OAK RIDGE NATIONAL LABORATORY

Operated by

UNION CARBIDE NUCLEAR COMPANY

Division of Union Carbide Corporation

Post Office Box X

Oak Ridge, Tennessee

MASTER

ORNL
CENTRAL FILES NUMBER

59-8-2

DATE: August 4, 1959

SUBJECT: Core Levitation in the EGCR in Case of Main
Coolant Pipe Failure

TO: Listed Distribution

FROM: M. H. Fontana

COPY NO. 46

External Distribution
AuthorizedAbstract

This memorandum summarizes the results of an analysis to determine the extent of displacement of the EGCR core due to blowdown in case of several postulated hot main gas coolant pipe failures. Results show that the core will be damaged for any hot pipe double-ended failure. Excepting the improbable case of no coolant flow existing prior to the break, the core will be damaged for any hot pipe fracture exposing a total flow area to the atmosphere equal to that of one pipe. Smaller breaks will probably be safe in this respect.

NOTICE

This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

The information is not to be abstracted, reprinted, or otherwise used for the determination without the approval of the ORNL patent branch, Legal and Information Control Department.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission.

- A. Makes any warranty or representation, 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 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" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Table of Contents

Introduction	Page 3
Calculational Procedure	3
Equations	7
Cases Examined	7
Analysis of Results	9
Conclusions	14
Nomenclature	16
Appendix A	17
Appendix B	23
Appendix C	25
Appendix D	34

Introduction

The EGCR is a graphite-moderated helium-cooled reactor producing 84.3 Mwt.⁽¹⁾ The core moderator is a vertical cylinder of stacked graphite blocks. Any violent "hump" or lifting of the core may cause misalignment of the blocks which could prevent insertion of control rods and removal of the fuel. The former of these possibilities could have very serious consequences. Since the emergency cooling mechanisms, such as the pony motors and the natural convection effect, are intended to remove afterheat only, inability to insert the control rods could result in serious overheating of the fuel elements. Even if the consequences of rod insertion inability were avoided, resultant fuel misalignment, breaking, and jamming would probably force abandonment of the reactor system.

This memorandum summarizes the results of an analysis performed to determine the extent of core damage resulting from a lifting differential pressure caused by rupture of a main coolant pipe in the EGCR. The most probable place for a pipe failure is at the hot junction with the core pressure vessel. A break at this point would also cause the largest lifting force on the core; for this reason, this analysis assumes the break occurs at this point.

Calculational Procedure

An elevation of the EGCR is shown in Fig. 1. Since the equations describing flow and blowdown through the core and heat exchangers are rather complicated, a simplified model more amenable to solution was devised. The gas volume in the reactor system was separated into six nodes separated by flow resistances. As indicated in Fig. 2, nodes 1 and 4 simulate the reactor upper and lower plenum, and are separated by a resistance equivalent to that of the core. Nodes 2 and 3 are each one-half of the void volume of one steam generator separated by a flow resistance equivalent to that of one steam generator. Similarly, nodes

(1) Experimental Gas-Cooled Reactor Preliminary Hazards Summary Report, Kaiser Engineers, Allis-Chalmers, and Oak Ridge National Laboratory, ORO-196, May 1959.

REACTOR BUILDING SECTIONS

Fig. 2

5 and 6 simulate the other steam generator. Since the gas volume of the core is small compared to the two plenums (see Table I), the assumption of the core being a resistance with no gas volume is fairly good. Dividing the heat exchangers into two volumes with the flow resistance in between is a compromise between the accuracy of the answer and the complexity of the solution.

TABLE I

Void Volumes of Various Components (approximate)

<u>Component</u>	<u>Void Volume (ft³)</u>
Upper plenum	~ 2097
One hot pipe (of 2)	327
One heat exchanger (of 2)	2070
One cold pipe (of 2)	275
Core	178
Lower plenum	~ 2097

The equations describing the pressures throughout the system during blowdown were written as shown in Appendix A. The resultant set of equations was too complex for hand solution, so they were solved by means of the ORNL Reactor Controls Analog Computer Facility. Solutions were obtained as pressure drop across the core vs time after pipe failure for various combinations of break sizes and cold line resistances. Cold line resistances were varied to bracket the effect of stalled blower resistance which could not be accurately determined at this time.

The displacement of the core if the determined pressure history were assumed to apply to it was calculated manually, and the effects of fluid momentum coastdown and blower effects were added as an approximation.

Tables I and II show the volumes and the full flow pressure drops from which the constants in this analysis were derived. The volumes in Table I were scaled from PEGCPR drawings, and the values of Table II were obtained by personal communications with J. Foster of ORNL. The final values as given in Ref. (1) were not known exactly at the time of this analysis, so approximate values were used. As will be seen later, the flow resistances as derived from Table II are in a square root term, so errors of this magnitude are negligible.

The flow resistances of the various components were taken from the following approximate full-flow design data:*

TABLE II

Full flow	=	118.5 lb/sec
Δp in core	=	7 psi
Δp hot pipe (one)	=	1.5 psi
Δp cold pipe (one)	=	1.5 psi
Δp heat exchanger (one)	=	2 psi
Total Δp	=	12 psi

* Final values as shown in the EGCR Hazards Summary Report⁽¹⁾ are:
 Δp core = 7.4 psi, and Δp total = 11.5 psi.

The flow resistance, k , for each component was found from the relation:

$$\Delta p = k w^2$$

Equations

The equations describing the pressure as a function of time at various points in the system with the appropriate constants introduced and reduced are:

$$\frac{dp_4}{dt} = - 2.282 \sqrt{p_4^2 - p_1^2} - B \sqrt{p_4^2 - p_3^2} - B \sqrt{p_4^2 - p_5^2} \quad (1)$$

$$\frac{dp_3}{dt} = - 5.36 \sqrt{p_3^2 - p_2^2} + C \sqrt{p_4^2 - p_3^2} \quad (2)$$

$$\frac{dp_2}{dt} = - 6.18 \sqrt{p_2^2 - p_1^2} + 5.36 \sqrt{p_3^2 - p_2^2} \quad (3)$$

$$\frac{dp_5}{dt} = - 5.36 \sqrt{p_5^2 - p_6^2} + C \sqrt{p_4^2 - p_5^2} \quad (4)$$

$$\frac{dp_6}{dt} = - D p_6 + 5.36 \sqrt{p_5^2 - p_6^2} \quad (5)$$

$$\frac{dp_1}{dt} = - E p_1 + 3.05 \sqrt{p_2^2 - p_1^2} + 2.828 \sqrt{p_4^2 - p_1^2} \quad (6)$$

Appendix A gives the derivations of these equations.

Cases Examined

The constants corresponding to the various cases analyzed are shown in Table III.

Case 1 is a double-ended pipe failure in the hot line with no credit for blower resistance, i.e., the hot line breaks and shears a sufficient amount to expose an area free for flow in each half of the broken pipe equal to the cross sectional area of one pipe, and

TABLE III

Numerical Value of Constants in Equations 1-6

<u>Case</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>
1	3.05	6.18	8.54	4.211
2	1.52	3.09	8.54	4.211
3	0.76	1.55	8.54	4.211
4	0.38	0.775	8.54	4.211
5	3.05	6.18	4.27	2.106
5(a)	3.05	6.18	2.14	1.053
6	1.52	3.09	4.27	2.106
7	0.76	1.55	4.27	2.106

only the cold line resistance is used for impedance to flow between volumes 3 and 4, and 4 and 5.

Case 2 is again a double-ended hot pipe failure with a blower plus cold line resistance equal to 4 times the cold line resistance alone.

Case 3 is a double-ended hot pipe failure with a blower plus cold line resistance equal to 16 times the cold line resistance alone.

Case 4 is a double-ended hot pipe failure with blowers plus cold line resistance 64 times cold line resistance alone.

Case 5 is a longitudinal or other hot pipe failure such that the flow area available to each end of pipe is halved. The blower resistance is neglected.

Case 5(a) is an attempt to solve the case for a hot pipe failure with a flow area available to each end of one-fourth that of the double-ended failure case.

Case 6 is a broken hot pipe flow area one-half that of a double-ended failure with a cold line and blower resistance 4 times that of the cold line alone.

Case 7 is a broken pipe flow area one-half that of a double-ended failure with a cold line and blower resistance 16 times that of the cold pipe alone.

Of these cases, case 7 deserves closest scrutiny. It is not likely that a brittle double-ended failure would occur in this system because ductile materials are to be specified throughout, and the concrete rooms surrounding the main coolant pipes are small enough to prevent sufficient lateral displacement to open a flow area equivalent to double the cross sectional pipe area, even if a brittle fracture does occur. The cold line resistance is high enough to include the effects of the blower. It will be seen from the results that case 7 is a marginal case.

Analysis of Results

The pressure differential across the core as a function of time after failure for cases 1-7 as traced out by the analog computer is shown in Fig. 3. A facsimile of the actual trace and the pressure of the other nodes in the system are shown in Appendix D. The solid line shows the Δp for the case in which no flow exists prior to failure. The dotted line shows the Δp due to fluid coastdown added directly to the blowdown Δp . The third line on case 7 shows the effect of adding Δp across the case due to the blower operation. The first of these additions is improbable because the effect of blowdown would probably alter the coastdown curve even if, by some unknown circumstance, the blowers should strip blades or otherwise disappear at exactly the same time as the pipe fracture.

The effect of continued operation of the blower would sustain a pressure drop across the core dependent on the gas density in the core and the density in the blowers.

The EGCR blowers are controlled to give constant flow during operating conditions.⁽¹⁾ Decrease in gas outlet temperature would cause the control system to decrease blower flow, but for purposes of this analysis it can be assumed that the blower speed remains constant in the first several seconds after the pipe break. The head output of the blower will remain constant with constant speed. The Δp across the blower and the mass flow rate will decrease with the change in density at the blower, while the resistance of the system will change as the density in the system. If the approximation is

FIG. 3. PRESSURE DIFFERENTIAL ACROSS CORE vs. TIME AFTER BREAK

made that the gas densities in the blower and the core decrease at roughly the same rate, then the Δp across the core will decrease linearly with the density.

Figure D-2, in Appendix D, shows the decrease in pressure of the lower plenum for case 7. If the approximation is made that the density decreases as the pressure during the first second (see Appendix A), the aforementioned argument leads to a Δp across the core vs time curve added to case 7, as shown in Fig. 3.

The momentary increase in Δp across the core at about 0.4 sec after rupture, as shown in Fig. 3, is probably due to a change in relative rate of flow between nodes 3 and 4, and nodes 3 and 2. As node 1 blows down, a greater fraction of the gas in node 3 probably goes toward 1 and out via 4 due to the lower resistance of the core. This relative increase of flow toward 4 will result in a slower rate of pressure drop in 4 compared to 1 relative to the initial rates. Further depletion of gas inventory and reduction in flow rates will decrease the Δp between 4 and 1 as the whole system tends toward a common pressure level. This effect is emphasized if the gas pressure in 4 is held for a greater time, as would be the case if the blower and cold line resistance of the flow path 4-5 were increased. Since the flow from 4 to 5 is greater than that from 3 to 4, the influence of an increase in flow resistance would be greater in 4-5 than in 3-4. Thus, increasing the cold line and blower resistance could accentuate this effect, as shown in Fig. 3.

The effect of the pressure differential on the displacement of the core is shown in Figs. 4 and 5. The vertical distance traveled by the core as shown in these two figures is based on the assumption that the pressure differential-time history, as traced out in Fig. 3, applies throughout the time during which the core is in motion. This assumption, of course, is not valid after the first inch or so of travel since the skirt between the core and the pressure vessel preventing flow bypass will be ruptured. Most of the flow would then go around the core rather than through it, and it would settle back down. A motion violent enough to do this must be presumed to render the core

UNCLASSIFIED
ORNL-LR-DWG 40065

FIGURE 4

UNCLASSIFIED
ORNL-LR-DWG 40066

FIGURE 5

useless. The height of travel shown in Figs. 3 and 4 is carried out to the maximum to show the effects of a short, seemingly low Δp burst. The derivations of Figs. 4 and 5 are shown in Appendix C along with a table of pressure and velocity.

It is apparent from Fig. 4 that all double-ended pipe failures, regardless of blower resistance, will damage the core.

Figure 5 shows that a pipe failure opening an area one-half that of the double-ended pipe failure would probably be safe if the break occurred at a time during which there was no flow. This possibility, however, is highly unlikely. Curve B shows the core displacement if the Δp due to fluid momentum alone is added. Direct addition of this coastdown is valid in the first few increments of time, but probably not for time greater than 0.5 sec or so due to flow reversals in the cold line 4-5 (Fig. 2). The only conceivable way in which this case could be physically possible would be for the blower blades to strip. Subsequent calculation has shown that the Δp across the cold legs 3-4 and 4-5 is about 0.2 psi and 0.8 psi, respectively, for case 4 which has the largest blower resistance for the double-ended pipe failure and the maximum Δp across the core. These pressures are not large enough to damage the blowers and therefore makes the less demanding case 7-B highly unlikely.

The most probable event would be the case in which the hot pipe fails and the blowers continue to operate. Since the pressure transients of interest take place within the first second after the break, it can be assumed that blower inertia and control system lag will allow the blowers to rotate at constant speed in the time period of interest. Curve C of Fig. 5 shows that if the Δp due to blower operation can, as an approximation, be added to the blowdown Δp , then the core would rise 0.2 ft, or about 2.5 in. It is not certain that the graphite stack could withstand this without some derangement.

Conclusions

A brittle fracture of a reactor main coolant outlet gas pipe that could result in a double-ended pipe failure would most certainly lift and derange the core. It is more likely, however, that any rupture

that would occur would be a ductile failure in the form of a longitudinal "laying open" of the pipe. The effect of this type of failure on the pressure drop across the core is dependent on the amount of flow area through which the gas may be allowed to escape. A total area larger than the cross section of one pipe would probably damage the core. An area considerably less than this probably would not.

Installation of a pressure relief bypass could protect the core against this type of accident, but must be extremely reliable in itself because accidental bypass while the reactor is in operation could pose a serious control problem.

Another alternative is to hold down the core by means of joining the top grid plate to the pressure vessel wall at a point of rigid support. This tiedown will need to be quite sturdy because the peak total lifting force for a double-ended pipe failure will approach 400,000 lb. This would have to be more of a travel limit stop than a rigid holddown because the graphite will contract gradually, shrinking about 3 in. in 20 years.⁽²⁾

The effect of the main valves depends on the location of the break relative to the valve. If the fracture occurs inboard of a closed valve, the lifting force on the core will be increased because more of the gas in the lower plenum and the heat exchanger will pass through the core since the valve prevents relief through the heat exchanger and the other end of the broken pipe. If the break occurs outboard of the valve, the lifting force on the core will be decreased because most of the flow will take the alternate path to the atmosphere through the heat exchanger. At any rate, it is doubtful that closing the main valves will be helpful because the period between pipe failure and time of peak pressure differential across the core is probably shorter than the closing time of the valve.

⁽²⁾ Personal communication, B. L. Greenstreet to M. H. Fontana, August 14, 1959.

Nomenclature

A	=	area, ft^2
f	=	friction factor, dimensionless
F	=	force, lb
g_c	=	conversion constant, $32.2 \text{ lb-mass/lb-force, ft/sec}^2$
k	=	proportionality constant between pressure drop and flow squared, $\text{sec}^2/\text{in.}^2\text{-lb}$
k	=	ratio of specific heats, dimensionless
m	=	mass, lb
p	=	pressure, psi
Δp	=	differential pressure, psi
p_{cr}	=	critical pressure ratio, dimensionless
r_h	=	hydraulic radius, ft
Δt	=	time increment, sec
T	=	absolute temperature, $^{\circ}\text{R}$
V	=	volume, ft^3
v	=	velocity, ft/sec
W	=	flow rate, lb/sec
w	=	weight, lb
x	=	linear distance, ft
ρ	=	density, lb/ft^3

Number subscripts refer to node. Letter subscripts m and n refer to node in general; i is time increment in general.

APPENDIX A

Derivations of Equations Describing the Pressure during Blowdown of the EGCR Main Coolant System

To render solution easier and to keep within the capabilities of the ORNL Analog Computer Facility, the EGCR main coolant system was broken down into six volumes separated by resistances as shown in Fig. 2. The assumptions were made that: 1) a main reactor outlet coolant pipe ruptured so that equal area was available for flow from each broken end; 2) turbulent flow exists throughout the resistances in the gas system during the early period of blowdown, which is of primary interest; 3) the resistances between each node vary with the average pressure of the two adjacent volumes; 4) the density change in each volume is dependent on the pressure in that volume; 5) temperature of the loop was taken as an average, and assumptions 3) and 4) neglect the decrease in temperature with decreasing pressure due to the adiabatic expansion of the loop gas in displacing the surrounding atmosphere. This was done for two reasons: 1) to make the equations more simple (the set of equations used required the use of some recorders as multipliers and increased complexity could not have been tolerated), and 2) the fact that heat was being transferred into the gas in the core, the resistance of which is of prime importance, probably more than offset the decreasing temperature of the two volumes adjacent, 4 and 1. Since resistance to flow and therefore pressure drop required to pass flow vary with temperature, it is conservative in this respect to neglect beneficial effects of decreasing temperature.

Assuming a perfect gas which approximates helium fairly well at these temperatures and pressures, the temperature change due to an adiabatic expansion is:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{(k-1)/k} \quad (A-1)$$

Substituting Eq. (A-1), the density change is:

$$\frac{\rho_2}{\rho_1} = \frac{p_2}{p_1} \frac{T_1}{T_2} = \left(\frac{p_2}{p_1} \right) \left(\frac{p_1}{p_2} \right)^{(k-1)/k} = \left(\frac{p_2}{p_1} \right)^{1-(k-1)/k}$$

Inserting the value $k = 5/3$ for helium:

$$\frac{\rho_2}{\rho_1} = \left(\frac{p_2}{p_1} \right)^{1-(5/3-1)/5/3} = \left(\frac{p_2}{p_1} \right)^{0.6} \quad (A-2)$$

The density correction to flow resistance, as will be seen in the following derivation, is used under a square root; therefore, for not too large variations in pressure, the use of a linear density correction is not a gross error.

It can be seen in Eq. (A-11) that decreasing temperature will increase the flow through the hole to the atmosphere, and thus would increase the flow rates and the pressure differentials within the system. Actually, during the early part of the blowdown period, hot gas is being ejected from the system, so the use of the average temperature, as done here, will give a greater than actual flow rate during the early part of the blowdown, and a lower flow rate later on. Since this analysis is primarily concerned with the time period immediately after rupture, it was felt that the simpler, more conservative expression should be used.

All pressures were assumed to be 300 psia before pipe breakage. This corresponds to no flow in the main coolant loops.

Writing a mass balance around the six volumes, the following equations are obtained:

$$w_{2-1} + w_{4-1} - w_{1-a} = dm_1/dt \quad (A-3)$$

$$w_{3-2} - w_{2-1} = dm_2/dt \quad (A-4)$$

$$-w_{3-4} - w_{3-2} = dm_3/dt \quad (A-5)$$

$$w_{3-4} - w_{4-5} - w_{4-1} = dm_4/dt \quad (A-6)$$

$$w_{4-5} - w_{5-6} = dm_5/dt \quad (A-7)$$

$$w_{5-6} - w_{6-a} = dm_6/dt \quad (A-8)$$

The direction of the flow w_{3-4} and w_{4-5} was determined by the necessary polarity adjustments without which the computer would not operate rationally.

The critical pressure ratio for helium as determined by the equation:

$$p_{cr} = \frac{p_t}{p_1} = \left(\frac{2}{k+1} \right)^{k/(k-1)} \quad (2) \quad (A-9)$$

is 0.487. Thus sonic velocity will exist through the broken ends of pipe until the internal pressure reaches a value of 30.2 psia if the pressure buildup in the containment shell is neglected, or about 44.5 psia if the pressure in the containment shell builds up to 7 psig.⁽¹⁾ Both of these pressures will not be reached until well past the time period of interest, so the flow out the broken ends of pipe, w_{1-2} and w_{6-a} , is sonic.

The equations for sonic flow are:⁽²⁾

$$w_1 = A \sqrt{\frac{2g_c k}{k-1}} (p_1 \rho_1) [(p_{cr})^{2/k} - (p_{cr})^{(k+1)/k}]$$

Substituting:

$$\frac{p}{RT} = \rho$$

for volumes 1 and 6:

$$w_{1-a} = A p_1 \sqrt{\frac{2g_c k}{(k-1)(RT)}} [p_{cr}^{2/k} - p_{cr}^{(k+1)/k}] \quad (A-10)$$

$$w_{6-a} = A p_6 \sqrt{\frac{2g_c k}{(k-1)(RT)}} [p_{cr}^{2/k} - p_{cr}^{(k+1)/k}] \quad (A-11)$$

The relationship between flow and pressure drop across a resistance is:

$$\Delta p_{m-n} = k_{m-n} w_{m-n}^2 \quad (A-12)$$

The constant k_{m-n} for the resistance between two volumes is obtained from the operating steady state values.

k is a function of density since it actually is:

⁽²⁾ D. A. Mooney, Mechanical Engineering Thermodynamics, p 299, Prentice Hall, New York, 1953.

$$k = f \frac{L}{2g_c r_h A^2 \rho}$$

A correction for density would then be of the form:

$$k(\rho) = \frac{\rho_i}{\rho} k_{m-n,i} \quad (A-13)$$

where

subscript i = initial value.

Solving Eq. (A-12) for w and substituting Eq. (A-13):

$$w_{m-n} = \sqrt{\frac{(p_m - p_n)}{k_{m-n,i}} \frac{\rho_{(m-n)}}{(\rho_{m-n})_i}} \quad (A-14)$$

If the density is taken directly proportional to the pressure and the average pressure between two nodes is used, the following equations are evolved:

$$w_{m-n} = \sqrt{\frac{(p_m - p_n)(p_m + p_n)}{k_{m-n,i} 2p_i}} = \sqrt{\frac{p_m^2 - p_n^2}{2 k_{m-n,i} p_i}} \quad (A-15)$$

where

m and n refer to the subscripts used in Eqs. (A-3) through (A-8).

The change in mass of the nodes in Eqs. (A-3) to (A-8) can be written as:

$$\frac{dm_n}{dt} = V_n \frac{d\rho_n}{dt}$$

where

V_n is the volume of the node in question.

Substituting:

$$\rho = p/RT$$

$$\frac{dm_n}{dt} = \frac{V_n}{RT} \frac{dp_n}{dt} \quad (A-16)$$

As explained previously, the assumption of a constant average temperature simplifies the analysis significantly and is conservative.

Table A-1 shows the values used in Eqs. (A-10), (A-11), (A-15), and (A-16).

TABLE A-1

k for helium	= 5/3
p _{cr}	= 0.487
A _{1-a} = A _{6-a}	= 3.142 ft ² (for double-ended pipe failure)*
p _i	= 300 psia (for all nodes)
R	= 386 ft-lb (force)/lb-mass °R
T	= 1210 °R
k ₄₋₁	= 4.99 x 10 ⁻⁴ sec ² /lb-in. ²
k ₄₋₃	= 4.29 x 10 ⁻⁴ sec ² /lb-in. ² **
k ₃₋₂	= 5.72 x 10 ⁻⁴ sec ² /lb-in. ²
k ₂₋₁	= 4.29 x 10 ⁻⁴ sec ² /lb-in. ²
k ₄₋₅	= 4.29 x 10 ⁻⁴ sec ² /lb-in. ² **
k ₅₋₆	= 5.72 x 10 ⁻⁴ sec ² /lb-in. ²
V ₄	= 2097 ft ³
V ₃	= 1035 ft ³
V ₂	= 1035 ft ³
V ₁	= 2097 ft ³
V ₅	= 1035 ft ³
V ₆	= 1035 ft ³

* This was varied to one-half to give the effects of one-half flow area to the atmosphere.

** These were varied to 4x, 16x, and 64x to bracket effects of blower resistance.

Substituting these values into Eqs. (A-10), (A-11), (A-15), (A-16), and then into (A-3) through (A-8), and inserting the correct factors for dimensional uniformity, the following is obtained for case 1:

$$1.972 \sqrt{p_2^2 - p_1^2} + 1.828 \sqrt{p_4^2 - p_1^2} - 2.725 p_1 =$$

$$0.647 dp_1/dt$$

(A-3a)

$$1.708 \sqrt{p_3^2 - p_2^2} - 1.972 \sqrt{p_2^2 - p_1^2} = 0.319 \, dp_2/dt \quad (A-4a)$$

$$-1.972 \sqrt{p_3^2 - p_4^2} - 1.708 \sqrt{p_3^2 - p_2^2} = 0.319 \, dp_3/dt \quad (A-5a)$$

$$1.972 \sqrt{p_3^2 - p_4^2} - 1.972 \sqrt{p_4^2 - p_5^2} - 1.828 \sqrt{p_4^2 - p_1^2} = 0.647 \, dp_4/dt \quad (A-6a)$$

$$1.972 \sqrt{p_4^2 - p_5^2} - 1.708 \sqrt{p_5^2 - p_6^2} = 0.319 \, dp_5/dt \quad (A-7a)$$

$$1.708 \sqrt{p_5^2 - p_6^2} - 2.725 \, p_6 = 0.319 \, dp_6/dt \quad (A-8a)$$

Rearranging and solving for dp_n/dt gives the equations shown on p 5. The variation in the constants are the effects of varying the flow area to the atmosphere contained in the coefficient of p_1 in Eqs. (A-3a) and of p_6 in (A-8a), and the flow resistance k_{3-4} and k_{4-5} , the inverse square root of which is contained in the coefficients of terms $\sqrt{p_3^2 - p_4^2}$ and $\sqrt{p_4^2 - p_5^2}$, respectively, in Eqs. (A-5a), (A-6a), and (A-7a).

The pressures have the dimensions of lb/in.^2 , and the time is in seconds.

APPENDIX B

Solution of the Six Coupled Nonlinear Differential Equations

The six equations, (A-3a) to (A-8a), describing the system pressures during blowdown can best be solved by means of an analog computer. Frank Green of the ORNL Analog Computer Facility is responsible for the solution. His diagram describing the setup is shown in Fig. B.1.

PEGCPR
6-2-59
CASE #1
t = 50 J

F16 B-1
ROAD MAP

APPENDIX C

Tabulated Data of Core Pressure Differential Velocity and Displacement

The lightest portions of the core subject to levitation are the graphite stack and the upper and lower grid plates. The weight of these items is 14 lb/in.². As the pressure rises across the core, displacement does not take place until the lifting force equals the weight. After this time the upward force on the core is the algebraic sum of the Δp and the weight where the weight is taken as a downward force. The upward inertia of the core after the initial time period will continue to raise it well after the time when the net force is negative, or downward.

The analysis proceeds as follows:

$$F_{\text{net}} = ma$$

$$F_{\text{net}} = (w/g_c) (\Delta v / \Delta t)$$

since

$$F_{\text{net}} = p - w$$

where

p is the upward pressure differential across the core.

$$\Delta t (p - w) = w/g_c \Delta v$$

Writing the equations for the increment of time, i:

$$\Delta t_i (p_i - w) = w/g_c (v_i - v_{i-1})$$

The distance traveled over the ith time element:

$$\Delta x_i = v_i \Delta t$$

Tables C-1 through C-7 show these calculations carried out in tabular form for cases 1-4, 7, 7a, and 7b.

TABLE C-1

Case 1

Δt	p	w	$p - w$	$\Delta v = \frac{\Delta t(F-w)}{(w/g)}$ $\Delta v_i = 0.092x \frac{(F-w)}{(F-w)}$	$\Delta v_i + v_{i-1}$	$\Delta x_i = v_i \Delta t_i$	$\Sigma \Delta x$
0.04	16	14	2	0.18	0.18	0.0072	0.0072
0.04	35	14	21	1.932	2.11	0.0844	0.0916
0.04	33.5	14	19.5	1.795	3.907	0.1563	0.2479
0.04	27.6	14	13.6	1.252	5.159	0.2062	0.4541
0.04	23	14	9	0.828	5.987	0.2395	0.6936
0.04	21.5	14	7.5	0.690	6.677	0.2670	0.9606
0.04	20	14	6	0.554	7.231	0.2892	1.2498
0.04	18.4	14	4.4	0.4046	7.6356	0.3052	1.555
0.04	17.5	14	3.5	0.322	7.9576	0.3182	1.8732
0.04	17.5	14	3.5	0.322	8.2796	0.331	2.2042
0.04	15.5	14	1.5	0.138	7.417	0.3366	2.5408
0.04	12.2	14	-1.8	-0.1655	8.2521	0.33	2.8708
0.04	10.4	14	-3.6	-0.331	7.921	0.317	3.187
0.04	9.6	14	-4.4	-0.405	7.516	0.3008	3.488
0.04	8.4	14	-5.6	-0.515	7.001	0.28	3.768
0.04	7.4	14	-6.6	-0.561	6.44	0.2576	4.0262
0.04	6	14	-8	-0.736	5.704	0.2282	4.2544
0.04	5	14	-9	-0.828	4.876	0.1950	4.449
0.04	3.6	14	-10.4	-0.956	3.920	0.1568	4.6062
0.04	3	14	-11	-1.012	2.908	0.1163	4.7225
0.04	~ 0	14	-14	-1.288	1.620	0.0648	4.7073
0.04	0	14	-14	-1.288	0.332	0.01328	4.800
0.04	0	14	-14	-1.288	-0.956	-0.03825	4.7623
0.04	0	14	-14	-1.288			

TABLE C-2

Case 2

Δt	p	w	$p - w$	$\Delta v = \frac{\Delta t(F-w)}{(w/g)}$ $\Delta v_1 = 0.092 \times \frac{\Delta t(F-w)}{(F-w)}$	$\Delta v_1 + v_{1-1}$	$\Delta x_1 = v_1 \Delta t_1$	$\Sigma \Delta x$
0.04	17.5	14	3.5	0.322	0.322	0.01288	0.01288
0.04	38	14	24	2.208	2.53	0.1011	0.1139
0.04	32	14	18	1.655	4.185	0.1673	0.2812
0.04	27	14	13	1.195	5.38	0.2152	0.4964
0.04	23.5	14	9.5	0.874	6.25	0.250	0.746
0.04	21	14	7.0	0.644	6.898	0.2758	1.02228
0.04	18.5	14	4.5	0.414	7.312	0.2922	1.314
0.04	16.5	14	2.5	0.230	7.542	0.3018	1.616
0.04	16	14	2	0.184	7.726	0.309	1.925
0.04	16	14	2	0.184	7.910	0.3162	2.241
0.04	16	14	2	0.184	8.094	0.3238	2.565
0.04	14	14	0	0	8.094	0.3238	2.889
0.04	12	14	-2	-0.184	7.91	0.3162	3.205
0.04	10	14	-4	-0.368	7.542	0.302	3.507
0.04	8	14	-6	-0.552	6.99	0.2792	3.786
0.04	6	14	-8	-0.736	6.254	0.2500	4.036
0.04	4.5	14	-9.5	-0.874	5.38	0.215	4.251
0.04	3	14	-11	-1.011	4.369	0.1746	4.426
0.04	2.2	14	-11.8	-1.085	3.284	0.1313	4.557
0.04	0	14	-14	-1.288	1.996	0.0798	4.637
0.04	0	14	-14	-1.288	0.708	0.0283	4.665
0.04	0	14	-14	-1.288	-0.580		
0.04	0	14	-14	-1.288			

TABLE C-3

Case 3

Δt	p	w	$p - w$	$\Delta v = \frac{\Delta t(F-w)}{(w/g)}$ $\Delta v_i = 0.092x$ $(F-w)$	$\Delta v_i + v_{i-1}$	$\Delta x_i = v_i \Delta t_i$	$\Sigma \Delta x$
0.04	17.5	14	3.5	0.322	0.322	0.01288	0.01288
0.04	40	14	26	2.39	2.712	0.1086	0.1214
0.04	37.5	14	20	1.84	4.552	0.1821	0.3035
0.04	33.5	14	19.5	1.793	6.345	0.2538	0.5537
0.04	29.5	14	15.5	1.425	7.77	0.311	0.868
0.04	25.2	14	11.2	1.03	8.80	0.352	1.220
0.04	22	14	8	0.736	9.536	0.3812	1.601
0.04	19	14	5	0.46	9.996	0.4000	2.001
0.04	18	14	4	0.368	10.364	0.4142	2.415
0.04	18	14	4	0.368	10.732	0.429	2.844
0.04	18.8	14	4.8	0.4415	11.1735	0.447	3.291
0.04	18.8	14	4.8	0.4415	11.61	0.4642	3.755
0.04	17	14	3	0.276	11.89	0.476	4.23
0.04	14.6	14	0.6	0.0052	11.95	0.478	4.709
0.04	13	14	-1	-0.092	11.85	0.474	5.183
0.04	11	14	-3	-0.276	11.57	0.463	5.646
0.04	8.6	14	-5.4	-0.496	11.08	0.4432	6.092
0.04	7	14	-7	-0.644	10.438	0.4172	6.504
0.04	5.5	14	-8.5	-0.782	9.65	0.386	6.89
0.04	4	14	-10	-0.92	8.73	0.349	7.239
0.04	3	14	-11	-1.011	7.72	0.309	7.548
0.04	2.8	14	-11.2	-1.03	6.695	0.2678	7.816
0.04	2	14	-12	-1.103	5.59	0.2237	8.039
0.04	0	14	-14	-1.286	4.306	0.1722	8.212
0.04	0	14	-14	-1.286	3.020	0.1208	8.332
0.04	0	14	-14	1.286	1.732	0.1093	8.442
0.04	0	14	-14	-1.286	0.448	0.1792	8.621
0.04	0	14	-14	-1.286	-0.838		
			-14				

TABLE C-4

Case 4

Δt	p	w	$p - w$	$\Delta v = \frac{\Delta t(F-w)}{(w/g)}$ $\Delta v_i = \frac{0.092x}{(F-w)}$	$\Delta v_i + v_{i-1}$	$\Delta x_i = v_i \Delta t_i$	$\Sigma \Delta x$
0.04	14	14	0	0	0	0	0
0.04	37	14	23	2.118	2.118	0.08472	0.08472
0.04	42	14	28	2.575	4.193	0.18772	0.27244
0.04	40	14	26	2.39	7.08	0.283	0.555
0.04	37	14	23	2.115	9.198	0.3679	0.923
0.04	30.5	14	16.5	1.518	10.716	0.428	1.351
0.04	29	14	15	1.38	12.096	0.484	1.835
0.04	26	14	12	1.103	13.19	0.5276	2.363
0.04	22.5	14	8.5	0.782	13.981	0.559	0.292
0.04	21	14	7	0.644	14.628	0.585	3.506
0.04	20	14	6	0.552	15.17	0.607	4.114
0.04	21	14	7	0.644	15.821	0.6328	4.746
0.04	21.5	14	7.5	0.690	16.51	0.6604	5.407
0.04	21	14	7	0.644	17.155	0.6862	6.093
0.04	19.5	14	5.5	0.506	17.661	0.7064	6.801
0.04	16	14	2	0.184	17.845	0.7138	7.515
0.04	13.5	14	-0.5	-0.036	17.79	0.7116	8.227
0.04	12	14	-2	-0.184	17.615	0.7046	8.932
0.04	10.5	14	-3.5	-0.322	17.293	0.6917	9.623
0.04	8.8	14	-5.2	-0.478	16.815	0.6726	10.296
0.04	7.4	14	-6.6	-0.607	16.208	0.648	10.944
0.04	6	14	-8	-0.736	15.472	0.619	11.56
0.04	5.2	14	-8.8	-0.810	14.662	0.5865	12.15
0.04	4.8	14	-9.2	-0.846	13.816	0.5526	12.70
0.04	4.0	14	-10	-0.92	12.896	0.5158	13.22
0.04	3.0	14	-11	-1.011	11.88	0.4752	13.69
0.04	0	14	-14	-1.286	10.69	0.424	14.117

TABLE C-4 (continued)

Δt	p	w	$p - w$	$\Delta v = \frac{\Delta t(F-w)}{(w/g)}$ $\Delta v_i = 0.092 \times \frac{(F-w)}{(F-w)}$	$\Delta w_i + v_{i-1}$	$\Delta x_i = v_i \Delta t_i$	$\Sigma \Delta x$
0.04		14	-14	-1.286	9.31	0.372	14.49
0.04		14	-14	-1.286	8.027	0.321	14.81
0.04		14	-14	-1.286	6.741	0.2696	15.08
0.04		14	-14	-1.286	5.455	0.2182	15.297
0.04		14	-14	-1.286	4.169	0.1676	15.465
0.04		14	-14	-1.286	2.883	0.1153	15.58
0.04		14	-14	-1.286	1.597	0.0638	15.649
0.04		14	-14	-1.286	0.311	0.01244	15.66
0.04		14	-14	-1.286	-0.975		

TABLE C-5

Case 7

15 psi for 0.04 sec

$$p - w = 1$$

$$\Delta v = 0.092(1) = 0.092$$

$$\Delta x = 0.092 \times 0.04 = 0.00368 \text{ ft} = 0.00368 \times 12 = 0.04416 \text{ in.}$$

Case 7 with Coastdown Added

Δt	p	w	$p - w$	$\Delta v = \frac{\Delta t(F-w)}{(w/g)}$ $\Delta v_i = 0.092 \times \frac{(F-w)}{(F-w)}$	$\Delta v_i + v_{i-1}$	$\Delta x_i = v_i \Delta t_i$	$\Sigma \Delta x$
0.04	17	14	3	0.276	0.276	0.01104	0.01104
0.04	17	14	3	0.276	0.552	0.02208	0.03312
0.04	11.5	14	-3.5	-0.322	0.220	0.0088	0.034
0.04	6.2	14	-7.8	-0.717	-0.497		
0.04	4.5	14	-9.5				
0.04	3.5	14	-10.5				
0.04	2.2	14	-11.8				
0.04	2	14	-11.8				
0.04	2	14	-11.8				
0.04	2	14	-11.8				
0.04	2.2	14					
0.04	3	14					
0.04	3	14					
0.04	3	14					
0.04	4	14					
0.04	4	14					
0.04	3	14					
0.04	2	14					
0.02	0	14					

Case 7 with Δp Due to Blower Operation Decreasing
with Density (Blowers Run at Same Speed)

Δt	p	w	$p - w$	$\Delta v = \frac{\Delta t(F-w)}{(w/g)}$ $\Delta v_i = 0.092x$ $(F-w)$	$\Delta v_i + v_{i-1}$	$\Delta x_i = v_i \Delta t_i$	$\Sigma \Delta x$
0.04	19	14	5	0.46	0.46	0.0184	0.0184
0.04	20	14	6	0.55	1.01	0.0404	0.0588
0.04	17	14	3	0.276	1.286	0.0514	0.1102
0.04	13	14	-1	-0.092	1.194	0.0478	0.158
0.04	11	14	-3	-0.276	0.918	0.367	0.1947
0.04	9	14	-5	-0.46	0.458	0.01832	0.213
0.04	7.5	14	-6.5	-0.598			
0.04	6.4	14	-7.6	-0.699			
0.04	6.4	14	-7.6	-0.699			
0.04	6.4	14	-7.6	-0.699			

APPENDIX D

Analog Recorder Traces

Fig. D-1	Core Δp ($p_4 - p_1$) vs time
Fig. D-2	p_4 vs time
Fig. D-3	p_1 vs time
Fig. D-4	$p_4 - p_5$ vs time
Fig. D-5	p_3 vs time
Fig. D-6	$p_5 - p_4$ vs time
Fig. D-7	$p_5 - p_6$ vs time

Case 6

3

2

Case 40 5

1

me 4 12

1

Case 2

10

Case 1

9

88

7

6

PA

上

P16 D-2

$$P_4/10 \rightarrow$$

P_4

$$\sqrt{10 \times \sqrt{P_4^2 - P_5^2}}$$

Plot 4

SCALE: 1.5 IN

$$\sqrt{10 \times \sqrt{P_4^2 - P_5^2}}$$

$$P_5^2 - P_4^2$$

Distribution

1. W. A. Albrecht
2. M. Bender
3. R. A. Charpie
4. W. B. Cottrell
5. H. N. Culver
6. W. Dodson, Kaiser Engineers
7. L. G. Epel
8. H. L. Falkenberry, AEC-ORO
- 9-13. M. H. Fontana
14. J. Foster
15. A. P. Fraas
16. B. L. Greenstreet
17. H. W. Hoffman
18. L. H. Jackson, AEC-ORO
19. R. B. Korsmeyer
20. P. G. Lafyatis
21. E. R. Mann
22. L. A. Mann
23. P. Perry, Allis-Chalmers
24. G. C. Robinson
25. G. Samuels
26. R. D. Stulting
27. C. S. Walker
28. M. M. Yarosh
- 29-30. Central Research Library
31. Document Reference Library
32. Laboratory Records (RC)
33. A. M. Perry
- 34-35. Laboratory Records
36. M. J. Skinner
- 37-51. TISE-AEC

A