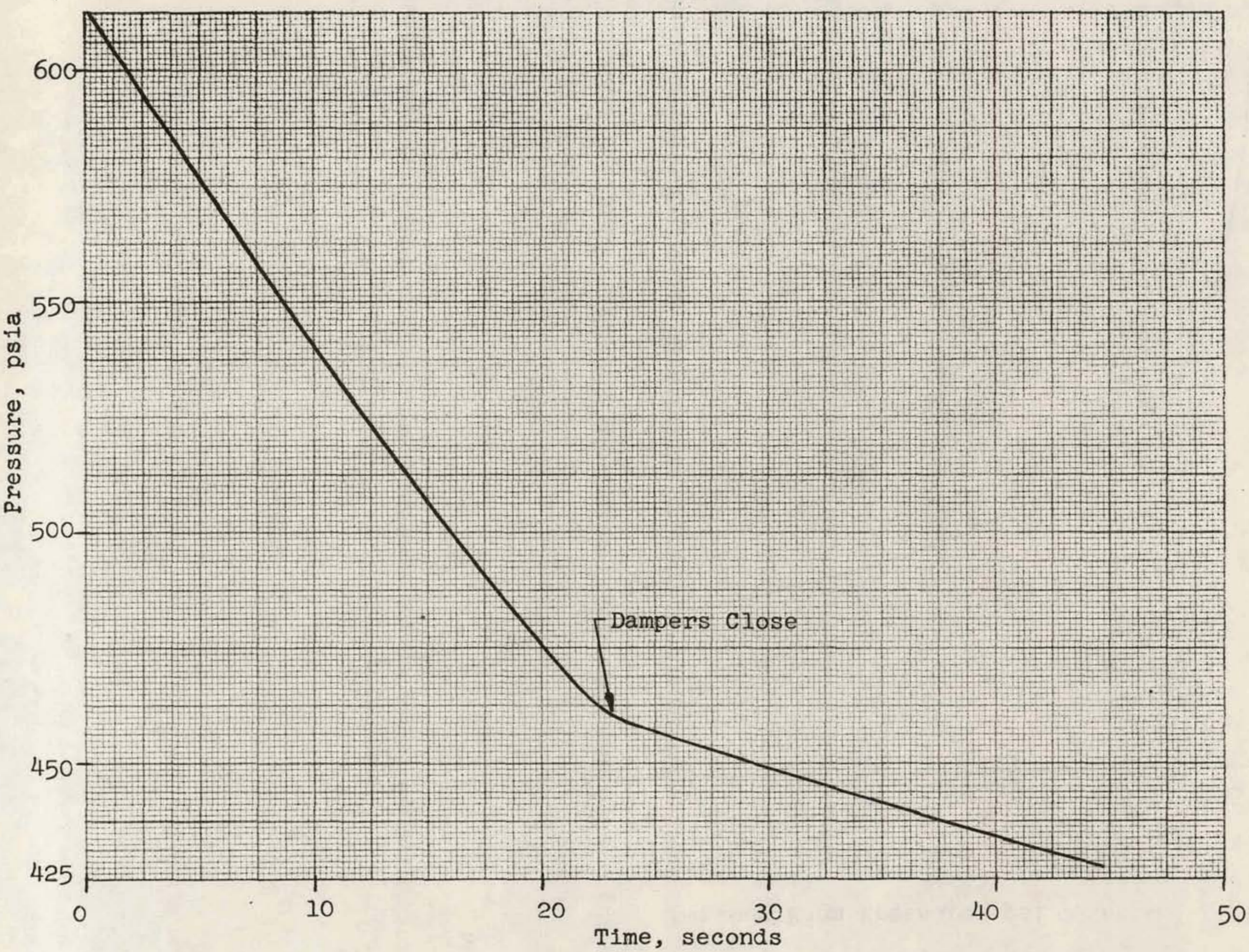


Figure 2.E

Compartment Pressures versus Time After Ductile Rupture

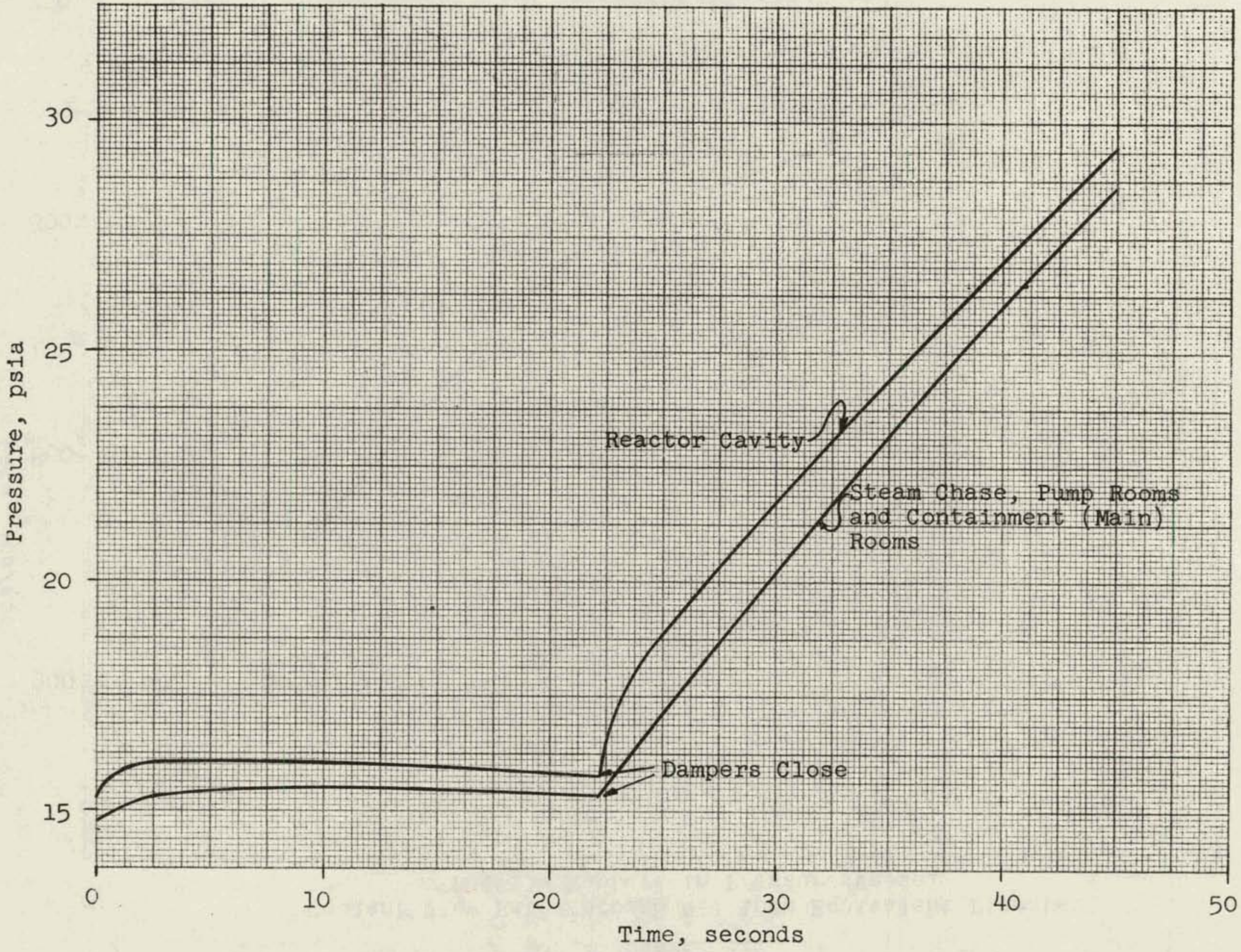
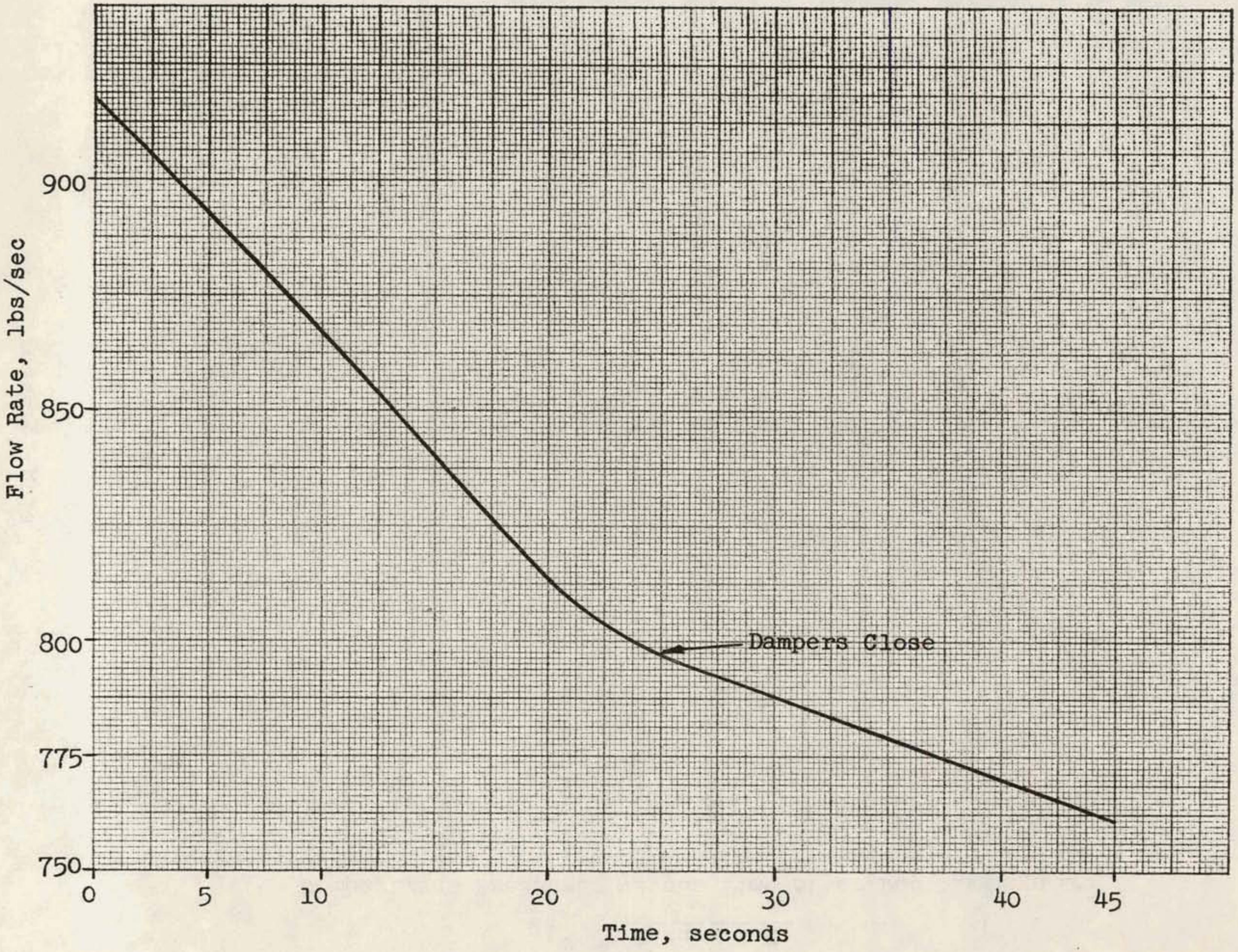


Figure 2.F

Coolant Flow Rate Through 4.1 inch Equivalent Diameter
Ductile Rupture in Pressure Vessel



3.0 RECOMMENDATIONS

It is estimated that substitution of pressure suppression containment for pressure vessel containment can create a cost saving of $500,000 on a large nuclear power plant. The removal of the pressure vessel can create a safety hazard in the event of accidents with resulting high pressure and dispersion of fission products. Before any power plants can be built without a pressure vessel, the methods of pressure suppression must be proven. Since the cost of proving pressure suppression containment should not approach $500,000 such work should be pursued to prove the validity of this method of reducing nuclear power plant costs.

As part of the work under purchase order WA491284-NSP an analytical tool for predicting pressures inside a containment building have been developed. Parallel experimental work to firm up uncertain heat transfer mechanisms and to prove out the predictions of the analytical tool is the next logical step in an experimental and analytical program designed to prove the validity of pressure suppression containment.

An outline of the recommended analytical and experimental program is presented:

1) a. Set up experimental program to determine effectiveness of pool quenching as a function of nozzle depth, nozzle pressure, degree of superheat in nozzle steam, and other pertinent parameters.

   b. Determine mechanisms of steam condensation in quenching pool and relate these mechanisms to the parameters.

   c. Set up a similar experimental program to determine the parameters important to rate of steam condensation on the compartment walls. Such parameters as wall temperature, steam superheat, and steam velocity should be investigated.

2) Modify "Press" subroutine of "Pathfinder" code* to allow for primary loop breaks in the pump room as well as in the reactor cavity, and to include effects of the steam superheating as it expands.

3) Using the information developed in 1)a, b, and c, use the electronic computer code to predict pressures in experiments such as those of Kolflat and Chittenden(9) and Whelchel and Robbins.**

---

* This is the name of the code developed under purchase order WA491284-NSP.

** Presented at November 29,-December 4, 1959 Meeting of ASME in Atlantic City, New Jersey.

4) Before any accurate pressure transients can be calculated, it will be necessary to determine experimentally the efflux rates of high pressure saturated water from a rupture. This data would then be applied to determine accurate flow coefficients for use in the computer program.

4.0 DISCUSSION

As is mentioned in Section 1.0, if the primary system of a reactor plant is breached, possible internal pressure and temperature loads in the containment structure must be determined in order to arrive at design figures.

Thermodynamic treatment for time independent expansion into a containment structure of a compressed liquid-vapor system has been reported by J. C. Heap.(3)

The time independent treatment consists of going from one state point to another, assuming the initial state point is known and the final mixture is in a state of static equilibrium. Changes in potential energy, non-mechanical forms of energy or sinks, such as chemical, etc., are not considered. Also heat sources or sinks (except the air mass) which may be present after the incident are omitted. Heap's results are shown plotted in Figure 2.A. Applying these results to the reference design Pathfinder Plant results in a maximum pressure of ~80 psia and is obtained as follows:

Containment structure free volume = 112000 ft^3

Core coolant mass at 615 psia (water in primary system) $= \frac{V}{N} = \frac{1810}{0.02018} = 89{,}800$ lbs.

Containment volume per pound of saturated water =

$$\frac{112{,}000}{89{,}800} = 1.25$$

Then from Figure 2.A, the pressure of the mixture in the containment shell would be ~ 80 psia. This value of 80 psia is however only an estimate since the system contains heat sources and sinks which, however, are time dependent.

In a time dependent analysis, the complexity of the problem arises chiefly from the fact that flow is time dependent. Solutions can be obtained only by numerical methods, implying application to specific cases. Furthermore, the problem of time dependence is somewhat more difficult due to the use of a compartmentalized building and the possibility of using the shield pool for quenching. Therefore,in order to determine the complex transient pressure behavior in the reference design Pathfinder Plant after a major leak occurs in the primary coolant system, an IBM-704 digital computer program was designed to solve the simultaneous non-linear set of equations evolving from the heat, mass, and force balances in the system.

In the program the method of analysis approximates the actual time solution of the partial differential equations by a set of finite difference equations which are solved in a series of time steps. The assumption is made that the time steps are small enough that the quantities involved do not change appreciably during the time step.

These equations are solved explicitly for water volumes at each time increment and system pressures are determined implicitly as time dependent variables. Thermodynamic equilibrium is assumed at any time after the rupture, which is essentially true for small rupture sizes causing extended blowdown.

The geometry of the reference design Pathfinder Plant is shown by Figure 1.A and 1.B. Since the pump rooms are essentially identical volumes and have identical inlets and outlets, they are combined into a single room with the volume of the three separate pump rooms. The steam chase and sump rooms are combined in a similar manner, and the plug and equipment rooms are included in the volume of the operating room; the resulting analytical model is shown in Figure 4.A.

The heat and mass balances are made for each of the five volumes and the force balance is supplied by the flow-pressure drop relationships between the volumes. The heat balance in the reactor vessel is complicated by the additional heat produced by fission product decay and by the heat released from the mass of metal in the reactor core and pressure vessel. Condensation occurs in the remaining four volumes. The heat capacity of the air in the operating room is important and is accounted for in the analytical model. The theory and equations used in the program are given in Appendix A1.0. An outline and operating instructions for the program are given in Appendix A2.0, and the flow coefficients used in the program for the reference design Pathfinder Plant are given in Appendix A3.0. The program has a very general input (Appendix A2.0) and thereby can be used with other containment designs. Input parameters include:

1) Initial pressures in reactor and throughout the building.

2) Heat capacity of vessel/^{o}F.

3) Decay heat.

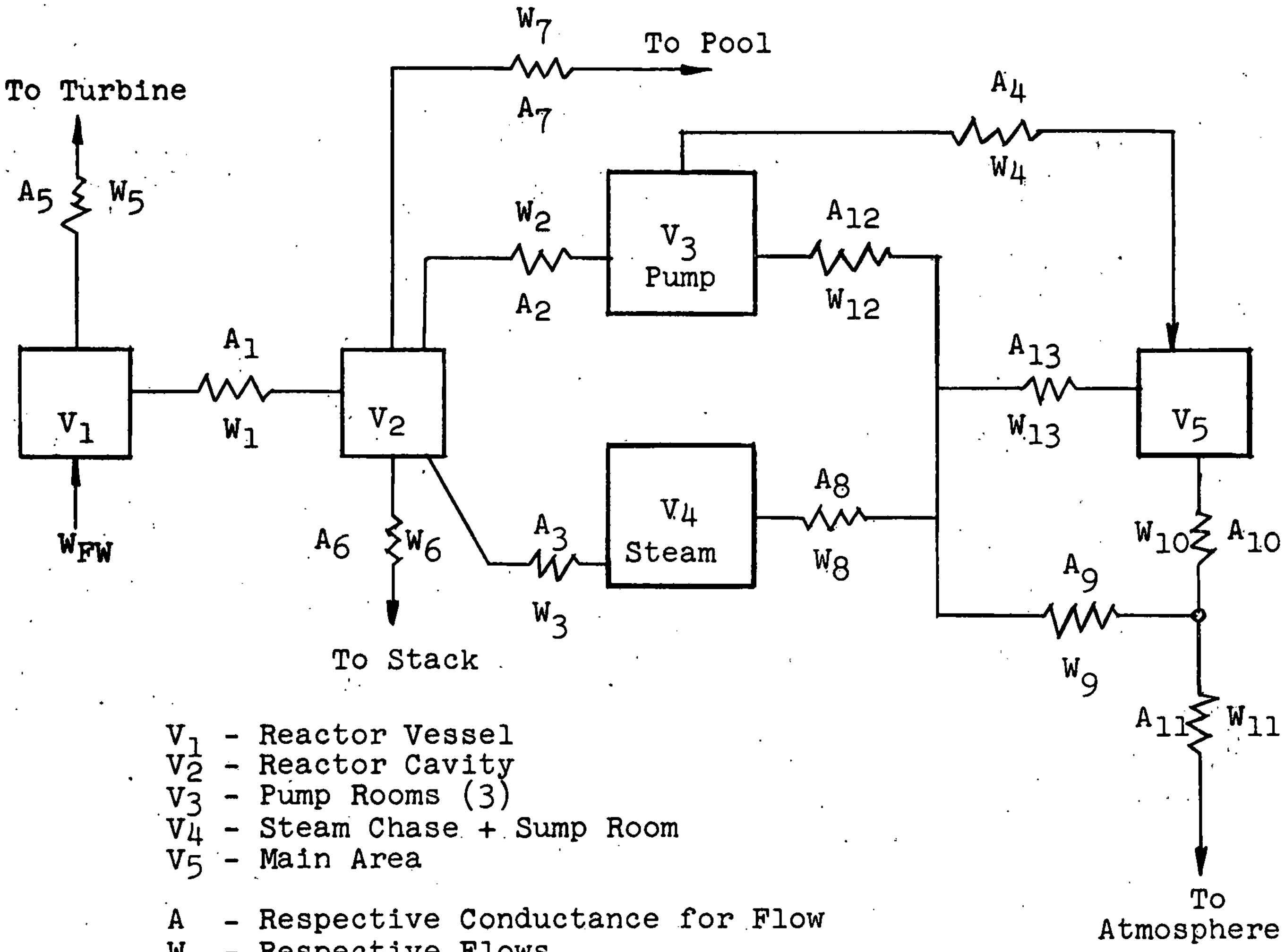
4) Feedwater flow rate.

5) Enthalpy (temperature) of feedwater.

6) Volume of primary coolant system.

Figure 4.A

Schematic Model of Reactor Plant for Transient Pressure Program



V_1 - Reactor Vessel
V_2 - Reactor Cavity
V_3 - Pump Rooms (3)
V_4 - Steam Chase + Sump Room
V_5 - Main Area

A - Respective Conductance for Flow
W - Respective Flows

7) Size of rupture.

8) Flow coefficients through reactor building.

9) Time increment.

10) Size of annuli leading from reactor cavity.

11) Size of reactor building compartments.

Other special features of the program include:

1) Provision for blowdown to be steam or water.

2) Provision for increased flow through ducts due to splitting of ducts when ΔP (across ducts) is greater than predetermined amount.

3) Provision for splitting rupture disc at bottom of shield pool when pressure in cavity reaches a predetermined value.

4) Provision to calculate transient pressures with a) ventilation dampers open; b) ventilation dampers closed, and c) after core is exposed, dampers and steam line to turbine closed.

The program, as written, was successfully run up to a time of 44 seconds following rupture. Results are given in Table 2.A and are plotted in Figures 2.D, 2.E, and 2.F. From Figure 2.E it is seen that after 22 seconds the pressure buildup is accelerated. At a time of 22 seconds after a primary system rupture, the reactor core is uncovered and, as desired, the dampers in the intake and exhaust ducts close. Also, the steam line to the turbine shuts off.

As mentioned in Section 2.0, a machine stop occurred after 22 and 44 seconds. In the program, in order to reduce the IBM-704 machine running time required, the time step is increased after each successful pressure calculation. It is believed that the long time steps resulted in the machine stops. The long time step at any point of irregularity in the partial derivatives cause a pressure estimation out of range of the steam table included in the program. A machine stop results.

After the 22 second machine stop a small time step was read into the code and a lower limit was put on the pressure estimates. These two corrections resulted in a successful run up to 44 seconds. It is believed that a minor program correction of a limit on the maximum pressure estimation will result in further successful operation of the code.

One point of interest in the program results are the negative values of the water inventory in the pump rooms and steam chase. (Table 4a). These negative values result from the fact that when steam is expanded from the reactor cavity into these rooms, it will superheat. However this is not accounted for in the operating program and to maintain an enthalpy balance, water is evaporated in these rooms thereby resulting in negative inventories. Ordinarily, there would be water in these rooms due to condensation, however, in the sample problem run,the condensation was made zero. The water inventory in the main area is greater than zero due to the air cooling the steam to saturation temperature.

In general, except for the negative water inventories, it is believed that the transient pressure program works as designed. As mentioned previously, the program stop that occurred in the sample problem is corrected by simply decreasing the time step (requiring one card change in the program deck) and minor corrections limiting the pressure estimations to the range of the steam tables. The calculations of negative water inventories, although not serious, can be avoided by the insertion of one equation in the heat balance calculation. This will require a recompilation of the subroutine "Press".

One problem that is not resolved is the quenching of steam by shield pool water. Provisions are made in the program for heat dissipation (or steam flow into the pool) however an adequate and reliable model has not been developed. After experimental research yields sufficient data to suggest a reliable model, it can readily be incorporated in the computer code.

Table 4.a

Reference Design Power Plant - Rupture in Reactor Cavity

	Time After Rupture (seconds)					
	.100	.210	.331	.464	.611	.772
Compartment Pressures, psia						
Reactor	614.208	613.423	612.508	611.485	610.351	609.096
Reactor Cavity	15.419	15.662	15.768	15.812	15.837	15.855
Pump Rooms	14.762	14.813	14.878	14.927	14.969	15.007
Steam Chase and Sump	14.768	14.836	14.911	14.974	15.080	15.079
Operating Room	14.722	14.753	14.784	14.819	14.857	14.897
Flow Rates, lbs per second						
W(1)	918.115	917.392	916.698	915.956	915.161	914.288
W(2)	84.491	95.940	87.361	98.259	97.464	96.459
W(3)	18.617	20.972	21.403	21.210	20.857	20.486
W(4)	44.647	55.604	69.585	74.657	75.926	75.560
W(5)	173.325	173.095	172.829	192.532	172.208	171.838
W(6)	123.151	142.216	149.667	152.699	154.346	155.539
W(7)	0.	0.	0.	0.	0.	0.
W(8)	6.219	9.010	11.110	12.713	13.955	14.889
W(9)	20.631	27.944	34.962	39.528	43.050	46.104
W(10)	-0.031	-3.418	-1.011	-2.587	-3.377	-4.101
W(11)	20.635	29.372	36.786	42.123	46.430	50.185
W(12)	16.332	21.190	26.654	29.633	31.645	33.289
W(13)	1.921	2.255	2.802	2.817	2.550	2.074
Volume of Water in each Compartment ft^3						
Reactor	1807.954	1005.731	1803.277	1800.576	1797.607	1794.34
Reactor Cavity	1.073	2.259	3.552	4.978	6.547	8.273
Pump Rooms	-0.000	0.011	-0.229	-0.519	-0.849	-1.222
Steam Chase and Sump	-0.002	0.003	-0.013	-0.020	-0.026	-0.031
Operation Room	0.009	0.001	0.241	0.529	0.060	1.237

Table 4.a (Continued)

	Time After Rupture (seconds)					
	.949	1.144	1.358	1.594	1.853	2.138
Compartment Pressures, psia						
Reactor	607.711	606.185	604.505	602.654	600.618	598.379
Reactor Cavity	15.871	15.885	15.900	15.913	15.926	15.938
Pump Rooms	15.045	15.082	15.120	15.157	15.194	15.232
Steam Chase and Sump	15.123	15.143	15.200	15.234	15.266	15.296
Operating Room	14.938	15.980	15.022	15.065	15.108	15.151
Flow Rates, lbs per second						
W(1)	916.326	912.267	911.099	909.813	908.396	906.835
W(2)	95.330	94.135	92.879	91.574	90.230	88.853
W(3)	20.142	19.831	19.546	19.281	19.032	18.795
W(4)	74.465	72.991	71.308	69.417	67.258	64.777
W(5)	171.438	170.998	170.514	169.984	169.402	168.764
W(6)	156.571	157.531	158.449	159.326	160.156	160.931
W(7)	0	0	0	0	0	0
W(8)	15.587	15.862	16.128	16.356	16.525	16.645
W(9)	49.051	51.969	54.627	47.005	59.192	61.231
W(10)	-4.752	-5.302	-5.839	-6.355	-6.840	-7.299
W(11)	53.800	57.278	60.467	63.348	66.049	68.565
W(12)	34.825	35.604	36.802	32.211	39.632	41.029
W(13)	1.360	-0.503	-1.696	-2.438	-3.035	-3.557
Volume of Water in each Compartment ft^3						
Reactor	1790.761	1786.826	1782.508	1777.769	1772.571	1766.870
Reactor Cavity	10.171	12.257	14.549	17.069	19.838	22.881
Pump Rooms	-1.62	-2.099	-2.605	-3.165	-3.779	-4.446
Steam Chase and Sump	-0.035	-0.035	-0.033	-0.030	-0.028	-0.025
Operating Room	1.659	2.107	2.597	3.141	3.740	4.388

Table 4.a (Continued)

	Time After Rupture (seconds)					
	2.452	2.797	3.177	3.595	4.034	4.560
Compartment Pressure, psia						
Reactor	595.916	593.207	590.231	587.016	583.541	579.722
Reactor Cavity	15.949	15.960	15.968	15.976	15.981	15.985
Pump Rooms	15.266	15.300	15.332	15.363	15.391	15.417
Steam Chase and Sump	15.324	15.351	15.376	15.398	15.418	15.436
Operating Room	15.193	15.234	15.274	15.312	15.348	15.382
Flow Rates, lbs per second						
W(1)	905.116	903.222	901.137	898.879	896.430	893.730
W(2)	87.448	86.023	84.580	83.120	81.655	80.189
W(3)	18.566	18.336	18.113	17.895	17.683	17.474
W(4)	62.003	58.977	55.601	51.892	47.889	43.624
W(5)	168.006	267.300	166.430	165.496	164.493	163.397
W(6)	161.644	162.285	162.839	163.293	163.644	163.875
W(7)	0	0	0	0	0	0
W(8)	16.737	16.809	16.850	16.860	16.935	16.802
W(9)	63.168	64.924	66.555	68.043	69.344	70.557
W(10)	-7.736	-8.137	-9.252	-9.860	-9.156	-9.450
W(11)	70.872	73.073	75.076	76.043	78.517	80.010
W(12)	42.399	43.671	44.877	46.003	47.016	47.972
W(13)	-4.027	-4.444	-4.828	-5.180	-5.493	-5.783
Volume of Waterin each Compartment ft^3						
Reactor	1760.621	1753.776	1746.375	1738.231	1729.277	1719.482
Reactor Cavity	26.225	29.898	33.932	38.363	43.230	48.573
Pump Rooms	-5.159	-5.911	-6.685	-7.468	-8.232	-8.951
Steam Chase and Sump	-0.023	-0.023	-0.024	-0.025	-0.027	-0.028
Operating Room	5.084	5.824	6.591	7.364	8.225	8.844

Table 4.a (Continued)

	Time After Rupture (seconds)					
	5.226	5.727	6.400	7.140	7.954	8.850
Compartment Pressure, psia						
Reactor	575.527	570.829	565.860	560.315	554.452	548.020
Reactor Cavity	15.937	15.986	15.982	15.975	15.967	15.957
Pump Rooms	15.440	15.461	15.477	15.491	15.503	15.513
Steam Chase and Sump	15.451	15.464	15.473	15.400	15.484	15.487
Operating Room	15.412	15.438	15.460	15.478	15.495	15.506
Flow Rate, lbs per second						
W(1)	890.752	887.466	883.840	879.846	875.597	870.900
W(2)	78.719	77.247	75.777	74.301	72.756	71.198
W(3)	17.265	17.054	16.842	16.628	16.420	16.207
W(4)	39.190	34.721	30.401	26.473	20.847	19.254
W(5)	162.203	160.901	159.480	157.875	156.196	154.376
W(6)	163.970	163.912	163.683	163.272	162.755	162.114
W(7)	0	0	0	0	0	0
W(8)	16.750	16.681	16.594	16.486	16.323	16.165
W(9)	71.614	72.511	73.242	73.807	74.290	74.669
W(10)	-9.710	-9.932	-10.117	-10.263	-10.407	-10.495
W(11)	81.319	82.436	83.349	84.059	84.690	85.155
W(12)	48.826	48.573	50.209	50.737	51.232	51.688
W(13)	-6.038	-6.257	-6.439	-6.584	-6.734	-6.816
Volume of Water in each Compartment, ft^3						
Reactor	1708.774	1697.074	1684.309	1670.565	1655.416	1638.913
Reactor Cavity	54.440	60.898	67.944	75.696	84.196	93.509
Pump Rooms	-9.594	-10.134	-10.547	-10.830	-10.821	-10.836
Steam Chase and Sump	-0.030	-0.032	-0.034	-0.037	-0.037	-0.038
Operating Room	9.492	10.044	10.478	10.783	10.660	10.545

Table 4.a (Continued)

	Time After Rupture (seconds)					
	9.835	10.918	12.110	13.421	14.863	16.449
Compartment Pressure						
Reactor	540.964	533.474	525.306	516.355	506.840	496.487
Reactor Cavity	15.944	15.936	15.919	15.890	15.857	15.820
Pump Room	15.520	15.536	15.532	15.514	15.493	15.469
Steam Chase and Sump	15.487	15.490	15.484	15.469	15.449	15.427
Operations Room	15.511	15.500	14.484	15.468	15.448	15.426
Flow Rates, lbs per second						
W(1)	865.706	860.145	854.028	847.260	839.990	831.977
W(2)	69.661	67.698	66.564	65.614	64.530	63.336
W(3)	15.988	15.806	15.585	15.337	15.086	14.808
W(4)	21.999	44.289	50.432	49.679	48.763	48.102
W(5)	152.403	150.239	147.898	145.377	142.654	139.731
W(6)	161.304	160.807	159.670	158.830	155.663	153.215
W(7)	0	0	0	0	0	0
W(8)	16.012	15.820	15.783	15.674	15.473	15.245
W(9)	74.896	75.496	75.277	74.476	73.492	72.365
W(10)	-10.523	-10.346	-10.197	-10.090	-9.965	-9.814
W(11)	85.409	85.831	85.463	84.556	83.447	82.176
W(12)	52.054	53.152	53.159	52.534	51.726	51.026
W(13)	-6.831	-6.524	-6.336	-6.267	-6.192	-6.094
Volume of Water in each Compartment, ft^3						
Reactor	1620.956	1601.508	1580.403	1557.517	1532.807	1506.186
Reactor Cavity	103.701	114.819	126.927	140.141	153.758	155.074
Pump Rooms	-11.318	-14.790	-19.431	-24.425	-29.835	-35.742
Steam Chase and Sump	-0.039	-0.046	-0.058	-0.072	0.723	15.131
Operating Room	10.888	14.257	18.857	23.831	29.228	35.131

Table 4.a (Continued)

	Time After Rupture (seconds)					
	18.194	20.114	22.225	24.078	25.402	27.341
Compartment Pressure						
Reactor	485.353	473.429	460.633	457.479	455.533	452.661
Reactor Cavity	15.780	15.737	15.691	18.304	19.157	20.248
Pump Room	15.442	15.412	15.379	16.465	17.302	18.537
Steam Chase and Sump	15.402	15.375	15.345	16.468	17.325	18.618
Operations Room	15.400	15.371	15.339	16.228	17.098	18.358
Flow Rate, lbs per second						
W(1)	823.242	813.746	803.386	798.423	796.035	792.657
W(2)	62.117	60.827	59.516	146.938	151.228	150.289
W(3)	14.512	14.195	13.860	32.508	33.300	32.571
W(4)	47.354	46.984	46.319	99.519	109.469	106.170
W(5)	136.584	133.203	129.582	0	0	0
W(6)	150.502	147.523	144.266	0	0	0
W(7)	0	0	0	0	0	0
W(8)	14.999	147.30	14.441	3.850	6.621	11.636
W(9)	81.069	68.625	68.003	6.951	7.708	7.563
W(10)	-9.638	-9.431	-9.203	6.951	7.707	7.550
W(11)	80.700	79.051	77.202	0	0	0
W(12)	50.091	49.058	47.879	9.532	8.222	2.911
W(13)	-5.980	-5.837	-5.682	6.431	7.134	6.984
Volume of Water in Each Compartment, ft^3						
Reactor	1472.339	1446.419	1413.221	1390.811	1375.161	1352.383
Reactor Cavity	156.482	158.023	159.651	142.044	143.256	145.066
Pump Rooms	-42.157	-49.200	-56.835	-54.082	-52.273	-48.722
Steam Chase and Sump	30.852	47.985	66.645	105.483	118.636	136.884
Operating Room	41.564	48.658	56.390	53.175	51.348	48.673

Table 4.a (Continued)

	Time After Rupture (seconds)					
	29.365	32.060	34.335	37.088	40.419	44.450
Compartment Pressure						
Reactor	449.631	445.549	442.147	438.036	432.980	426.738
Reactor Cavity	21.374	22.809	24.075	25.540	27.331	29.423
Pump Room	19.839	21.447	22.824	24.427	26.357	28.554
Steam Chase and Sump	19.860	21.456	22.839	24.406	26.306	28.490
Operating Room	19.641	21.320	22.649	24.320	26.229	28.484
Flow Rate, lbs per second						
W(1)	789.077	784.310	780.246	775.362	769.311	761.869
W(2)	147.288	144.354	142.537	139.034	135.034	132.558
W(3)	32.405	31.857	31.380	31.052	30.625	30.368
W(4)	114.930	95.634	115.874	93.449	106.046	82.016
W(5)	0	0	0	0	0	0
W(6)	0	0	0	0	0	0
W(7)	0	0	0	0	0	0
W(8)	6.803	5.011	6.347	-4.058	-8.150	-10.679
W(9)	8.086	6.709	8.137	6.224	6.868	5.020
W(10)	8.086	6.709	8.138	6.224	6.870	5.019
W(11)	0	0	0	0	0	0
W(12)	8.762	7.891	9.309	16.019	21.352	20.321
W(13)	7.479	6.193	7.518	5.737	6.334	4.622
Volume of Water in Each Compartment, ft^3						
Reactor	1328.771	1297.619	1271.580	1240.386	1203.085	1158.609
Reactor Cavity	146.944	149.485	151.542	154.163	157.072	160.425
Pump Rooms	-47.132	-44.364	-45.049	-43.645	-44.361	-41.776
Steam Chase and Sump	156.008	181.878	203.219	231.153	266.589	309.715
Operating Room	47.841	45.541	47.449	45.142	43.488	37.841

5.0 REFERENCES

1. Allis Chalmers Company, "Summary Hazards Report for Pathfinder Nuclear Power Plant", March 10, 1959.
2. Ketchum, H. B., "A Simple Method for Calculating the Maximum Size of Ductile Rupture in Pressurized Systems", WAPD-TM-56, July, 1957.
3. Heap, J. C., "Equilibrium PV-T Relations for Expanding Liquid-Vapor Systems in a Containment Shell", ANL-5828 November, 1958.
4. Mohr, D., Allis Chalmers Company, Private Communication.
5. Leppke, D. M., "Containment Vessel Study", Pioneer and Engineering Service Company Report to Allis Chalmers Mfg. Co., on Pathfinder Nuclear Power Plant, October, 1958.
6. Harris, T. A., "Analysis of the Coolant Expansion Due to a Loss-of Coolant Accident in a Pressurized Water, Nuclear Power Plant", WAPD-T-861.
7. McAdams, W. H., Heat Transmission, McGraw-Hill Book Co., Inc. 1942.
8. Burnell, J. G., "Flow of Boiling Water Through Nozzles, Orifices, and Pipes", Engineering, December, 1947.
9. Kolflat, A., and Chittenden, W. A., "A New Approach to the Design of Containment Shells for Atomic Power Plants", Paper prepared for presentation at 19th Annual American Power Conference, Sherman Hotel, March 27-29, 1957.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A1.0

Program Theory and Equations

The model chosen for this program is that developed by Harris[6] and is a simple pressure vessel in which the assumption of pressure uniformity may be supported.

A1.1 Mass and Heat Balance Analysis

For a given volume, consider a change in pressure from P_o to P_1 over a finite time interval (Δt). Then

$$H_o = h_{fo}M_{fo} + h_{go}M_{go} \qquad (1)$$

in which H_o is the total heat content of coolant, h_{fo} is the enthalpy of saturated water, h_{go} is the enthalpy of saturated steam, and M is the mass of fluid in each phase, all at P_o. Similarly

$$H_1 = h_{f1}M_{f1} + h_{g1}M_{g1} \qquad (2)$$

all at P_1.

The following relationship between H_1 and H_2 can be written:

$$\Delta H = H_o - H_1 + \sum_i \Delta Qi \qquad (3)$$

in which ΔH is the energy loss from the primary loop through the rupture, and ΔQi is any other heat source or sink.

A mass balance can be taken over the volume at any time such that:

$$M_o = M_{fo} + M_{go} \qquad (4)$$

and

$$M_1 = M_{f1} + M_{g1} \qquad (5)$$

in which M is the mass of water and steam in the volume at P. The fluid mass lost in the time interval can be written as:

$$\Delta M = \sum_i (W_i \ \Delta t) \qquad (6)$$

where W_i is the mass flow rate and Δt is the time increment.

The following relationships are introduced at this point:

$$M = V_f\rho_f + V_g\rho_g \qquad (7)$$

in which ρ is density and V is volume at pressure P.

Since:

$$V_T = V_f + V_g \qquad (8)$$

in which V_T is the volume of fluid and gas, therefore equation (7) can be written at any pressure P:

$$M = V_f(\rho_f - \rho_g) + V_T\rho_g \tag{9}$$

Now, substitution of equations (7) and (8) into (1) and (2) yields

$$H = V_f(h_f\rho_f - h_g\rho_g) + V_T(h_g\rho_g) \tag{10}$$

Similarly, substitution of equations (1) into (3) gives

$$\begin{aligned} &V_{f1}(h_{f1}\rho_{f1} - h_{g1}\rho_{g1}) + V_T(h_{g1}\rho_{g1} - h_{go}\rho_{go}) - \\ &V_{fo}(h_{fo}\rho_{fo} - h_{go}\rho_{go}) = \Delta H + \sum_{1} \Delta Qi \end{aligned} \tag{11}$$

and substitution of equations (9) into (6) gives

$$\begin{aligned} &V_{f1}(\rho_{f1} - \rho_{g1}) + V_T(\rho_{g1} - \rho_{go}) - \\ &V_{fo}(\rho_{f1} - \rho_{go}) = - \Delta M \end{aligned} \tag{12}$$

The term on the right hand side of equation (12) is evaluated as follows:

$$\Delta M = \frac{1}{\Delta P} \int_{t_1}^{t_2} \int_{P_1}^{P_2(t)} W(P)dPdt \tag{13}$$

in which W(P) is mass rate of efflux at a given pressure and t_1 is the time at P_1.

Equation (13) can be approximated by (14) if ΔP and Δt are chosen sufficiently small.

$$\Delta M = W_1(t_1 - t_o) \tag{14}$$

The terms on the right hand side of equation (11) are evaluated as follows:

$$\Delta H = \frac{1}{\Delta P} \int_{t_1}^{t_2} \int_{P_1(t)}^{P_2(t)} W(P)h(P)dPdt \tag{15}$$

in which $h_1(P)$ is the energy per pound of effluent at a given pressure. Equation (15) can be approximated by (16) if again ΔP and Δt are sufficiently small.

$$\Delta H = W_1\ h_1\ (t_2 - t_1) \tag{16}$$

Decay heat generation is described as follows:

$$\Delta Q_d = k_1(V,T)\int_{t_1}^{t_2} q_d(t)dt \tag{17}$$

in which $q_d(t)$ is the rate of decay heat generation within the core and $k_1(V,T)$ a variable dependent upon heat transfer capability. It was assumed that decay heat is generated uniformly in the axial direction and k_1 is constant for small intervals depending only upon water level in the core. The latter statement is essentially true since heat transfer from thin fuel elements to boiling water is excellent. Axial distribution of decay heat is not uniform, but little error follows from this assumption.

Thus

$$\Delta Q_d = \frac{V_{fcave}}{V_c} \int_{t_1}^{t_2} q_d(t)dt \tag{18}$$

in which V_{fcave} is average volume of water in the core during the interval and V_c is the total free volume of the core. If the interval is sufficiently small such that the change in V_{fc} is small and since decay heat may be approximated by a simple exponential function, equation (18) may be approximated by (19).

$$\Delta Q_d = \frac{V_{fco}}{V_c} (t_1^n - t_o^n)q_o \tag{19}$$

in which q_o is a constant based upon previous core power and operating history.

If it is assumed that core metal temperature follows fluid temperature by a constant temperature increment, then ΔQ_c can be approximated by

$$\Delta Q_c = \frac{V_{fc1}}{V_c} M_m c_m (T_2 - T_1) \tag{20}$$

in which M_m is core metal mass, c_m is specific heat of core metal, and T_1 and T_2 are fluid temperatures at P_1 and P_2 respectively. A similar term has been added for plant metal heat capacity;

$$\Delta Q_v = \frac{(V_{fo} - VP)}{VPV} (T_1 - T_o) M_v C_v \tag{21}$$

where V_{fo} is the total volume of water in the primary system, VP is the volume outside the pressure vessel, and VPV is the volume of the pressure vessel. M_v is the mass of the pressure vessel and C_v is the specific heat of the pressure vessel metal.

Use of core heat generation terms is predicated on the assumption that temperature is transmitted uniformly through the plant. (Coolant temperature is expected to be higher in the core region; turbulence during blowdown tends to reduce any temperature difference). This assumption enables a solution to be obtained while introducing negligible inaccuracy insofar as the overall problem is concerned.

Now, substitution of equation (14) into (12) yields

$$V_{f1}\left(\frac{1}{v_{f1}} - \frac{1}{v_{g1}}\right) + V_T\left(\frac{1}{v_{g1}} - \frac{1}{v_{go}}\right) - V_{fo}\left(\frac{1}{v_{fo}} - \frac{1}{v_{go}}\right) = \Delta M \qquad (22)$$

Similarly, substitution of equations (16), (19), (22) into (11) yields:

$$V_{f1}\left(\frac{h_{f1}}{v_{f1}} - \frac{h_{g1}}{v_{g1}}\right) + V_T\left(\frac{h_{g1}}{v_{g1}} - \frac{h_{go}}{v_{go}}\right) - V_{fo}\left(\frac{h_{fo}}{v_{fo}} - \frac{h_{go}}{v_{go}}\right) = \Delta H + \sum_{i} \Delta Q_i \qquad (23)$$

To determine the ΔM quantities in the mass balance equations, the mass flow rates into and out of each volume must be accounted for. Mass leaving a particular volume will be assigned a negative sign and mass entering a volume will be positive.

In volume 1, the reactor itself, there are the rupture efflux (W_1), the steam flow to the turbine (W_5) and the feedwater flow (W_{fw}) into the main pressure vessel.

Thus
$$\Delta M_1 = (-W_1 - W_5 + W_{fw})(\Delta t) \qquad (24)$$

In volume 2, the reactor cavity, there is the rupture efflux (W_1) entering, flow out to volume 3 (W_2) and to volume 4 (W_3), the steam flow out through the ventilator (W_6), and the possible flow (W_7) up into the pool if the bottom diaphram of the pool is ruptured. Therefore

$$\Delta M_2 = (W_1 - W_2 - W_3 - W_6 - W_7)(\Delta t). \qquad (25)$$

Volume 3 has flow from volume 2 (W_2) coming in, and flow out to volume 5 through manholes (W_4) and through the ventilation ducts (W_{12}), thus

$$\Delta M_3 = (W_2 - W_4 - W_{12})(\Delta t) \qquad (26)$$

Volume 4 only has flow in from volume 2 (W_3) and out through the ventilation ducts (W_8)

$$\Delta M_4 = (W_3 - W_8)(\Delta t) \qquad (27)$$

Volume 5 has flow coming in from the manholes (W_4) and from the ventilation ducts (W_{13} and W_{10}).

$$\Delta M_5 = (W_4 + W_{10} + W_{13})(\Delta t) \tag{28}$$

If flow #7 is non-zero, it is assumed to be absorbed in the pool and does not effect the mass and heat balance for volume 5.

A1.2 Condensation(7)

Since the walls of the various rooms are expected to be no hotter than 100°F during normal operation, condensation would occur on the walls if higher temperature steam were in the rooms. It is assumed that the wall temperatures do not rise due to the condensation, but remain at 100°F. The calculation of the heat released by condensation is expressed by the following equation:

$$\Delta Q = \frac{0.943p}{3600} \left[\frac{32.2k^3\rho^2h_{gf}}{\mu_f}\right]^{1/4} L(T-100)^{3/4} \tag{29}$$

where p is the perimeter of the room L is the height of the walls of the room, and T is the temperature of the steam, k is the conductivity of the film formed by condensation, ρ is the density of the film, and μ is the viscosity of the film, h_{gf} is the latent heat of condensation. The units of Q are Btu/sec and the remaining units are consistent.

The heat added to or subtracted from a volume is the summation of the mass flow rates times enthalpy times the delta time, plus any other source or sink such as the radiation decay and heat capacity sources and the condensation sinks.

The following equations give the heat transferred in each volume.

$$Q_1 = (W_1 \cdot h_{f1} - W_5 \cdot h_{g1} + W_{fw} \cdot h_{fw})\ \Delta t + \frac{V_{fco}}{Vc}\ qo(t_1^n - t_o^n) + \underline{V_{fco}}\ M_m c_m (T_1 - T_o) + \frac{V_{fo} - V\rho}{V\rho v}\ M_v c_v (T_1 - T_o) \tag{30}$$

$$Q_2 = (W_1 \cdot h_{f1} - W_2 \cdot h_{g2} - W_3 \cdot h_{g2} - W_6 \cdot h_{g2} - W_7 \cdot h_{g2} - \text{CONDENSATION})\Delta t \tag{31}$$

$$Q_3 = (W_2 \cdot h_{g2} - W_4 \cdot h_{g3} - W_{12} \cdot h_{g3} - \text{CONDENSATION})\ \Delta t \tag{32}$$

$$Q_4 = (W_3 \cdot h_{g2} - W_8 \cdot h_{g4} - \text{CONDENSATION})\ \Delta t \tag{33}$$

$$Q_5 = (W_4 \cdot h_{g3} - W_{10} \cdot h_{g4} + W_{13} \cdot h_{g3} - \text{CONDENSATION})\ \Delta t \tag{34}$$

Equations (22) through (34) can be combined and written for each volume to produce the heat and mass balance equations shown below:

A1.3 Mass Balance Equations

Subscripts

A_{ij}

i = volume ident.

j = 0 = beginning of time step

j = 1 = end of time step

1. $$V_{f11}(\rho_{f11} - \rho_{g11}) + V_1(\rho_{g11} - \rho_{g10}) - V_{f10}(\rho_{f10} - \rho_{g10}) - \\ (W_1 + W_{fw} - W_5)(t_1 - t_o) = 0$$

2. $$V_{f21}(\rho_{f21} - \rho_{g21}) + V_2(\rho_{g21} - \rho_{g20}) - V_{f20}(\rho_{f20} - \rho_{g20}) - \\ (W_1 - W_2 - W_3 - W_6 - W_7)(t_1 - t_o) = 0$$

3. $$V_{f31}(\rho_{f31} - \rho_{g31}) + V_3(\rho_{g31} - \rho_{g30}) - V_{f30}(\rho_{f30} - \rho_{g30}) - \\ (W_2 - W_4 - W_{12})(t_1 - t_o) = 0$$

4. $$V_{f41}(\rho_{f41} - \rho_{g41}) + V_4(\rho_{g41} - \rho_{g40} - V_{f40}(\rho_{f40} - \rho_{g40}) - \\ (W_3 - W_8)(t_1 - t_o) = 0$$

5. $$V_{f51}(\rho_{f51} - \rho_{g51} - \rho_{a51}) + V_5(\rho_{g51} - \rho_{g50} - \rho_{a51} - \rho_{a50}) - \\ V_{f50}(\rho_{f50} - \rho_{g50} - \rho_{a50}) - (W_4 + W_{13} + W_{10})(t_1 - t_o) = 0$$

A1.4 Heat Balance Equations

1. $$\begin{aligned}&V_{f_{11}}(\rho_{f_{11}}h_{f_{11}} - \rho_{g_{11}}h_{g_{11}}) + V_1(\rho_{g_{11}}h_{g_{11}} - \rho_{g_{11}}h_{g_{11}}) - \\ &V_{f_{10}}(\rho_{f_{10}}h_{f_{10}} - \rho_{g_{10}}h_{g_{10}}) + \left[+ W_1 h_{f_{10}} - k_1 W_{f_w} h_{f_w} + W_5 h_{g_{10}}\right](t_1 - t_0) + \\ &\frac{V_{fc_0}}{Vc}\, q0\, (t_1^{-n} - t_0^{-n}) + \frac{V_{fc_0}}{Vc} M_m c_m (T_{11} - T_{10}) = 0\end{aligned}$$

2. $$\begin{aligned}&V_{f_{21}}(\rho_{f_{21}}h_{f_{21}}) + V_2\,(\rho_{g_{21}}h_{g_{21}} - \rho_{g_{20}}h_{g_{20}}) - V_{f_{20}}(\rho_{f_{20}}h_{f_{20}} - \\ &\rho_{g_{20}}h_{g_{20}}) + \left[-W_1 h_{f_{10}} + W_2 h_{g_{20}} + W_3 h_{g_{20}} + W_6 h_{g_{20}} + W_7 h_{g_{20}} + \right. \\ &\left.\gamma_2 h_{fg_{20}} P_{20}\right]\,(t_1 - t_0) = 0\end{aligned}$$

3. $$\begin{aligned}&V_{f_{31}}(\rho_{f_{31}}h_{f_{31}} - \rho_{g_{31}}h_{g_{31}}) + V_3(\rho_{g_{31}}h_{g_{31}} - \rho_{g_{30}}h_{g_{30}}) - \\ &V_{f_{30}}(\rho_{f_{30}}h_{f_{30}} - \rho_{g_{30}}h_{g_{30}}) + \left[-W_2 h_{g_{20}} + W_4 h_{g_{30}} + W_{12} h_{g_{30}} + \right. \\ &\left.\gamma_3 h_{fg_{30}} P_{30}\right]\,(t_1 - t_0) = 0\end{aligned}$$

4. $$\begin{aligned}&V_{f_{41}}(\rho_{f_{41}}h_{f_{41}} - \rho_{g_{41}}h_{g_{41}}) + V_4(\rho_{g_{41}}h_{g_{41}} - \rho_{g_{40}}h_{g_{40}}) - \\ &V_{f_{40}}(\rho_{f_{40}}h_{f_{40}} - \rho_{g_{40}}h_{g_{40}}) + \left[-W_3 h_{g_{20}} + W_8 h_{g_{40}} + \gamma_4 h_{fg_{40}} P_{40}\right] \\ &(t_1 - t_0) = 0\end{aligned}$$

5. $$\begin{aligned}&V_{f_{51}}(\rho_{f_{51}}h_{f_{51}} - \rho_{g_{51}}h_{g_{51}} - \rho_{a_{51}}h_{g_{51}}) + V_5(\rho_{g_{51}}h_{g_{51}} - \rho_{g_{50}}h_{g_{50}} + \\ &\rho_{a_{51}}h_{a_{51}} - \rho_{a_{50}}h_{a_{50}}) - V_{f_{50}}(\rho_{f_{50}}h_{f_{50}} - \rho_{g_{50}}h_{g_{50}} - \rho_{a_{50}}h_{a_{50}}) + \\ &\left[-W_4 h_{g_{30}} - W_{13} h_{g_{30}} - W_{10} h_{g_{40}} + \gamma_5 h_{fg_{50}} P_5\right]\,(t_1 - t_0) = 0\end{aligned}$$

A1.5 Force Balance Equations

The Force balance equations are obtained from the pressure drop and mass flow relationships. Seven of the thirteen flow rates can be solved explicitly in terms of pressures, but the remaining six must be solved simultaneously since they are interconnected.

The flow equations are listed here.

1. $W_1 = A_1 C \sqrt{(P_1 - P_2)\rho f1}$ for water flow

$= A_1 Y_1 \sqrt{(P_1 - P_2)\rho g1}$ for steam flow

2. $W_2 = A_2 Y_2 \sqrt{(P_2 - P_3)\rho g2}$

3. $W_3 = A_3 Y_3 \sqrt{(P_2 - P_4)\rho g2}$

4. $W_4 = A_4 Y_4 \sqrt{(P_3 - P_5)\rho g3}$

5. $W_5 = A_5 Y_5 \sqrt{(P_1 - P_9)\rho g1}$

6. $W_6 = A_6 Y_6 \sqrt{(P_2 - P_9)\rho g2}$

7. $W_7 = A_7 Y_7 \sqrt{(P_2 - P_5 - 10)\rho g2}$

8. $W_8 + W_{12} = W_{13} + W_9$

9. $W_9 = W_{10} + W_{11}$

10. $P_4 - P_5 = \dfrac{W_8^2}{A_8^2 Y_8^2 \rho_4} + \dfrac{W_{13}^2}{A_{13}^2 Y_{13}^2 \rho_4}$

11. $P_3 - P_5 = \dfrac{W_{12}^2}{A_{12}^2 Y_{12}^2 \rho_3} + \dfrac{W_{13}^2}{A_{13}^2 Y_{13}^2 \rho_3}$

12. $P_4 - P_5 = \dfrac{W_8^2}{A_8^2 Y_8^2 \rho_4} + \dfrac{W_9^2}{A_9^2 Y_9^2 \rho_4} + \dfrac{W_{10}^2}{A_{10}^2 Y_{10}^2 \rho_4}$

13. $P_4 - P_8 = \dfrac{W_8^2}{A_8^2 Y_8^2 \rho_4} + \dfrac{W_9^2}{A_9^2 Y_9^2 \rho_4} + \dfrac{W_{11}^2}{A_{11}^2 Y_{11}^2 \rho_4}$

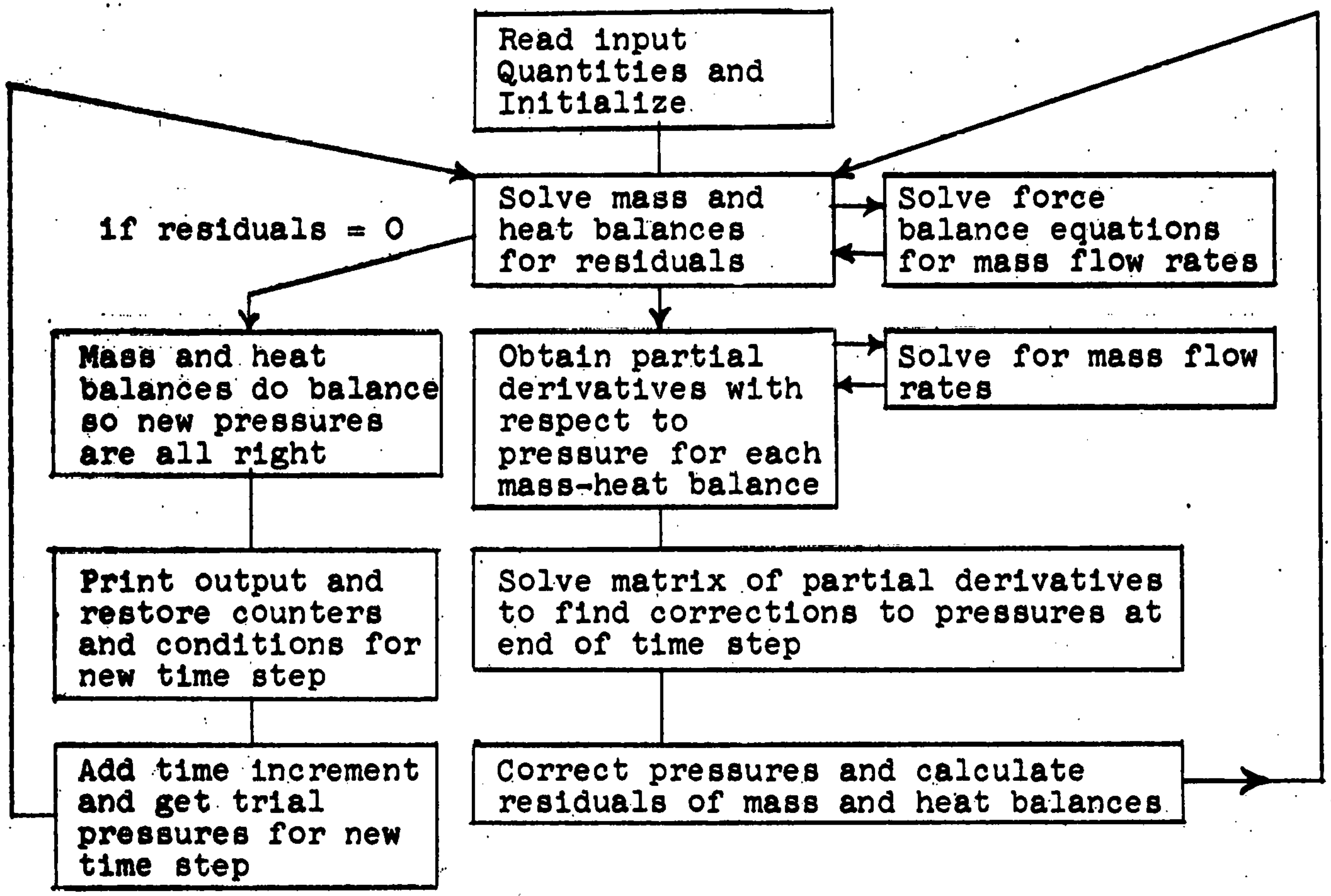
A1.6 Method of Solution of Equations

After the original consideration of methods of solution of the equations shown above, two methods were considered in detail. One being an iterative method of solution and the other a Newton-Raphson procedure. It was decided that the iterative solution had a higher probability of being programmed and coded within the alloted time and funds. However, after the code was completed and running, it was found to be unstable after an elapsed real time of approximately one second. At this point it was decided that any modifications to the present formulation would have to be rather extensive. This being the case, the program was modified to include the Newton-Raphson procedure to solve for the pressures at each time step. The Newton-Raphson method requires a longer time for each iteration but has a much higher probability of producing a stable solution.

APPENDIX 2.0

Program Outing and Running Instructions

The flow diagram for the program to calculate transient pressure buildup following a primary system rupture is shown in the figure below:



The program consists of a main program and 7 subroutines which are outlined as follows:

A2.1 Main Program

1. Read input cards.

2. Point input on line (SS 6 down)
   Write input on tape 2 (SS 5 up)

3. Initialize NUM = 0 (counter for on-line printing)
   Set ASTAR = 2.0 (to bypass first test of water level in core)

4. Set sense lights 1 and 2 on for later use in subroutine RESIST

5. Call steam table quantities for 10 values of PO(I) (Use Subroutine STEAM)

6. For initial pressure guess at end of time step (P1(I)) let P1(I) equal PO(I).
   Also let new density of air (RHOA1) = old density of air (RHOAO)

7. Call RESIST to see if flow path resistances must be changed - if necessary - then they are changed.

8. Increase time.

9. If temperature inside reactor is less than feedwater temperature, reduce the feedwater enthalpy (HFW).

10. Change name of pressures for use in matrix manipulations, let X(I) = P1(I).

11. For economy in writing, define F1(P.L,P2,P3,P4,P5) = residual or unbalance of heat and mass balance for volume 1, and similarly for F2(P), F3(P), F4(P), and F5(P). Since each balance function Fi is a function of the pressures in some or all of the other volumes, the most probable way of finding the new pressures at the end of a time step is to determine the partial derivative $\frac{dFi}{dPj}$ for each Fi and each Pj. If the residuals (R) are found for the new pressure guesses at the new time point, then all the partial derivatives are determined at this new time point, and a matrix solution for the corrections to each pressure can be obtained which should reduce the residuals to a negligible value.

$$\begin{bmatrix} \frac{dF1}{dP1} & \frac{\delta F1}{\delta P2} & \frac{\delta F1}{\delta P3} & \frac{\delta F1}{\delta P4} & \frac{\delta F1}{\delta P5} \\ \frac{dF2}{dP1} & \frac{\delta F2}{\delta P2} & \frac{\delta F2}{\delta P3} & \frac{\delta F2}{\delta P4} & \frac{\delta F2}{\delta P5} \\ \frac{dF3}{dP1} & \frac{\delta F3}{\delta P2} & \frac{\delta F3}{\delta P3} & \frac{\delta F3}{\delta P4} & \frac{\delta F3}{\delta P5} \\ \frac{dF4}{dP1} & \frac{\delta F4}{\delta P2} & \frac{\delta F4}{\delta P3} & \frac{\delta F4}{\delta P4} & \frac{\delta F4}{\delta P5} \\ \frac{dF5}{dP1} & \frac{\delta F5}{\delta P2} & \frac{\delta F5}{\delta P3} & \frac{\delta F5}{\delta P4} & \frac{\delta F5}{\delta P5} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \end{bmatrix}$$

The residuals (R) are determined by calling PRESS with the new guesses at Δ1(I), or X(I).

12. Then one pressure at a time is changed a small fraction and the residuals are reevaluated and thus knowing the change in the functions for a given change in pressure Pj, the partial derivatives can be approximated $\frac{\delta Fi}{\delta Pj} = \frac{\text{Residual}, - \text{Residual}:}{Pj - Pj}$

13. The new corrections (AB(I,6)) to the pressures (I) are found and added to the pressures P1(I).

14. If these corrections are all less than a certain fraction of their corresponding pressure, the pressure P1(I) are close enough to the correct values and the program will then print on line (SS 6 down) or on tape 2 (SS 6 up) the pressures, flow rates, water volumes, and time.

15. If any one of the corrections is a larger fraction of its corresponding pressure than the TESTP input quantity, the program iterates through steps 10-15 until the desired degree of convergence is reached.

16. After convergence is reached in step 14 and the output is written, the time step is increased 10% and the new values of water volumes, pressures, and air density are renamed to old quantities for the next time step and the program transfers back to step 5 and repeats 5-16 for the next time step.

A2.2 Subroutine PRESS

1. If PRESS is being called to solve for the residues of the Mass and Heat balance equations it first calls subroutine STEAM for the steam table quantities for the new pressure guesses P1(I).

2. If SS 4 is down, the steam table quantities are written on the output tape.

1A. If PRESS is being called to solve for a partial derivative, the previous values of pressure and steam quantities are temporarily stored, and the new steam quantities are looked up for the P1 that is being varied.

2A. If SS 4 is down, the steam quantities for the newly varied P1 are written on tape 2.

3. Subroutine FLO is called to calculate the mass flow rates throughout the system for the new pressures.

4. The water volume in the core (VFCO) is determined and the level of the water in the core (CLEVEL) with respect to the top of the core is determined. Positive values are above the top of the core and negative values are below the top of the core.

5. ASTAR, the fractional portion of the core covered by water is determined.

6. The heat input from fission products is determined (DECAY).

7. The heat released from the pressure vessel heat capacity is calculated (BHEAT).

8. The heat released from the core heat capacity is calculated (AHEAT).

9. The mass transfer for each volume is determined.

10. The condensation for volumes 2 through 5 is determined.

11. The heat transfer is determined for each volume.

12. If SS 4 is down - intermediate quantities are written on Tape 2.

13. Intermediate quantities AMA, AMB, AMC, AMD, AME, and AMF are calculated for each volume.

14. If SS 4 is down, the quantities calculated in 13 are written on tape 2.

15. The mass and heat balance equations are solved for the new mass of water in each volume, using quantities from 13 above.

16. The residual values are determined (RESDUE(I)) or

16A. The residual values for the partial derivatives are calculated (RESID(I)).

17. If SS 4 is down, write intermediate data on tape 2.

18. If calculating partial derivative, restore pressure to original value (See step 1A).

19. Set column vector = AB(I,6)

20. Set columns of matrix = $\frac{\text{RESID(I) - RESDUE(I)}}{\text{DA}}$

20A. If SS 3 is down, set off-diagonal elements of matrix to zero leaving only main diagonal.

21. If SS 4 is down, write intermediate data on tape 2.

22. Return to MAIN.

A2.3
SUBROUTINE FLO - (Solves for mass flow rates for a given set of pressures)

1. If Major = 1, rupture is steam flow
   = 2, rupture is water flow

2. For each of first seven flow rates do following:
   a. ΔP = Pin - Pout pressure drop

   b. ΔPP = (Pin - Pout)/Pin fraction of inlet pressure

   c. Y = 1.0.(AK)(ΔPP) See CRANE U.C. Handbook

   d. If Y is less than critical value, meaning that flow velocity is greater than sonic velocity - set Y = YSTAR, the value of Y at critical velocity and set ΔP = DSTAR*Pin the limiting pressure drop.

   e. Calculate $W = AY\sqrt{\Delta P x P}$

3. Call subroutine RELAX to calculate simultaneous flow rates.

4. If SS 2 is down, write intermediate output on tape 2.

5. RETURN

A2.4 Subroutine RELAX

1. Define new flow coefficients $B = 1/A^2Y^2P$

2. Solve six simultaneous equations for mass flow rates 8 through 13 by iterative procedure.

3. Test flow rates for convergence if converged - go to RETURN.

4. If not converged - calculate new ΔP, ΔPP, and Y and check for critical flow velocity as in subroutine FLO. The various pressure drops will change as the currents change so they must be recalculated at each iteration.

5. Call subroutine STEAM for new gas densities.

6. If SS 4 is down, write intermediate data on tape 2.

7. Go to step 2 and repeat 2-6.

8. Return to FLO.

A2.5

SUBROUTINE RESIST - Calculates the values of flow resistance for the flow paths from the reactor cavity to the pump rooms and the steam chase and sump room as a function of water height in the reactor cavity.

1. Height of water in reactor cavity (H) = volume of water (VFO(2)) divided by room equivalent cross sectional area (AREA2).

2. If H is less than HZ(1) (See Figure A2.A)no change in A_2 or A_3 occurs and program transfers to statement 777.

3. If H is between HZ(1) and HZ(2), subroutines ADMIT and BUICK are used to calculate the effective cross-section of the passageway and its friction factor and these are used to determine the flow coefficient.

4. If H is between HZ(2) and HZ(3), the steam line clearance is closed off and if the pressures in the cavity and steam chase are unequal, water will be transferred until a static head of water equalizes the pressures.

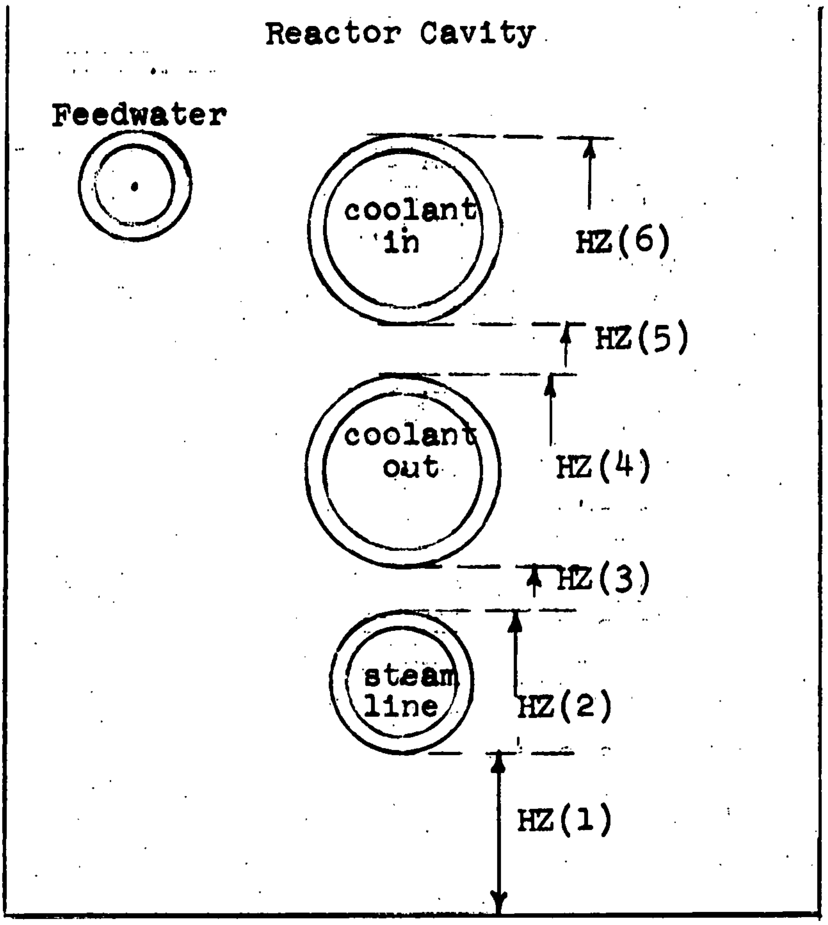
5. As the water level(H) increases past HZ(3) through HZ(6), the flow coefficients around the main coolant pipes are decreased until the time when H exceeds HZ(6), then A(3) and A(2) are set equal to zero, and control passes to statement 777.

6. Statement 777 begins a series of tests for pressure break points.

7. If the cavity pressure exceeds the input quantity (PPOOL), the bottom of the shield pool is assumed to rupture and A(7) is set equal to the input quantity TESTWW. This will then give a flow rate for the steam bubbling through the pool.

Figure A2.A

Schematic of Pipe Lines Out of Reactor Cavity



flow coefficient A_3 = steam line + feedwater line

flow coefficient A_2 = 3(coolant inlet + coolant outlet)

8. If the pressure differential across the walls of the air conditioning duct in the operating room exceeds 5 psi, the duct bursts, which increases A(13) by an arbitrary factor of 1000.

9A. If the input quantity ITEM1 has the value of 1, the damper flow coefficients A_6 and A_{11} are set to zero and ITEM1 is set to 2.

9B. If ITEM1 has the value of 2, the dampers are open and A_6 and A_{11} have mass flows. The water level in the core is checked and if the core becomes uncovered, the flow coefficients A_6, A_{11} and A_5 are set to zero, that is, the dampers are closed and the main steam valve is closed.

10A. If the core is still covered, the pressure at the exit damper is checked and if the pressure in the reactor cavity exceeds atmospheric by 6 psi, the duct will rupture and the flow coefficient is arbitrarily multiplied by the factor BRK, read in as an input quantity. ITEM1 is set to 3.

10B. If ITEM1 is 3, the exit duct (A_6) has ruptured and the core water level is checked to see if the core is covered, if not, A_5, A_6 and A_{11} are set to zero.

In summary, the main program contains the input and output routines and the routine which solves the partial derivative matrix for the corrections to the pressures. It also corrects the pressures and calls subroutine PRESS to solve the heat and mass balances. Subroutine PRESS determines how well the heat and mass balances for the various rooms actually balance. The volumes of water in the various rooms are obtained explicitly while the pressures are obtained implicitly. Subroutine PRESS calls subroutine FLO to determine the flow rates as needed, and FLO in turn calls subroutine RELAX to solve the six current equations which are interconnected and must be solved simultaneously. Subroutine STEAM furnishes steam table data when and where it is needed. Subroutine RESIST checks the water level in various volumes and determines how and when any of the flow coefficients must change, such as by covering up a flow path with water, or by breaking a duct by over pressures. Subroutine ADMIT calculates the effective resistance of the flow passages out of the reactor cavity, and subroutine BUICK determines the friction factors for the flow coefficients. With a convergence criteria of .001 for the pressures, it takes approximately 8 seconds per time step. With a convergence criteria of .01, the machine time for each time step is about 3 seconds.

Complete listings of the FORTRAN statements for the program are included in this report.

A2.6 Definition of Terms in FORTRAN Routines

PO(I)	Pressures at beginning of time step	(PSIG)
P1(I)	Pressures at end of time step	(PSIG)
ZMCM	Mass of core metal times specific heat	(Btu/^{o}F)
QZERO	Original rate of heat production by radioactive decay	Btu/sec
WFW	Feedwater flowrate	222#/sec
HLFW	Enthalpy of feedwater	332 $\frac{\text{Btu}}{\#}$
VBC	Volume of primary coolant system below bottom of core	ft^3
VFC	Free volume of core	ft^3
MAJOR	= 1, rupture is steam flow, = 2 rupture is water flow	
DZERO	size of rupture	4.11 in
TESTP	Convergence criteria for pressures	.01-.001
BRK	Multiples for A(6) when duct breaks	5
TESTW	Convergence criteria for flow rates in RELAX	.0001
TESTWW	Value of A(7) after rupture in bottom of pool	1000
PPOOL	P(2) pressure at which bottom of pool ruptures	50 PSIG
PDUCT	Pressure difference across duct wall which will cause duct to rupture	5 PSIG
ITEM1	= 1, ventilation dampers open, = 2, ventilation dampers closed, = 3, after core is exposed, dampers closed	
AREA1	Free area in core	ft^2
AREA11	Free area above core	ft^2
AREA2	Free area in reactor cavity	ft^2

AREA3	Free area in pump rooms	ft^2
AREA4	Free area in steam chase and sump room	ft^2
BZERO	Mass of pressure vessel times specific heat	$\frac{BTU}{^{o}F}$
TZERO	Original temperature at times of rupture	489^{o}F
VPV	Volume of pressure vessel	ft^3
VPIPES	Volume of primary coolant pipes	ft^3
CP	Specific heat of air	.245 $\frac{BTU}{\#^{o}F}$
RHOAO	Density of air in volume 5 at beginning of time step	lb/ft^3
RHOA1	Density of air in volume 5 at end of time step	lb/ft^3
TIME	Time after rupture	seconds
DELTAT	Time step	seconds
D	Incremental factor used to get started in Newton-Raphson iteration	.01
HZ(I)	Height of various flow passages from reactor cavity	ft
RO(I)	Outside radii of flow passages in reactor cavity	ft
R1(I)	Inside radii of flow passages in reactor cavity	ft
TALL(I)	Height of volumes	ft
PERIM(I)	Perimeter of volumes	ft
V(I)	Volume of each room	cu ft
VFO(I)	Volume of water in each room at beginning of time step	cu ft
VF1(I)	Volume of water in each room at end of time step	
A(I)	Flow coefficients	
AK(I)	Flow coefficients (expansion factors)	

Y(I)	Flow coefficients (expansion factors)	
DSTAR(I)	Fractional value of inlet pressure drop at sonic velocity steam flow	
YSTAR(I)	Value of Y at sonic velocity steam flow	
ASTAR	Fraction of core covered by water	
TEMP(I)	Temperature	°F
HL(I)	Enthalpy of water	$\frac{\text{BTU}}{\#^{\circ}\text{F}}$
HG(I)	Latent heat	
HLG(I)	Enthalpy of saturated steam	BTU/#
RHOL(I)	Density of water	$\#/\text{ft}^3$
RHOG(I)	Density of steam	$\#/\text{ft}^3$
COND(I)	Conductivity of water	BTU/hr°F-ft
VISC(I)	Viscosity of water	#/ft-hr
AB(I,J)	Elements of partial derivative matrix	
FRACT1,2,3	Not used by program	
P2(I)	Not used by program	
CLEVEL	Level of water in pressure vessel with respect to top of core, + = above core, - = below top of core	ft
H	Height of water in reactor cavity	ft
ABC1	Components used to calculate flow coefficients	
ABC2	" " " " " "	
ABC3	" " " " " "	
ABC31	" " " " " "	
WP1	" " " " " "	
WP2	" " " " " "	
WP3	" " " " " "	
WP31	" " " " " "	
DE1	" " " " " "	
DE2	" " " " " "	
DE3	" " " " " "	
DE31	" " " " " "	

FACT1	Components used to calculate flow coefficients	
FACT2	" " " " " "	
FACT3	" " " " " "	
FACT31	" " " " " "	
XYZ1	" " " " " "	
XYZ2	" " " " " "	
XYZ3	" " " " " "	
RESDUE(I)	Amount by which heat and mass balances do not balance	BTU
DELTAM(I)	Mass transfer during time interval	#
W(I)	Mass flow rates	#/sec
QUEUE(I)	Heat transfer during time interval	BTU
RESID(I)	Amount by which heat and mass balances do not balance when calculating partial derivatives	BTU
AMA(I)	Components used to calculate mass and heat balances	
AMB(I)	" " " " " " " "	
AMC(I)	" " " " " " " "	
AMD(I)	" " " " " " " "	
AME(I)	" " " " " " " "	
AMF(I)	" " " " " " " "	
DECAY	Heat contribution from fission product decay	BTU/sec
AHEAT	Heat contribution from core heat capacity	BTU/sec
BHEAT	Heat contribution from pressure vessel heat capacity	
CONDEN(I)	Condensation in each room	$\frac{BTU}{sec}$
DELTAP(I)	Pressure drop for each mass flow	psi
DELTPP(I)	Fraction of inlet pressure used across flow path	
B(I)	Flow coefficients = $1/A^2Y^2\rho g$	

A2.7 Running Instructions and Sample Data

1. Input consists of 18 separate cards, and all data must be entered for each problem.

2. All data is entered in fixed point. Decimal points are required in all numbers to be used as data, while numbers such as MAJOR, and ITEM1 must NOT have decimals. All numbers are separated by commas, and the last number on the card would be followed by an asterisk to indicate the end of the field.

2A. Date card

3. CARD1 - 6 words with decimal points, 1 word without decimal, 3 words with decimal,
    a. Core mass x specific heat $(\#)(\frac{BTU}{\#^{o}F})=(\frac{BTU}{^{o}F})$
    b. Original strength of fission product heat rate $(\frac{BTU}{sec})$
    c. Feedwater flow rate (#/sec)
    d. Enthalpy of feedwater (BTU/#^{o}F)
    e. Volume of primary system below core (ft^3)
    f. Free volume in pressure vessel between top and bottom of core (ft^3)
    g. 1 = steam flow from rupture, 2 = water flow from rupture
    h. Diameter of rupture inches
    i. Pressure convergence ratio (.01-.001)
    j. Multiplier for A^6 when duct breaks (5)

4. CARD2 - 4 words with decimal points, 1 word without decimal
    a. Convergence test for mass flow rates (.0001)
    b. Value of flow coefficient A7 when bottom of pool is ruptured (1000.)
    c. Pressure at which bottom of pool ruptures (50psig)
    d. Pressure difference at which airconditioning duct ruptures (5 psig)

5.	CARD3 - 5 words with decimal points	
	a. Free area in pressure vessel at core midplane	
	b. Free area in pressure vessel above core	ft^2
	c. Area in reactor cavity	ft^2
	d. Area in pump rooms	ft^2
	e. Area in sump and steam chase	ft^2
6.	CARD4 - 6 words with decimals	
	a. Mass of pressure vessel times specific heat	BTU/°F
	b. Original temperature of primary system	°F
	c. Volume of pressure vessel	ft^3
	d. Volume of pipes	ft^3
	e. Specific heat of air	BTU/#°F
	f. Original density of air in operating room	.09#/cuft
7.	CARD5 - 3 words, with decimals	
	a. Time at start of problem	0
	b. Original time increment	0.10 sec
	c. Multiplier for pressures to get partial derivatives	.01
8.	CARD6 - 6 numbers with decimals	
	a. Height of bottom of steam pipe tunnel above floor of reactor cavity	(ft)
	b. Height of top of steam pipe tunnel above floor of reactor cavity	(ft)
	c. Height of bottom of main coolant outlet pipe tunnel above floor of reactor cavity	(ft)
	d. Height of top of main coolant outlet pipe tunnel above floor of reactor cavity	(ft)
	e. Height of bottom of main coolant inlet pipe tunnel above floor of reactor cavity	(ft)
	f. Height of top of main coolant inlet pipe tunnel above floor of reactor cavity	(ft)

9. CARD7 - 3 numbers with decimals
   a. Radius of steam tunnel (ft)

   b. Radius of feedwater tunnel (ft)

   c. Radius of main coolant tunnel (ft)

10. CARD8 - 3 numbers with decimals
   a. Radius of (steam pipe + insulation) (ft)

   b. Radius of (feedwater pipe + insulation) (ft)

   c. Radius of (main coolant pipe + insulation) (ft)

11. CARD9 - 5 numbers with decimals
   a. Wall height of pressure vessel (ft)

   b. Wall height of reactor cavity (ft)

   c. Wall height of pump rooms (ft)

   d. Wall height of steam chase (ft)

   e. Wall height of operating room (ft)

12. CARD10 - 5 numbers with decimals
   a. Circumference of pressure vessel (ft)

   b. Circumference of reactor cavity (ft)

   c. Circumference of pump rooms (ft)

   d. Circumference of steam chase (ft)

   e. Circumference of operating room (ft)

13. CARD11 - 10 numbers with decimals
   a. Original pressure in reactor psia 615

   b. Original pressure in reactor cavity 14.7

   c. Original pressure in pump rooms 14.7

   d. Original pressure in steam chase 14.7

   e. Original pressure in operating room 14.7

   f. Original pressure in air conditioning duct (6) 14.7

   g. Original pressure in air conditioning duct (7) 14.7

h. Original pressure in inlet air duct to containment 14.7

i. Original pressure in exit air duct to containment 14.7

j. Original pressure in turbine condenser 14.7

14. CARD12 - 5 numbers with decimals
    a. Volume of primary system ft^3

    b. Volume of reactor cavity ft^3

    c. Volume of pump rooms ft^3

    d. Volume of steam chase ft^3

    e. Volume of operating room 84000 ft^3

15. CARD13 - 5 numbers with decimals
    a. Original volume of water in primary system 1810 ft^3

    b. Original volume of water in reactor cavity 0

    c. Original volume of water in pump rooms 0

    d. Original volume of water in steam chase 0

    e. Original volume of water in operating room 0

16. CARD14 - 13 numbers with decimals
    flow coefficients A_1 for mass flow channels 1 - 13

17. CARD15 - 13 numbers with decimals
    coefficients AK_1 for flow channels 1 - 13

18. CARD16 - 13 numbers with decimals
    coefficients $YSTAR_1$ for flow channels 1 - 13

19. CARD17 - 13 numbers with decimals
    coefficients $DSTAR_1$ for flow channels 1 - 13.

APPENDIX 3.0

Calculation of Flow Constants for Reference Design

The flow constants used in the program are input and thereby can be varied for program versatility. For flow coefficients A_2 and A_3, initial values must be read into the program. However after one iteration these values are calculated by subroutine RESIST. The reason for this is that the reactor cavity, pump rooms and the steam chase will be flooded and thereby the values A_2 and A_3 are changed.

According to J. G. Burnell,[8] when saturated water flows through a sharp-edged orifice no flashing occurs until after the water is through the orifice, and, contrary to the theory based on a change of state, no critical-pressure condition is evident. The quantity of saturated water that will flow through a sharp-edged orifice for given pressure can be calculated with sufficient accuracy by the formula used to determine the flow of cold water through an orifice, and the discharge coefficients found for saturated water are approximately the same as those generally used for cold water.

∴ The formula for maximum flow is:

$$\frac{M(\#/\text{sec})}{A(\text{ft}^2 \text{ of orifice})} = 0.6\rho\sqrt{(2g/\rho)(P_1 - P_2)}$$

where ρ = density of saturated water at P_1

0.6 = coefficient of contraction for a sharp-edged orifice

∴ calculation of Flow Coefficient

$$W = 0.6\,A_r\sqrt{2g\Delta P\rho(144)}$$

$$A_r = \frac{\pi}{4}D^2 \quad \frac{\pi}{4}\,\frac{[4.110^2]}{144} = (.7854)\frac{(16.8921)}{144} = \frac{13.26705}{144} = .09213 \text{ ft}^2$$

$$\therefore W = 0.6 \times .09213\sqrt{2 \times 32.2}\;\sqrt{\Delta P\rho}\;\sqrt{144}$$

$$W = 0.6 \times .09213 \times 8.05\sqrt{\Delta P\rho} \times 12$$

$$\therefore A_1 = 0.6 \times .09213 \times 8.05 \times 12$$

$$A_1 = 4.83 \times .09213 \times 12$$

$$A_1 = 0.4448 \times 12 = 5.33$$

For all other flow coefficients (steam flow) Darcy's equations for compressible flow are used

That is: 1) $W(\#/hr) = 1891Yd^2 \sqrt{\frac{\Delta P}{KV_1}}$ $K = F\frac{L}{D}$

from equation 1

$$W = \frac{1891Y\cancel{d}^2 A_r}{\frac{\pi}{4} \times \frac{\cancel{d}^2}{144}} \sqrt{\frac{\Delta P}{K\bar{V}_1}} = \#/hr$$

$$W = \frac{1.891}{3.600} \times \frac{4 x 144 A_r}{\pi} \sqrt{\frac{\Delta P}{K\bar{V}_1}} = \#/sec$$

$$\therefore A = \frac{96.3067 A_r}{K} \qquad (A_r = \text{AREA})$$

A_2 = Water Recirculating Line (2" clearance)

$$D_e = (D_O - D_1) = 4" = 1/3 \underline{\underline{Ft}}$$

$$A_r = \frac{\pi}{4}\left[2\frac{2}{3} - 2\frac{1}{3}\right]\left[2\frac{2}{3} + 2\frac{1}{3}\right] = \frac{\pi}{4}\left(\frac{1}{3}\right) 5 = 1.309 \text{ ft}^2$$

From p A-24 Crane Handbook

$$F = .0163$$

$$\therefore K = .0163 \times \frac{10}{1/3} = 0.489$$

$$K_e = K_{ent.} + K_{frict.} + K_{exit}$$

$$K_e = 1.0 + .489 + 0.5 = 1.989$$

$$\sqrt{K} = \sqrt{1.989} = 1.410$$

$$A_2 = \frac{9.65x10}{1.410} A_r = \frac{96.5x1.309}{1.410} = 96.5 \times .9283 = 89.58$$

Since there are six holes

$$A_2 = 6 \times 89.58 = 537.48$$

A_3 = Steam Line + Water Return 2" Clearance

$$D_e = D_o - D_i = 4'' = 1/3'$$

$$AR_s = \pi/4 \,[2.333-2]\,[2.333+2] = 1.13 \text{ ft}^2$$

As previous $\sqrt{K} = 1.410$

$$\therefore A3_s = \frac{9.65 \times 10 \times 1.13}{1.410} = 77.34$$

$$A_{R_{wr}} = \pi/4 \,[1/3]\,[7/3] = 0.61087 \text{ ft}^2$$

$$A3_{wr} = \frac{9.65 \times 10 \times 0.61087}{1.410} = 41.72$$

$$\therefore A_3 = 77.34 + 41.72 = 119.06$$

A_4 = 30" Manhole

$$\text{Area} = 1/4\, \pi D^2 = 1/4\, \pi \,[30/12]^2 = 4.92 \text{ ft}$$

$D_e = 30'' = 2\text{-}1/2'$

$f = 0.011^1$

$$A_4 = \frac{9.65 \times 10 \times 4.92}{1.226}$$

$L = 1$

$A_4 = \underline{\underline{387}}$

$F\, L/D = .004$

$A_4 = 387 \times 3 = 1161$ for 3 manholes

$K = 1.54 + .004 = 1.504$

$\sqrt{K} = 1.226$

A_5 = Turbine Steam Line

$$\frac{614{,}000}{3{,}600} = AY\sqrt{\frac{\Delta P \rho}{K}} = 170.8$$

$$\frac{\Delta P}{P} = \frac{586}{600} = .9+$$

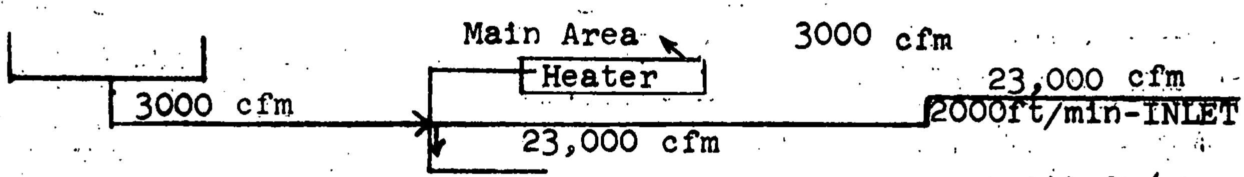
$$\therefore \text{Max } \frac{\Delta P}{P} = 0.593$$

$$\therefore \Delta P = .593 \times 600 = 355.8 \cong 356$$

$$\Sigma Y = 0.64$$

$$170.8 = A_5 \times .64 \sqrt{\frac{356}{1 \times .7698}} = A \times 6.4 \sqrt{4.63}$$

The duct system is designed for the following air flow rates: 1) 23,300cfm through pump chambers and pipe chase and 2) 3,000 cfm through heating and ventilating system.



The air velocity through the duct is assumed to be 2,000 ft/min this may tend to be noisy but was agreed upon with Allis Chalmers.

Length of duct through water treatment building $\simeq$ 60 ft

Length of Duct to Equipment Floor - 14'
+ 2 90° elbow at operating floor
1 90° elbow at equipment floor

Length of Duct to Equipment Room - 8 ft

Length of Duct to Pump Rooms - 26 ft
+ 2 elbows

Length of Duct for By-Pass Air - 56'
+ 4 elbows.

Length of Exhaust Duct - 84 ft
+ 3 elbows (90°)

A_6 = **Exhaust Duct**

$$A_R = \frac{23,000}{3,000} = 11.5 \text{ ft}^2$$

Assume square duct $\therefore x$ **(length of side) = 3.4 ft**

For a Square Duct $D_e = X$

For Ducts Use $F = .007$

$$L/D = 84/3.4 + 3(30) = 115$$

$$F\ L/D = .007 \times 115 = 0.805$$

$$K = 1.5 + .805 = 2.305$$

$$\sqrt{K} = 1.518$$

$$\therefore A_6 = \frac{96.3067 A_r}{1.518} = \frac{96.3067}{1.518}(11.5) = 749$$

$$A_6 = \underline{\underline{749}}$$

A_7 = 0 until the diaphram at the bottom of the pool ruptures and then the A_7 will be arbitrarily increased to the value read in the input cards. There is no applicable empirical data available on equivalent resistances of steam flow through pools of water.

A_8 = Duct from Steam Chase

$$A_2 = \frac{23,000}{4x2000} = 2.9125$$

$$x = 1.71 \text{ ft}$$

$$L/D = 26/1.71 + 60 = 15.2 + 60 = 75$$

$$f = .007$$

$$f\ L/D = .007(75) = 0.525$$

$$K = 1.5 + 0.525 = 2.025$$

$$\sqrt{K} = 1.490$$

$$\underline{\underline{A_8}} = \frac{96.3067x2.9125}{1.490} \text{ x } \underline{\underline{187.8}}$$

R_9 = Duct through Large Room

Use L = 60' and 1 elbow

$$L/D = 60/3.4 + 30 = 17.6 + 30 = 47.6$$

$$f\ L/D = .007\ (47.6) = .3332$$

$$K = 1.5 + .333 = 1.833$$

$$\sqrt{K} = 1.357$$

$$\therefore A_9 = \frac{96.3067(115)}{1.357} = \underline{\underline{816.0}}$$

R_{10} = Length of Duct = 60 ft.

Assume 4 elbows

Assume ΔP for Heater = 60 ft.

$$L/D = 1/1.225\ [120] + 120 = 218 \text{ ft.}$$

$$f\ L/D = 1.526$$

$$K = 1.526 + 1.5 = 3.026$$

$$\sqrt{K} = 1.738$$

$$A_{10} = \frac{96.3067x(1.5)}{1.738} = \underline{\underline{\underline{83.1}}}$$

R_{11} = Duct from Outside to Equipment Room Use Resistance to flow of Filter Equal to total L/D of St. Pipe Use L/D = 30 for each elbow

$$L/D = 2/3.4\ [60 + 14 + 8] + 3[30]$$

$$L/D = 1/1.7\ [82] + 90 = 138$$

$$f\ L/D = 007(138) = .966$$

$$K = .966 + 1.5 = 2.466$$

$$\sqrt{K} = 1.561$$

$$\therefore A_{11} = \frac{96.3067(11.56)}{1.561} = \underline{\underline{\underline{713}}}$$

A_{12} = Duct from Pump Room

Each duct from each pump room is identical and equal to duct from steam chase.

$$\therefore A = 187.8$$

However, there are three ducts

$$\therefore \underline{A_{12}} = 3A_8 = 3(187.8) = \underline{\underline{\underline{563.4}}}$$

R_{13} = Length = 56 ft 4 elbows; L/D = 120

$$L/D = 56/1.225 + 120 = 166$$

$$f\ L/D = 166\ (.007) = 1.162$$

$$K = 1.162 + 1.5 = 2.662$$

$$\sqrt{K} = 1.895$$

$$\underline{\underline{A_{13}}} = \frac{96.3067(1.5)}{1.875} = \underline{\underline{76.2}}$$