MAY 14 1965

GEAP-4847
APRIL 1965

MASTER

EUR/AEC Report. 1365

RADIAL VANE STEAM SEPARATOR DEVELOPMENT

THIRD QUARTERLY REPORT JANUARY - MARCH 1965

R.H. MOEN

PATENT CLEARANCE OBTAINED, RELEASE TO
THE PUBLIC IS APPROVED. PROCEDURES
ARE ON FILE IN THE RECEIVING SECTION.

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
PROJECT AGREEMENT 42

ATOMIC POWER EQUIPMENT DEPARTMENT

GENERAL ELECTRIC

SAN JOSE, CALIFORNIA

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.

LEGAL NOTICE

This document was prepared under the sponsorship of the United States Atomic Energy Commission pursuant to the Joint Research and Development Program established by the Agreement for Cooperation signed November 8, 1958 between the Government of the United States of America and the European Atomic Energy Community (Euratom). Neither the United States, the U. S. Atomic Energy Commission, the European Atomic Energy Community, the Euratom Commission, nor any person acting on behalf of either Commission:

- A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this document, or that the use of any information, apparatus, method, or process disclosed in this document 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 document.

As used in the above, "person acting on behalf of either Commission" includes any employee or contractor of either Commission or employee of such contractor to the extent that such employee or contractor or employee of such contractor prepares, handles, disseminates, or provides access to, any information pursuant to his employment or contract with either Commission or his employment with such contractor.

UNITED STATES-EURATOM JOINT RESEARCH
AND DEVELOPMENT PROGRAM

EURAEC
GEAP-4847
JOINT US-EURATOM
Research and
Development Program
April 1965

RADIAL VANE STEAM SEPARATOR DEVELOPMENT

Third Quarterly Report

January - March 1965

R. H. Moen

Prepared for the
U. S. ATOMIC ENERGY COMMISSION
Contract AT(04-3)-189
Project Agreement 42

*Printed in U.S.A. Available from the
Clearing House for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia
Price: \$3.00 per copy*

2349 - TIO
90-SF-4/65

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

LEGAL NOTICE

THIS DOCUMENT WAS PREPARED UNDER THE SPONSORSHIP OF THE ATOMIC ENERGY COMMISSION PURSUANT TO THE JOINT RESEARCH AND DEVELOPMENT PROGRAM ESTABLISHED BY THE AGREEMENT FOR COOPERATION SIGNED NOVEMBER 8, 1958, BETWEEN THE GOVERNMENT OF THE UNITED STATES OF AMERICA AND THE EUROPEAN ATOMIC ENERGY COMMUNITY (EURATOM). NEITHER THE UNITED STATES, THE U.S. ATOMIC ENERGY COMMISSION, THE EUROPEAN ATOMIC ENERGY COMMUNITY, THE EURATOM COMMISSION, NOR ANY PERSON ACTING ON BEHALF OF EITHER COMMISSION:

- A. MAKES ANY WARRANTY OR REPRESENTATION, EXPRESS OR IMPLIED, WITH RESPECT TO THE ACCURACY, COMPLETENESS, OR USEFULNESS OF THE INFORMATION CONTAINED IN THIS DOCUMENT, OR THAT THE USE OF ANY INFORMATION, APPARATUS, METHOD, OR PROCESS DISCLOSED IN THIS DOCUMENT 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 DOCUMENT.

AS USED IN THE ABOVE, "PERSON ACTING ON BEHALF OF EITHER COMMISSION" INCLUDES ANY EMPLOYEE OR CONTRACTOR OF EITHER COMMISSION OR EMPLOYEE OF SUCH CONTRACTOR TO THE EXTENT THAT SUCH EMPLOYEE OR CONTRACTOR OR EMPLOYEE OF SUCH CONTRACTOR PREPARES, HANDLES, DISSEMINATES, OR PROVIDES ACCESS TO, ANY INFORMATION PURSUANT TO HIS EMPLOYMENT OR CONTRACT WITH EITHER COMMISSION OR HIS EMPLOYMENT WITH SUCH CONTRACTOR.

To expedite dissemination of technical information to those persons requiring it, this report has been issued without the administrative review necessary to protect the interest of the U.S. Government, the European Atomic Energy Community (Euratom) and the contractor. The recipient of this report agrees that it is passed on to him in confidence, that he will maintain that confidence and make no disclosures or publication of the contents, that would be detrimental to the interests of the U.S. Government, the European Atomic Energy Community (Euratom) and the contractor.

TABLE OF CONTENTS

	<u>Page No.</u>
1.0 SUMMARY	1-1
2.0 PRINCIPAL INVESTIGATORS AND REPORTS ISSUED	2-1
2.1 Principal Investigators	2-1
2.2 Reports Issued	2-1
2.3 Background Report	2-1
3.0 STATEMENT OF PROBLEM	3-1
3.1 Task A, Wall Flow	3-1
3.1.1 Task A-I, Upper Vortex Thickness	3-1
3.1.2 Task A-II, Wall Flow Model	3-3
3.1.3 Task A-III, Lower Vortex Characteristics	3-3
3.1.4 Task A-IV, Water-Steam Interface	3-3
3.2 Task B, Plenum	3-3
3.3 Task C, Vanes	3-3
3.4 Task D, Carryover	3-4
3.5 Task E, Carryunder	3-4
3.6 Task F, Model Separators	3-4
3.7 Task G, Test Facility Modification	3-4
4.0 ACCOMPLISHMENTS DURING REPORT PERIOD	4-1
4.1 Task A, Wall Flow	4-1
4.1.1 Task A-I, Upper Vortex Flow	4-1
4.1.2 Task A-II, Wall Flow Model	4-1
4.1.3 Task A-III, Lower Vortex Characteristics	4-10
4.1.4 Task A-IV, Steam-Water Interface	4-10
4.2 Task B, Plenum	4-10
4.3 Task C, Vanes	4-13
4.4 Task D, Carryover	4-13
4.5 Task E, Carryunder	4-16
4.6 Task F, Model Separator	4-20
4.7 Task G, Test Facility Modification	4-20
5.0 FUTURE WORK	5-1

	<u>Page No.</u>
APPENDIX A ON CARRYOVER FROM VANE FLOW IN THE RADIAL SEPARATOR	A-1
APPENDIX B DRAWINGS FOR FCRV-3 AND FCRV-4	B-1
APPENDIX C DRAWINGS FOR CLEAR PLASTIC TWO-VANE TEST UNIT	C-1
APPENDIX D DRAWINGS FOR MODIFICATION OF LARGE AIR-WATER TEST FACILITY	D-1
REFERENCES	-1-
APPROVALS	-2-
DISTRIBUTION LIST	-3-

LIST OF ILLUSTRATIONS

<u>Figure No.</u>		<u>Page No.</u>
1	Sketch of the Full Circle Radial Vane Separator, FCRV-2 with Annular Outlet	3-2
2a	Velocity Distribution in the Wall Flow; Eighteen 6-inch Nozzles	4-8
2b	Velocity Distribution in the Wall Flow; Six 6-inch Nozzles	4-9
3	FCRV-2 Steam-Water Head Loss Data Compared	4-11
4	Effect of Plenum Deflectors on Steam-Water Head Loss in FCRV-2	4-12
5	Nozzle Pressure Drop in the Two-Vane Test Unit	4-15
6	Carryover Breakpoint Versus Homogeneous Nozzle Velocity Squared	4-18
7	Carryunder Breakpoint Versus Homogeneous Nozzle Velocity Squared	4-19
B-1	Separator (FCRV-3)	B-2
B-2	Radial Vane Separator (FCRV-3)	B-3
B-3	Radial Vane Separator (FCRV-4)	B-4
B-4	Separator (FCRV-4)	B-5
B-5	Separator (FCRV-4)	B-6
C-1	Inner Vane Assembly	C-2
C-2	Outer Vane	C-3
C-3	Inner Vane	C-4
C-4	Clear Vane Separator Installation	C-5

<u>Figure No.</u>		<u>Page No.</u>
C-5	Clear Vane Separator	C-6
C-6	Stand Assembly	C-7
C-7	Outer Vane Assembly	C-8
C-8	Air Box Assembly	C-9
C-9	Return Duct	C-10
D-1	Large Air-Water Loop Modification	D-2
D-2	Excavating and Paving	D-3
D-3	Test Tank	D-4

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
Ia	Velocity Data in Wall Flow; Eighteen 6-inch Nozzles	4-2
Ib	Velocity Data in Wall Flow; Six 6-inch Nozzles	4-6
II	Two-Vane Test Unit Steam-Water Data	4-14
III	Shortened Vane Test Steam-Water Data	4-17
IV	Some Design Data for FCRV-3 and FCRV-4	4-21

FOREWORD

The United States and the European Atomic Energy Community (EURATOM), on May 29, and June 18, 1958, signed an agreement which provides a basis for cooperation in programs for the advancement of the peaceful applications of atomic energy. This agreement, in part, provides for the establishment of a Joint U. S. -EURATOM research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

The work described in this report represents the Joint U. S. -EURATOM effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in Western Europe and the United States.

1.0 SUMMARY

During the report period, further analyses of the data obtained last quarter were carried out, more data on water-layer thickness and velocity using eighteen 6-inch nozzles were obtained, an experiment to determine the effect of operating with vanes shortened below the nozzles was carried out, the two-vane adjustable test unit was tested in the Steam-Water Test Facility at Moss Landing, and an attempt was made to analyze and predict carryover between the vanes. Two new model separators were designed, drawn up, and sent out for bid. The clear plastic two-vane unit was designed, drawn up, and sent out for bid. A vendor was selected, and the order for this unit was placed. The design for the Large Air-Water Test Facility modification was completed, request for bids were sent out, and a low bidder was accepted.

2.0 PRINCIPAL INVESTIGATORS AND REPORTS ISSUED

2.1 Principal Investigators

R. H. Moen	Project Engineer
J. E. Gifford	Test Engineer
J. A. Hansen	Test Engineer
E. R. Kilsby, Jr.	Design of the Large Air-Water Test Facility Modification and Test Pieces
A. A. Kudirka	Analysis of Carryover and Carryunder Phenomena
C. C. Ripley	Design of the Steam-Water Test Pieces and Carryunder Test Pieces

2.2 Reports Issued

<u>EURAEC Number</u>	<u>Report Number</u>	<u>Title</u>
1253	GEAP-4728	Radial Vane Steam Separator Development First Quarterly Report, June - September 1964
1301	GEAP-4783	Radial Vane Steam Separator Development Second Quarterly Report, October - December 1964

2.3 Background Report

GEAP-4272, "Nuclear Superheat Project, Internal Steam Separation, Development of Radial Vane Steam Separators," R. H. Moen, May 31, 1963.

3.0 STATEMENT OF PROBLEM

The purpose of this program is to complete the development (begun under Project Agreement 13 of this contract and reported in GEAP-4272⁽¹⁾) of the radial vane steam separator for use as an improved internal steam separator for boiling water reactors. This development will be accomplished by means of analysis and tests of the various components of the radial vane steam separator, in addition to tests of model, full circle, radial vane separators. Assuming a successful development program, a Phase II of this program will be requested which will involve the design, installation, and test of a radial vane steam separator in an operating boiling water reactor such as the reactor being built for Kernkraftwerk RWE - Bayernwerk, GmbH (KRB reactor) at Gundremmingen, Germany. The program has been classified into tasks corresponding to the various regions of flow, to the performance characteristics, and to the type of work. The various regions of flow are discussed in the following paragraph, and then a discussion of the purpose of each task is presented.

The radial vane separator utilizes the centrifugal force imposed on a stream flowing on a concave surface to bring about separation of the steam and water. This centrifugal force is many times larger than the gravitational force; e. g., the centrifugal force on the fluid on a vane of the model separator (FCRV-2) used in the tests reported here is about 55 times the gravitational force at the surface of the earth. The steam-water mixture from the core of a reactor flows from the plenum chamber over the core into nozzles from which the mixture flows onto the concave surface of vanes attached to the periphery of the plenum. The steam which is separated on the vanes flows upward between the vanes. The water flows off the ends of the vanes onto the circular reactor wall where it forms a vortex of water accelerating downward called the upper vortex. This vortex flows into a lower vortex below the vanes, and from there to the recirculating pumps. A sketch of the model separator is shown on Figure 1.

3.1 Task A, Wall Flow

A knowledge of the characteristics of flow on the circular wall of the model is needed to know how to design for flow on the wall of a reactor. This task has been broken into four related sub-tasks to aid understanding: 1.) the upper vortex thickness, 2.) the wall flow model, 3.) the lower vortex characteristics, and 4.) the water-steam interface.

3.1.1 Task A-I, Upper Vortex Thickness

The thickness of the upper vortex formed by the water from the vanes (the vane jets) flowing onto and down the wall of the reactor is important to know in order to aid in predicting the maximum allowable vane circle radius, to predict the time necessary to remove entrained steam caused by the vane jets flowing into the upper vortex, and to determine the optimum or desirable vane length. This upper vortex thickness was predicted in GEAP-4272, and the purpose of this task is to verify the prediction experimentally as a function of the system variables (volumetric flow rate, nozzle length, and wall radius), or develop an improved prediction.

Figure 1. Sketch of the Full Circle, Radial Vane Separator, FCRV-2 with Annular Outlet

3.1.2 Task A-II, Wall Flow Model

To better understand the flow on the wall, the interaction between the upper and lower vortexes should be known. The purpose of this task is to determine experimentally whether the predicted (in GEAP-4272) jetting action of the upper vortex flowing into the lower vortex and the resultant eddy between the upper vortex jet and the plenum wall do, in fact, exist, and what the characteristics are. If the flow does not behave as predicted, then a new model must be developed, if possible.

3.1.3 Task A-III, Lower Vortex Characteristics

The behavior of the lower vortex should be known in order to predict how much of the entrained steam carried under from the upper vortex flowing into the lower can be removed in the available space, how deep the lower vortex should be, and what effects obstructions might have. The purpose of this task is to determine analytically and experimentally what the relation is between the surface area and shape of the lower vortex, and its capability for removing steam carried under.

3.1.4 Task A-IV, Water-Steam Interface

The maximum vane circle radius and the amount of entrainment of steam into the upper vortex by the vane jets is a function of the surface characteristics of the upper vortex. The purpose of this task is to determine analytically and experimentally the shape of this interface - the height and frequency of waves, the amount of spray droplets, and the disturbing action of the vane jets.

3.2 Task B, Plenum

Knowledge of the flow in the inlet steam-water plenum of the radial vane separator and in the nozzles from which flow moves on to the vanes is important for rational design of the separator. The purpose of this task is to consider analytically and experimentally what the optimum or most desirable flow conditions are within the plenum, at the entrance to the nozzles, and in the nozzles. The design in this region can affect the pressure drop, the steam-water separation, the carryover between the vanes, and the surface characteristics of the vane jet. For these reasons a study of these regions is important.

3.3 Task C, Vanes

The primary purpose of this task is to study the effect of nozzle length on performance of the radial vane separator. Current indications, as reported in GEAP-4272, are that the nozzle length may be extended to a greater value than is now used (18 inches). To find the point where the separated steam velocity causes carryover from the vane jet and, thus, limits performance, is the major purpose of this task. A review of the reasons and experimental data on the basis of which the present design was chosen will be carried out, and, possibly, changes in the nozzle and vane design will be carried out.

3.4 Task D, Carryover

The purpose of this task is to determine the source of carryover droplets and the distribution of carryover with height within and above the vanes.

3.5 Task E, Carryunder

The purpose of this task is to determine the source, size, and distribution of carryunder within the lower vortex. Related studies will involve the flow on the vane and on the wall in the upper vortex.

3.6 Task F, Model Separators

Under this task are included all of the tests of new, full-circle, radial vane separators. These model separators will be of larger diameter, have a greater number of active vanes and nozzles, or be of some improved design. The tests will be carried out in the Air-Water Test Facility and the Steam-Water Test Facility.

3.7 Task G, Test Facility Modification

The purpose of this task is to modify the Large Air-Water Test Facility at San Jose for the purpose of testing the separators of Task F which will require more flow than can be obtained in the Small Air-Water Test Facility. This latter facility is identical in size and configuration to the Steam-Water Test Facility.

4.0 ACCOMPLISHMENTS DURING REPORT PERIOD

4.1 Task A, Wall Flow

Data were obtained on the wall water layer thickness and the vortex velocity and direction distribution in the upper and lower vortices using the FCRV-2 with eighteen 6-inch nozzles and the usual 28-inch wall cylinder. In addition, further data were obtained using six 6-inch nozzles with the other geometry the same and the volumetric flow rate one-third of that with the eighteen nozzles. In general, it was found that the case using eighteen 6-inch nozzles agreed well with prediction; the case using six 6-inch nozzles does not compare as well. It is felt that the use of the six 6-inch nozzles makes the test more like a discontinuous series of nozzles rather than a continuous radial vane separator. For example, a definite variation in water level thickness was observed between the place where one vane jet hit the wall and the place where the next jet hit. Further studies of the wall water layer thickness will be made using a greater number of nozzles (FCRV-3 and FCRV-4 tests). The data for these tests are shown on Tables Ia and Ib.

4.1.1 Task A-I, Upper Vortex Flow

The measured velocity (3.8 to 4.0 feet per second) at the level of the nozzle bottoms is close to that predicted in GEAP-4272 (3.87 feet per second). The measured water layer thickness at the same level is less than predicted, but this is believed to be due to the effect of the nearness of vane jets to the measuring points. At the lower measuring points (various distances below the nozzle bottoms), the correlation between velocity and thickness is good. Since the velocity distribution is the same as that calculated, the thickness must also be the same and the prediction is confirmed. The water in the upper vortex does not accelerate in the region below the nozzle bottoms as predicted. This same phenomenon was observed in the tests using six 18-inch nozzles, and is believed to be due to frictional resistance. Figures 2a and 2b are plots of the data obtained showing the velocity and water layer thickness at 6-inch increments beginning at the nozzle bottoms.

4.1.2 Task A-II, Wall Flow Model

The annular jet formed by the upper vortex falling into the lower vortex spreads at an angle of about 5.5 degrees, compared to the predicted 7 degrees, as may be seen on Figure 2a. A jet spread of approximately 6.5 degrees was observed with six 18-inch nozzles (Figure 2 of the First Quarterly Progress Report). On Figure 2b the jet spread is less, but it is not as good a measurement since the velocities in this case were much lower. These velocities in the lower vortex were so low that the velocity data are not reported under 48 inches below the nozzle bottoms. The tangential velocities observed in the test with eighteen 6-inch nozzles were the same as those observed with the six 18-inch nozzles reported in the First Quarterly Progress Report. On Figure 2b it may be seen that the tangential velocities are considerably less, but it is felt that this is due to the relatively large frictional effects with the relatively small flows used in that test.

TABLE Ia
VELOCITY DATA IN WALL FLOW
EIGHTEEN 6-INCH NOZZLES⁽¹⁾

Sensing Tap At:				
Distance Below Nozzle Bottoms (inches)	Distance from Wall (inches)	Angle of Flow (Degrees from Horizontal)	Axial Velocity (ft/sec)	Tangential Velocity (ft/sec)
0.0	0.05	14	3.87	15.52
0.0	0.10	13	3.78	16.4
0.0	0.20	13	4.0	17.34
0.0	*	-	-	-
*Water layer is thicker than 0.20; manometer limit was reached				
6.0	0.05	24	6.13	13.78
6.0	0.10	24	6.49	14.57
6.0	0.20	24	6.53	14.89
6.0	0.30	23	6.5	15.31
6.0	0.40	23	6.55	15.43
6.0	0.50	24	6.55	14.72
12.0	0.05	31	7.35	11.35
12.0	0.10	29	7.61	13.72
12.0	0.20	30	8.0	13.86
12.0	0.30	30	8.1	14.0
12.0	0.40	32	8.65	13.85
12.0	0.50	36	9.5	13.08
18.0	0.05	31	6.75	11.23
18.0	0.10	31	7.23	12.04
18.0	0.20	30	7.28	12.61
18.0	0.30	30	7.6	13.16
18.0	0.40	32	7.87	12.59
18.0	0.50	32	7.08	11.53
24.0	0.05	33	7.61	11.73
24.0	0.10	33	7.80	12.02
24.0	0.20	33	7.96	12.26
24.0	0.30	33	8.1	12.48
24.0	0.40	34	8.25	12.23

- (1) Equipment: FCRV-2 with 2-foot plenum extension.
 Eighteen 6-inch nozzles open.
 Small Air-Water Test Facility.
- Conditions: Water flow rate = 630,000 lb/h.
 Air flow rate = 1,530 lb/h.
 Water level at radius of 9 inches = 24 inches.

<u>Sensing Tap At:</u>				
<u>Distance Below Nozzle Bottoms (inches)</u>	<u>Distance from Wall (inches)</u>	<u>Angle of Flow (Degrees from Horizontal)</u>	<u>Axial Velocity (ft/sec)</u>	<u>Tangential Velocity (ft/sec)</u>
27.0	0.05	35	8.09	11.55
27.0	0.10	35	8.26	11.8
27.0	0.20	36	8.73	12.01
27.0	0.30	36	8.8	12.12
27.0	0.40	38	9.0	11.52
30.0	0.05	37	8.31	11.03
30.0	0.10	37	8.78	11.65
30.0	0.20	37	9.05	12.01
30.0	0.30	37	9.21	12.22
30.0	0.40	37	8.94	11.86
36.0	0.05	41	9.06	10.42
36.0	0.10	40	9.11	10.85
36.0	0.20	43	9.97	10.69
36.0	0.30	42	10.06	11.18
36.0	0.40	42	9.76	10.84
42.0	0.05	42	9.35	10.39
42.0	0.10	42.	9.68	10.75
42.0	0.20	43.	10.26	11.0
42.0	0.30	45.	10.89	10.89
42.0	0.40	36.	8.0	11.0
42.0	0.50	37.	7.79	10.33
42.0	0.60	28.	5.23	9.83
42.0	0.70	22.	3.35	8.28
48.0	0.05	22.	4.06	10.05
48.0	0.10	21.	4.0	10.4
48.0	0.20	20.	3.9	10.7
48.0	0.30	27.	5.3	10.41
48.0	0.40	22.	4.3	10.64
48.0	0.60	22.	4.3	10.64
48.0	0.80	22.	4.24	10.5
48.0	1.00	8.	1.53	10.82
48.0	1.25	8.	1.45	10.25

Sensing Tap At:				
Distance Below Nozzle Bottoms (inches)	Distance from Wall (inches)	Angle of Flow (Degrees from Horizontal)	Axial Velocity (ft/sec)	Tangential Velocity (ft/sec)
48.0	1.65	0	0.0	9.38
48.0	1.75	0	0.0	10.35
48.0	1.85	2	-0.34	9.82
48.0	2.00	5	-0.86	7.8
48.0	2.25	8	-1.38	9.73
48.0	2.50	-10	-1.67	9.46
48.0	2.75	-12	-1.97	9.27
48.0	3.00	-13	-2.06	8.93
48.0	3.25	-12	-1.81	8.51
48.0	3.50	-12	-1.73	8.13
48.0	4.00	-12	-1.56	7.35
48.0	4.50	-9	-1.01	6.39
48.0	5.00	-6	-0.59	5.57
48.0	5.55	-0	-0.00	3.23
54.0	0.10	8	1.4	9.93
54.0	0.30	6	1.11	10.58
54.0	0.50	12	2.29	10.79
54.0	0.50	7	1.37	11.15
54.0	1.00	3	0.6	11.37
54.0	1.50	6	1.19	11.33
54.0	2.00	3	0.6	11.46
54.0	2.50	0	0.00	11.39
54.0	2.75	-2	-0.40	11.38
54.0	3.00	-4	-1.89	11.1
54.0	4.00	-6	-1.08	10.29
54.0	5.00	-6	-0.85	8.14
54.0	6.00	-3	-0.34	6.46
54.0	7.00	0	-0.0	4.56
60.0	0.10	5	0.81	9.24
60.0	0.50	0	0.0	9.7
60.0	1.00	0	0.00	10.25
60.0	2.00	0	0.00	10.35
60.0	2.25	-1	-0.18	10.45
60.0	2.50	-2	-0.35	10.0
60.0	2.75	-5	-0.8	9.11
60.0	3.00	-3	-0.4	7.92
60.0	6.00	-4	-1.89	11.1

Sensing Tap At:				
Distance Below Nozzle Bottoms (inches)	Distance from Wall (inches)	Angle of Flow (Degrees from Horizontal)	Axial Velocity (ft/sec)	Tangential Velocity (ft/sec)
60.0	4.00	- 6	-1.08	10.29
60.0	5.00	- 6	-0.85	8.14
60.0	6.00	- 3	-0.34	6.46
60.0	7.00	0	0.0	4.56
66.0	0.10	4	0.64	9.14
66.0	0.55	3	0.52	9.92
66.0	1.06	2	0.36	10.24
66.0	2.00	0	0.0	10.35
66.0	2.10	- 2	-0.36	10.24
66.0	2.50	- 3	-0.54	10.33
66.0	3.00	- 5	-0.89	10.21
66.0	4.00	- 1	-0.12	6.78
66.0	5.00	-10	-1.28	7.27
66.0	6.00	-10	-1.21	6.85
66.0	7.00	- 5	-0.28	3.22

TABLE Ib
VELOCITY DATA IN WALL FLOW
SIX 6-INCH NOZZLES⁽¹⁾

Sensing Tap At:				
Distance Below Nozzle Bottoms (inches)	Distance from Wall (inches)	Angle of Flow (Degrees from Horizontal)	Axial Velocity (ft/sec)	Tangential Velocity (ft/sec)
0.0	0.05	7	1.46	11.9
0.0	0.10	7	1.51	12.3
0.0	0.20	8	1.47	10.48
6.0	0.05	20	3.81	10.46
6.0	0.10	20	3.88	10.67
6.0	0.20	21	3.62	9.42
12.0	0.05	29	5.08	9.15
12.0	0.10	28	5.05	9.5
12.0	0.20	29	4.55	8.2
18.0	0.05	33	5.25	8.1
18.0	0.10	35	5.9	8.42
18.0	0.20	35	5.9	8.42
18.0	0.25	37	5.6	7.42
24.0	0.05	40	6.46	7.7
24.0	0.10	41	6.85	7.87
24.0	0.20	42	6.75	7.5
24.0	0.25	41	5.08	5.84
24.0	0.30	40	3.66	4.36
30.0	0.05	46	7.05	6.8
30.0	0.10	46	7.23	6.98
30.0	0.20	46	6.75	6.52
30.0	0.25	50	4.75	5.65
36.0	0.05	50	7.14	6.0
36.0	0.10	50	7.48	6.28
36.0	0.15	53	7.5	5.65
36.0	0.20	50	4.22	3.54

(1) Equipment: FCRV-2 with 2-foot plenum extension.
 Six 6-inch nozzles open.
 Small Air-Water Test Facility.

Conditions: Water flow rate = 210,000 lb/h.
 Air flow rate = 510 lb/h.
 Water level at radius of 9 inches = 24 inches.

<u>Sensing Tap At:</u>				
<u>Distance Below Nozzle Bottoms (inches)</u>	<u>Distance from Wall (inches)</u>	<u>Angle of Flow (Degrees from Horizontal)</u>	<u>Axial Velocity (ft/sec)</u>	<u>Tangential Velocity (ft/sec)</u>
42.0	0.05	55	7.87	5.52
42.0	0.10	56	7.97	5.37
42.0	0.20	59	7.26	4.37
48.0	0.05	53	4.55	3.43
48.0	0.10	51	4.83	3.91
48.0	0.20	50	4.4	3.68
48.0	0.35	41	2.68	3.08
48.0	0.50	35	1.85	2.64
48.0	0.75	8	0.36	2.69
48.0	1.00	0	0.0	2.49
48.0	1.25	-14	-0.66	2.46
48.0	1.75	-28	-1.28	2.4
48.0	2.25	-13	-0.61	2.65
66.0	0.10	8	0.52	3.65

Water flow rate = 630,000 lb/h; air flow rate = 1530 lb/h; 18 6-inch nozzles open;
water level (at radius = 9 inches) = 24 inches; annular outlet base plate used.
Outlet annular gap extends 3 inches in from wall. Data obtained on January 21, 1965
in The Small Air-Water Test Facility. Inlet plenum wall located 8.6 inches from wall.

Figure 2a. Velocity Distribution in the Wall Flow, Eighteen 6-inch Nozzles

Water flow rate = 210,000 lb/h; air flow rate = 510 lb/h; six 6-inch nozzles open;
 water level (at radius = 9 inches) = 24 inches; annular outlet base plate used.
 Outlet annular gap extends 3 inches in from wall. Data obtained on January 21, 1965
 in The Small Air-Water Test Facility. Inlet plenum wall located 8.6 inches from wall.

Figure 2b. Velocity Distribution in the Wall Flow; Six 6-inch Nozzles

4.1.3 Task A-III, Lower Vortex Characteristics

No progress was made on this task during the report period.

4.1.4 Task A-IV Steam-Water Interface

No progress was made on this task during the report period.

4.2 Task B, Plenum

An analysis of all the pressure drop data obtained on the FCRV-2 has been carried out, and the following conclusions have been obtained.

1. All of the tests run on the FCRV-2, including those reported in the GEAP-4272, show the same pressure drop to volumetric flow relationship. This is shown on Figure 3, which shows head loss as a function of volumetric flow rate for the tests of October and December 1964 and January 1965. Test data shown on Figure 3 include data for six 18-inch nozzles and eighteen 6-inch nozzles. The line drawn on Figure 3 is a corrected line which replaces the line incorrectly drawn on Figure I-2 of GEAP-4272. One air-water point is shown on Figure 3.
2. The head loss curve reported in GEAP-4272 on Figure I-2 is incorrect. The corrected curve is shown on Figure 3. The incorrect curve of Figure I-2 resulted from a calculational error, and is not due to the actual pressure drops being as low as shown on that curve.
3. The pressure drop of the FCRV-2 with only a top plenum deflector in use is about six percent lower than with the three deflectors. This is shown on Figure 4. The conclusion reached from this is that the plenum deflectors are undesirable. As reported in the Second Quarterly Progress Report, carryover also increased when three deflectors were used.
4. Plots of pressure drop in psi for the recent data follow the same curves as reported in GEAP-4272 on Figure I-1.

Figure 3. FCRV-2 Steam-Water Head Loss Data Compared

Figure 4. Effect of Plenum Deflectors on Steam-Water Head Loss in FCRV-2

4.3 Task C, Vanes

The two-vane adjustable nozzle test unit was received during the report period and tested in the Air-Water Test Facility to check its readiness for steam-water testing. The unit was then tested in the Moss Landing Steam-Water Test Facility at the following nominal conditions:

<u>Nozzle Length (inches)</u>	<u>Nominal Inlet Quality (weight percent)</u>	<u>Nominal Volumetric Flow Rate (M ft³/h)</u>
18	4	8 to 10
18	10	4.5 to 12
18	14	10 to 12
54	10	17 to 27

The unit performed well at all conditions, and was only limited from going to higher volumetric flow rates by the instrumentation used at the time of the test. The results of the tests are shown on Table II. The carryover performance was never limiting, and it was found that the carryover was lowest at a quality of 10 percent, that it increased as the volumetric flow rate increased above 10,000 cubic feet per hour, and that the carryover with the 54-inch nozzle for a flow rate equivalent to an 18-inch nozzle case showed a higher carryover than the 18-inch nozzle. Carryunder performance cannot be tested with a two-vane unit.

The nozzle pressure drop in the two-vane unit was found to be considerably lower than that of the FCRV-2, as can be seen on Figure 5. The pressure drop is one-half to one-third of that for the FCRV-2, and the slope of the pressure drop curves is about 2.5 rather than 2 as it should be. The pressure drop data for the 54-inch nozzle falls above the curve for the 18-inch nozzle on Figure 5, but this is probably due to the fact that the instrument measuring pressure drop measures the total head of the inlet fluid. When a correction is made for the difference in velocity head in the two cases, the pressure drop curves are more nearly equal. It is anticipated that the pressure drop across the nozzle of the two-vane unit would be less than the FCRV-2 because of a smaller entrance loss due to a more favorable inlet geometry; however, the difference in slope is not anticipated. The reason for this is not known at the present time. Similar results are obtained when the head loss curves are plotted. The lower pressure drop may be due to an oversize nozzle gap due to improper installation in the test facility.

The drawings of the two-vane test unit were included in the Second Quarterly Report.

4.4 Task D, Carryover

During this report period, tests were carried out in the FCRV-2 using shortened vanes to determine the effect of this on carryover; in addition, an analysis was attempted for the purpose of predicting carryover from vane flow in the radial vane separator. These items are discussed on the following pages.

TABLE II
TWO-VANE TEST UNIT STEAM-WATER DATA

	March 1965												
	03251 ⁽¹⁾	03252	03253	03254	03261	03262	03263	03264	03265	03266	03267	03268	03269
Total Weight Flow Rate (M lb/h)	79	91	119	150	166	199	138	163	266	217	374	291	425
Water Flow Rate (M lb/h)	71	81	107	135	150	180	120	142	255	208	337	265	382
Steam Flow Rate (M lb/h)	7.9	7.7	9.9	12.0	15.7	18.8	17.7	20.7	10.8	9.5	37.0	26.2	43.0
Inlet Quality (weight percent)	9.8	10.9	10.0	10.0	10.5	10.4	14.7	14.6	4.2	4.5	11	9.9	10.1
Total Volumetric Flow (M ft ³ /h)	4.9	6.1	7.6	9.5	10.1	12.1	10.3	12.2	10.2	8.7	23.5	17.2	27.1
Nozzle Pressure Drop (psi)	1.3	2.1	4.0	7.1	7.85	>9.5	5.1	9.5	>9.5	8.3	5.8	2.8	8.4
Nozzle Head Loss (lb _f -ft/lb of homogeneous mixture)	18.6	20.3	36.8	64.8	>3.5	>88.6	60.7	112.5	>53.4	48.0	56.1	25.7	76.8
Carryover at Isokinetic Sample Flow (weight percent)													
C2	1.3	1.3	1.3	1.3	3.9	44.0	2.4	7.0	12.0	7.0	3.7 ⁽²⁾	~1.0 ⁽²⁾	15.0 ⁽²⁾
C4	-	-	-	-	-	-	1.3	-	7.0	<7.0	-	~1.0	15.0
C11	1.6	1.6	1.3	1.6	2.4	15.0	<1.3	3.5	4.6	<7.0	8.6	~1.0	15.0
Carryover at 1 gph Sample Flow Rate (weight percent)													
C2	-	-	1.6	3.5	17.8	14.5	-	-	-	-	-	-	-
C4	-	-	-	-	10.0	4	-	-	-	-	-	-	-
C11	-	-	3.0	3.5	9.0	4.5	-	-	-	-	-	-	-
Nozzle Length (inches)	18	18	18	18	18	18	18	18	18	18	54	54	54

(1) These five-digit numbers are run identification. The first two digits denote the month, the next two denote the day, and the last digit denotes run number. For example, 01062 is the second run of January 6.

(2) Data taken at 4.5 gph which is about one-half isokinetic flow.

Figure 5. Nozzle Pressure Drop in the Two-Vane Test Unit

The full circle radial vane separator (FCRV-2) was tested in the Moss Landing Steam-Water Test Facility after shortening the vanes below the nozzles by 10 inches (see Table III). This was done because the last series of tests in October indicated that the carryover became exceedingly high when the lower vortex hit the bottom of the vane. Furthermore, the December tests of spread of the vane jets on the vane indicated that there is no spread, so shorter vanes could be used. Data were obtained at the following nominal conditions.

<u>Total Weight Flow</u> (M lb/h)	<u>Quality</u> (weight percent)
400	4
400	8
400	10
400	14
450	10
550	10

The carryover performance curves versus water level have the same general shape as reported in the Second Quarterly Report (e.g., Figure 4 of that report). On Figure 6 are shown the data points obtained in this test on a plot showing the results of tests with the longer vanes which were obtained from Figure 7 of the Second Quarterly Progress Report. It may be noted that the carryover break point in the short vane tests is just about independent of the nozzle velocity, and it occurs at about the level of the nozzle bottoms. This indicates that at no time does this effect of the lower vortex hitting the bottom of the vane affect the performance in this test. The test at 550-10 is obviously beyond the operating capabilities of the FCRV-2, and the results of this test indicate that some other mechanism is controlling the performance.

An attempt to predict carryover from the vane flow in the radial separator analytically was made during the report period. Predictions of carryover due to wave entrainment caused by Kelvin-Helmholtz-type instabilities and entrainment due to bursting of gas bubbles were considered in this analysis. This analysis has not yet been put to the test of experiment. The analysis is presented in Appendix A.

4.5 Task E, Carryunder

The carryunder performance observed with the shortened vanes of the FCRV-2 in the January test was improved over the performance with the longer vanes. The results are shown on Figure 7, where the carryunder break point (i.e., the point where the carryunder becomes less than 0.2 weight percent) is shown to fall below that observed in the test of the regular length FCRV-2 vane as presented in Figure 9 of the Second Quarterly Progress Report.

TABLE III
SHORTENED VANE TEST STEAM-WATER DATA

	January 1965					
	<u>01061</u> ⁽¹⁾	<u>01062</u>	<u>01063</u>	<u>01071</u>	<u>01072</u>	<u>01073</u>
Total Weight Flow Rate (M lb/h)	402	449	399	541	395	397
Water Flow Rate (M lb/h)	362	405	368	487	341	384
Steam Flow Rate (M lb/h)	40	44	31	54	54	13
Total Volumetric Flow Rate (10 ³ ft ³ /h)	25.2	28.2	21.8	34.2	31.5	14.4
Inlet Quality (weight percent)	9.8	9.7	7.9	10.0	13.7	3.5
Nozzle Velocity (ft/sec)	37.3	41.2	32.3	50.7	46.7	21.3
(Nozzle Velocity) ²	1391	1697	1043	2570	2180	454
Upper Plenum Pressure (psi)	2.89	3.75	2.11	5.43	3.78	1.57
Head Loss (ft of homo. Mix.)	26.2	33.8	16.6	49.5	43.3	8.17
Water Level (inches) at Which Carryover Break Point Occurs	61	60	62	0	58.8	66
Water Level (inches) at Which Carryunder Break Point Occurs	6	2	4	11	3	13
Carryover Before Break Point (weight percent)	2	7	1	33-42	10	0
Carryunder After Break Point (weight percent)	0.1	0.08	0.05	0.08	0.07	0.03

- (1) These five-digit numbers are run identification. The first two digits denote the month, the next two denote the day, and the last digit denotes run number. For example, 01062 is the second run of January 6.

Figure 6. Carryover Break Point Versus Homogeneous Nozzle Velocity Squared

Figure 7. Carryunder Break Point Versus Homogeneous Nozzle Velocity Squared

4.6 Task F, Model Separator

During the report period the design of and drawings for the FCRV-3 and FCRV-4 were completed and bids requested. The design and drawings for the clear plastic two-vane test unit were completed and sent out for bid. A vendor was chosen, and the unit is scheduled for delivery in early April 1965. These items are discussed below.

The design of the FCRV-3 and FCRV-4 and the drawings for this design have been completed and sent out for bid. The FCRV-3 has been designed to have the same geometry as the FCRV-2, but have 48 active nozzles and vanes rather than a maximum of 18 as in the FCRV-2. This unit will be used for demonstrating the performance of the radial vane separator when many vanes, side by side, are in operation. The nozzle-and-vane design are the same as in FCRV-2 except that the nozzle length is 30 inches. Variable lengths of nozzles will be attained by means of plugging.

The FCRV-4 has essentially the same nozzle-and-vane design as the FCRV-2 but was modified slightly to assure the same discharge area at the end of the vanes. This unit has a plenum diameter of 42 inches, and is designed to be used to demonstrate the effect of radius on the performance of the radial vane separator. The drawings for these units are shown in Appendix B.

The design and drawings for the clear plastic two-vane test unit have been completed, sent out for bid, and awarded. This unit is scheduled for delivery in April 1965. The purpose of this unit is to aid in the study of carryunder and nozzle design by permitting visual observation of the flow from the nozzle and on the vanes. Provision has been made to pump extra air between the vanes to study the effect of air velocity between the vanes on carryover. The drawings for this unit are shown on Appendix C.

4.7 Task G, Test Facility Modification

The design of and drawings for the modification of the Large Air-Water Test Facility at San Jose have been completed and sent out for bid. The low bidder has been awarded the job, and it is anticipated that the modification will be completed by the end of April 1965.

The modification consisted of designing a test tank complete with air-water mixers and supporting structure for the various separators in addition to the connecting piping to the carry-under separation tank, the water pump, and the air compressor. The test tank is designed for mixing the air and water streams and passing these streams after mixing into the FCRV-3 or FCRV-4 with various size wall cylinders. The unit is designed to use the maximum capacity of the pump (10,000 gpm), and the maximum capacity of the air compressor (3150 scfm). The drawings for the modification are shown in Appendix D. In Table IV some of the pertinent information concerning these units is presented.

TABLE IV
SOME DESIGN DATA FOR FCRV-3 AND FCRV-4

Item	FCRV-3	FCRV-4
Plenum Diameter (in.)	16 below vanes 10 in vane region	42
Plenum Height (in.)	110	110
Estimated Plenum $\Delta P/\Delta L$ (psi/ft)	~ 0.1	$\sim 0.01^{(1)}$
Plenum Deflector	1	1
Nozzle Dimensions ^{(2) (3)}	$30 \times 1/4$ in.	$30 \times 1/4$ in.
Vane Radius (in.)	4	4
Vane Length (in.)	36	36
Number of Vanes	48	144
Number of Nozzles	48	72
Wall Cylinder Diameters (in.)	32, 34, & 36	68, 72
Corresponding Safety Factor at Maximum Flow with 6-inch Nozzles ⁽⁴⁾	1.3, 1.8, & 2.3	1.5, 2.1
Annular Outlet Gap (in.)	3	2.5

(1) Plenum design based on mixture velocity being comparable to reactor case; not based on $\Delta P/\Delta L$.

(2) Nozzle length will be adjustable by means of plugs of various lengths.

(3) The nozzle-and-vane geometry is the same in FCRV-3 as in the FCRV-2. The nozzle-and-vane geometry in the FCRV-4 is slightly different from FCRV-2 in order to have the same clearance between the vane ends as in FCRV-2.

(4) The safety factor is the ratio of the actual to the calculated wall-to-vane clearance.

5.0 FUTURE WORK

The following list represents the anticipated major accomplishments for the remainder of fiscal year 1965.

	<u>Completion</u>
1. Construction and test of clear plastic two-vane unit.	April 30, 1965
2. Completion of modification to Large Air-Water Test Facility.	April 30, 1965
3. Completion of FCRV-3 and FCRV-4.	April 30, 1965
4. Completion of tests of FCRV-3 and FCRV-4.	May 31, 1965
5. Completion of Wall Flow studies except steam-water interface.	June 30, 1965

APPENDIX A

ON CARRYOVER FROM VANE FLOW IN THE RADIAL SEPARATOR1. SUMMARY

Since the capacity of a radial separator may be limited by carryover, it is important to know how much moisture would be entrained for various conditions in the flow of steam from the radial vanes. Therefore, it was attempted here to identify the sources of entrainment for flow between the vanes, and then to predict when entrainment would start and how it would increase.

Entrainment from waves occurring on the gas-liquid interface was discussed, and two different correlations to predict the start of it were prepared. One was arrived at from empirical considerations, and the other from the Kelvin-Helmholtz stability criterion. Their predictions for start of wave entrainment were significantly different, with the Kelvin-Helmholtz type correlation showing more promising agreement with limited steam-water results. Additional tests would be required to clear up existing discrepancies and to improve predictions of entrainment from waves.

Entrainment due to bursting of gas bubbles on the gas-liquid interface was discussed. Since the controlling parameters for this type of entrainment in the radial separator would be expected to be different than in a horizontal nonflow system, any quantitative extension of nonflow system results was not really feasible. This situation again suggested that tests would have to be relied upon for quantitative information.

To help predict and identify the sources of entrainment from the results of future carryover tests, some tentative formulations were prepared which related carryover to the parameters that were expected to control entrainment.

2. INTRODUCTION⁽¹⁾

In a radial separator, two-phase flow leaves a plenum through a nozzle and flows on a vane of a given radius.

Centrifugal acceleration due to the curved flow path separates gas and liquid. Liquid flows out from the end of the vane, and gas escapes upward through the space between vanes.

(1) The nomenclature and references are included at the end of this Appendix.

To evaluate the performance of a radial separator, it is required to know under what conditions carryover of moisture from the vanes will occur, and also how the amount of carryover will increase once it starts.

The possible causes and mechanisms of carryover from flow on a vane in a radial separator are:

- a. Entrainment of water from surface waves. This mechanism depends on the presence of surface waves on the gas-water interface from which water can be stripped and entrained in the gas stream.

We would like to know what water and air velocities and film thicknesses initiate entrainment from waves, and also how the amount of entrainment increases with increasing air and/or water velocities and film thicknesses.

- b. Entrainment of liquid droplets when gas bubbles burst on the gas-liquid surface and project liquid drops into the gas stream. We would like to know how much carryover is caused by this process, and how it may be kept to a minimum under various operating conditions.
- c. Entrainment may also occur due to splashing of liquid on the vane. Since this depends on geometry, an effort should be made to minimize this cause of carryover by proper geometrical design. Analytical predictions based on a given geometry would necessarily be very uncertain, but a study of water flow on a vane should help in arriving at the proper design.

In addition, de-entrainment probably occurs above vane flow on vanes.

3. DESCRIPTION OF FLOW ON A VANE

To investigate the causes of entrainment, we need a description of flow on a vane that can be used as a model for analysis.

- a. The present nozzle geometry can be represented by

The important parameters for a nozzle in this case are R_V/D and L_0/D . To be sure that a vena contracta does not form, one should have $R_V \geq D$.

- b. Flow on the vane.

The spread of flow on a vane was analyzed in Reference (1), where it was found that Froude No. $= \sqrt{R/y}$.

For typical design conditions Fr. No. ≈ 4 , hence the flow of water on a vane is hydraulically "supercritical." Also $R/y = 16$, thus the film thickness is small compared to vane radius, and the influence of curvature on flow can be neglected. Therefore, the flow can be considered as horizontal open channel flow with a "gravitational acceleration" of $\frac{V^2}{R}$, as illustrated in the sketch below.

For purposes of analysis, y may be approximated as being equal to the nozzle width, thus neglecting the influence of flow spread [see Reference (1)] on flow velocity and film thickness.

4. ENTRAINMENT OF LIQUID FROM SURFACE WAVES

The information available on entrainment of liquid from a gas-liquid surface in shear flow is very limited. Van Rossum⁽²⁾ obtained data for entrainment of liquid from horizontal films to air flowing above at near atmospheric pressures. The data was correlated empirically. Atomization and entrainment of liquid films in shear flow was discussed by Zuber in Reference (3), where the available data was also analyzed. The start of entrainment in annular flow of gas-liquid mixtures in a pipe was also studied by Steen and Wallis,⁽⁴⁾ who correlated their results for start of entrainment with the following empirical relationship:

$$V_C = 2.46 \times 10^{-4} \left(\frac{\sigma g_c}{\mu_g} \right) \left(\frac{\rho_1}{\rho_g} \right)^{1/2} \text{ ft/sec.}$$

Van Rossum's results for thick films can also be correlated with the above relationship if 1.74×10^{-4} is used as the constant of proportionality.

Although Wallis made tests with different gas densities, the range of gas densities tested was very limited. Therefore, there is very little basis for extending the density relationship to (ρ_1/ρ_g) ratios much smaller than 500. However, since a better basis is not available, the experimental constants for Van Rossum's and Wallis' data were averaged to arrive at a possible correlation given by Equation (1).

$$V_C = 2.1 \times 10^{-4} \left(\frac{\sigma g_c}{\mu_g} \right) \left(\frac{\rho_1}{\rho_g} \right)^{1/2} \quad (1)$$

The correlation of Equation (1) does not include the effect of centrifugal acceleration on entrainment, but this acceleration has to be taken into account when analyzing flow on a radial vane. To find how acceleration, or " g ," influences the start of entrainment, stability of two different stratified fluids in relative parallel motion may be examined.

The case of two deep uniform nonviscous fluids in relative horizontal motion separated by a horizontal boundary may be analyzed in terms of stability of the governing hydrodynamic equations. The Kelvin-Helmholtz stability analysis⁽⁵⁾ predicts that such a gas-liquid interface will be stable if

$$V_R < \sqrt{2} \left[g \sigma g_c (\rho_1 - \rho_g) \right]^{1/4} \left(\frac{1}{\rho_1} + \frac{1}{\rho_g} \right)^{1/2} \quad (2)$$

Thus, the critical velocity for start of instability will be the limiting value of

$$V_R = \vec{V}_g - \vec{V}_1 .$$

A form very similar to Equation (2), i. e.,

$$V_o = K \left[\sigma g_c g (\rho_1 - \rho_g) \right]^{1/4} \left(\frac{1}{\rho_g} \right)^{1/2}, \quad (3)$$

where V_o is the superficial vapor velocity from the heated surface at burnout (calculated from the heat flux and thermodynamic properties), has been used by Kutateladze to correlate horizontal pool burnout data successfully.⁽⁶⁾ Kutateladze considered burnout heat flux to be a hydrodynamic phenomenon and arrived at the form of Equation (3) from dimensional considerations. It is significant as far as the "g" dependence in the present case is concerned that the form of Equation (3) may be also arrived at by treating burnout as a Kelvin-Helmholtz instability [see Reference (6)]. The dependence of burnout heat flux on centrifugal acceleration has been checked by Ivey⁽⁶⁾ who found that

$$V_o \propto \left(\frac{g}{g_o} \right)^{0.273}, \text{ where } g_o = 32.2 \text{ ft/sec}^2 .$$

The similarity of relationships for burnout heat flux and Kelvin-Helmholtz stability gives us a good basis to believe that centrifugal acceleration has the same influence in both types of processes. If we assume that the start of entrainment can be associated with gas-liquid interface instability, the influence of "g" on interface stability and start of entrainment should be the same.

Therefore, adding the acceleration influence to correlation of Equation (1), we get

$$V_C = 2.1 \times 10^{-4} \left(\frac{\sigma g_c}{\mu_g} \right) \left(\frac{\rho_1}{\rho_g} \right)^{1/2} \left(\frac{g}{g_o} \right)^{1/4} \quad (4)$$

as a possible correlation for start of entrainment. Because of the weak basis for the $V_C \propto \left(\frac{\rho_1}{\rho_g} \right)^{1/2}$ relationship, Equation (4) should be used with caution, and should be checked against experimental results if possible.

In addition to Equation (4), another relationship can be arrived at to predict the start of entrainment by considering that the Kelvin-Helmholtz instability criterion can be associated with

the start of entrainment. Numerically, the Kelvin-Helmholtz instability criterion predicts the formation of waves closer than it predicts the start of entrainment from waves, as comparison with Van Rossum's data shows.

If it is agreed, however, that the relationships occurring in the Kelvin-Helmholtz criterion determine the start of entrainment from waves, Equation (2) can be adjusted by a proportionality constant to agree with the experimental results discussed previously. The result is an alternative correlation, Equation 5, for the start of wave entrainment:

$$V_C = C_1 \left[4 g \sigma g_c (\rho_1 - \rho_g) \right]^{1/4} \left(\frac{1}{\rho_1} + \frac{1}{\rho_g} \right)^{1/2}, \quad (5)$$

where $C_1 \approx 3$ for the results discussed.

When $\rho_1 \gg \rho_g$, it may be noted that correlations of Equations (4) and (5) would be very similar, except for the different dependence of V_C on surface tension. The reason for this difference cannot be accounted for at this time, but new experimental data might help to explain this discrepancy.

Typical radial separator conditions from Reference (7) are now chosen to compare the two correlations in an illustrative example. For steam-water operation at 1000 psi, we have

$$\sigma = 10^{-3} \text{ lb}_f/\text{ft},$$

$$\frac{g}{g_0} = 55,$$

$$\mu_g = 0.216 \times 10^{-4} \text{ lb/ft-sec},$$

$$\rho_1 = 46.2 \text{ lb/ft}^3, \text{ and}$$

$$\rho_g = 2.25 \text{ lb/ft}^3.$$

Equation (5) gives

$$V_C = 3 (4 \times 32.2 \times 55 \times 10^{-3} \times 32.2 \times 44)^{1/4} (0.466)^{1/2} = 20 \text{ ft/sec.}$$

Equation (4) gives

$$V_C = 2.1 \times 10^{-4} \left(\frac{32.2 \times 10^{-3}}{0.216 \times 10^{-4}} \right) (20)^{1/2} (55)^{1/4} = 4.25 \text{ ft/sec.}$$

Limited steam-water entrainment results for a radial separator [Reference (7), Figure 5] indicate that entrainment starts at vertical steam velocity of about 20 ft/sec for 18-inch-long nozzles, but only at about 6 ft/sec for 6-inch-long nozzles. This difference in results suggests that either entrainment in the two cases is due to different causes, or that the cause in both cases is not wave entrainment. If carryover in the 18-inch nozzles is caused by wave entrainment, then Equation (5) seems to predict it quite closely.

However, the causes of the differences in predictions and in results should be investigated with detailed air-water and steam-water tests. These tests should provide information about the start and sources of entrainment so that prediction of carryover in the radial separator can be improved.

5. ENTRAINMENT DUE TO GAS SEPARATION FROM THE LIQUID

Entrainment of liquid by a gas stream can occur from bursting of gas bubbles on the gas-liquid interface. Bursting gas bubbles project liquid droplets and liquid jets into the gas stream, some of which are then entrained in the gas flow. This type of carryover in nonflowing systems with horizontal gas-liquid interfaces has been discussed extensively by Yeh and Zuber. The quantitative correlations reviewed in Reference (8) were empirical, although a power dependence of carryover on the superficial gas velocity was noted; i. e., $C. O. \propto (V_S)^n$, where n can have several values depending on the type of entrainment involved.

The horizontal free-surface results are difficult to apply to the radial separator case because in horizontal free-surface systems V_S from the two-phase mixture is in the direction of entrainment flow. However, in the radial vane system the superficial gas velocity is normal to the direction of entrainment flow.

Although quantitative comparison of the two systems is not really feasible, some controlling parameters may be investigated, and their influence on carryover results observed. From dimensional considerations [see Reference (8)] one can arrive at

$$\text{Entrainment} = \frac{\rho_g (V_S)^n}{\sigma_g} \sqrt{\frac{\rho_g}{\rho_l}} \times \text{Const.},$$

with the value of n being

Region	n
Low Bubble Entrainment	0 to 1
Medium Jet Entrainment	3 to 4
Splashing Entrainment	7 to 8

Since carryover needs to be limited to reasonable values in the radial separator, the main interest here would most likely be in the first two regions, with emphasis on defining the transition point between them. Quantitative information about this type of entrainment should be obtained from steam-water flow experiments on a radial vane.

To help interpret carryover results, an attempt will be made to describe the type of results that can be expected from the various entrainment mechanisms.

6. INTERPRETATION OF CARRYOVER RESULTS

It would be interesting to know how the carryover measurements taken at the top of the vanes can be interpreted in terms of the entrainment mechanisms discussed. A tentative description of controlling parameters is now presented to help in this interpretation.

Droplet entrainment was seen to be proportional to $(V_S)^n$. Assuming that V_S is uniform over the whole area of flow on the vane

$$V_S = \frac{Q_g}{LH}$$

Carryover also depends on the local gas velocity between the vanes. Since V_S is uniform,

$$(V_g)_z = V = \frac{V_{\max}}{H} z \quad \begin{cases} V = 0, & z = 0 \\ V = V_{\max}, & z = H \\ V = \text{Constant } z \end{cases}$$

where

$$V_{\max} = \frac{V_S - LH}{LS}$$

is the gas velocity at the top of the vanes. Assuming that the power dependence of carryover on superficial gas velocity holds in the radial separator case, the total carryover can be expressed as

$$C. O. = C_1 \int_0^H (v_s)^n v \, dz$$

$$C. O. = C_1 (v_s)^{n+1} H^2/2S .$$

Wave entrainment (once it starts) was found by Steen and Wallis⁽⁴⁾ to be proportional to the air velocity. Assuming that this proportionality also applies in the radial separator case, we have

$$\text{Entrainment} = C_2 (V - v_c) .$$

Carryover measured at the top of vanes from this source would be

$$C. O. = C_3 \int_0^H (V - v_c) \, dz$$

$$C. O. = C_3 H \left[H \frac{v_s}{2S} - v_c \right] .$$

Although the above formulations are quite approximate, it is hoped that they may help predict and separate the sources of entrainment from carryover measurements until better formulations can be developed as more knowledge about carryover from radial vanes is gained.

NOMENCLATURE

C	-	Constant.
D	-	Nozzle diameter, ft.
H	-	Nozzle height, ft.
K	-	Constant.
L	-	Vane length, ft.
L_o	-	Nozzle length, ft.
Q_g	-	Gas flow rate, ft^3/sec .
R	-	Vane radius, ft.
R_V	-	Nozzle inlet radius, ft.
S	-	Distance, ft.
V	-	Velocity, ft/sec .
V_c	-	Relative gas velocity at start of entrainment.
V_o	-	Superficial vapor velocity at burnout.
V_R	-	Relative gas velocity.
V_S	-	Superficial gas velocity.
g	-	Acceleration, ft/sec^2 .
g_o	-	Gravitational acceleration, ft/sec^2 .
g_c	-	Gravitational constant, $\text{lb-ft}/\text{lb}_f\text{-sec}^2$.
y	-	Film thickness, ft.
z	-	Distance, ft.
ρ	-	Density, lb/ft^3 .
σ	-	Surface tension, lb_f/ft .
μ	-	Viscosity, $\text{lb}/\text{ft-sec}$.

Subscripts

g	-	Gas.
l	-	Liquid.

REFERENCES

(for Appendix A)

1. Robbins, C. H., "Analyses of the Radial Separator," GEAP-4012 (1962).
2. Van Rossum, J. J., "Experimental Investigation of Horizontal Liquid Films," Chem. Engr. Sci., Vol. 11, pp 35-52 (1959).
3. Zuber, N., "On the Atomization and Entrainment of Liquid Films in Shear Flow," GE Report No. 62GL153 (1962).
4. Steen, D. A., and Wallis, G. B., "The Transition from Annular to Annular-Mist Co-Current Two-Phase Downflow," NYO-3114-2 (1964).
5. Chandrasekhar, S., "Hydrodynamic and Hydromagnetic Stability," Oxford Press, p 486 (1961).
6. Ivey, H. J., "Acceleration and the Critical Heat Flux in Pool Boiling Heat Transfer," Inst. Mech. Engrs., P1/63 (1962).
7. Moen, R. H., "Radial Vane Steam Separator Development, Second Quarterly Report," GEAP-4783 (January 1965).
8. Yeh, C. K., and Zuber, N., "On the Problem of Liquid Entrainment," RWD-RL-183 (1960).

APPENDIX B

DRAWINGS FOR FCRV-3 AND FCRV-4

This appendix consists of the drawings for the FCRV-3 and the FCRV-4, and includes the following drawings.

<u>Figure No.</u>	<u>Drawing No.</u>	<u>Title</u>
B-1	706E236	Separator (FCRV-3)
B-2	706E242	Radial Vane Separator (FCRV-3)
B-3	148F716	Radial Vane Separator (FCRV-4)
B-4	706E244	Separator (FCRV-4)
B-5	706E248	Separator (FCRV-4)

12		GENERAL ELECTRIC		70GE242
APPROVED PRACTICES	145ASAB1	SURFACES	1/32"	1/2"
TITLE				
RADIAL VANE SEPARATOR				
FIRST MADE FOR FCRV-3

Figure B-2. Radial Vane Separator (FCRV-3)

12		GENERAL ELECTRIC		706E244	
UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:					
APPLICABLE PRACTICES	SURFACES	TOLERANCES	FINISHES	TEMPERATURES	UNIT
145AS4B1	125	✓	1/32	2"	SEPARATOR
FIRST MADE FOR FCRV-4				Q1 PT NAME DESCRIPTION

Figure B-4. Separator (FCRV-4)

12				GENERAL ELECTRIC		706E24B	
UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:				TITLE			
APPLIED PRACTICES		SURFACES		FINISHES		STRAIGHTENING	
145A54B1		12.5		1/2		2°	
PT NAME				DISCRIPTION

Figure B-5. Separator (FCRV-4)

APPENDIX C

DRAWINGS OF THE CLEAR PLASTIC TWO-VANE TEST UNIT

This appendix includes the drawings for the clear plastic two-vane separator assembly, and includes the following drawings.

<u>Figure No.</u>	<u>Drawing No.</u>	<u>Title</u>
C-1	112C2142	Inter Vane Assembly
C-2	112C2143	Outer Vane
C-3	129B2569	Inner Vane
C-4	148F493	Clear Vane Separator Installation
C-5	237E983	Clear Vane Separator
C-6	846D880	Stand Assembly
C-7	846D881	Outer Vane Assembly
C-8	846D882	Air Box Assembly
C-9	846D893	Return Duct

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING—		112C2142		GENERAL ELECTRIC		112C2142	
APPLIED PRACTICES	SURFACES	TOLERANCES ON DIMENSIONS	112C2142	TITLE			
1.45A5481	125	FRACTIONS	112C2142	INNER VANE ASM.			
		DIMENSIONS	112C2142	FIRST MADE FOR CLEAN VANE SEPARATOR TEST			
		DECIMALS	112C2142	DRAWING NO., DESCRIPTION, MATERIAL, WEIGHT			
		ANGLES	112C2142				
		CONV. ON SHEET	112C2142				
		SCALE	112C2142				
		PART NO.	112C2142				
		NAME	112C2142

Figure C-1. Inner Vane Assembly

4		5		GENERAL ELECTRIC		112C21A3	
UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:							
APPLIED PRACTICES	SURFACES	TOLERANCES BY DECIMAL INCHES		TITLE			
145A5481	125	FRACTIONS	DECIMALS	OUTER VANE			
		$\pm \frac{1}{32}$	$\pm .01$	FIRST MADE FOR CLEAR VANE SEPARATOR TEST			
FCF 8460881

① 1/8 THK. LEXAN POLYCARBONATE SHEET
GENERAL ELECTRIC CO. CHEMICAL MAT. DEPT.,
ONE PLASTIC AVE. PITTSFIELD, MASS.
OR ENG. APPD. EQ.

② SAME AS P1
EXCEPT AS SHOWN

Figure C-2. Outer Vane

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:		GENERAL ELECTRIC		237E983
APPLICABLE PRACTICES	SURFACES	FINISHES	STRENGTHS	TITLES
125	✓	✓	✓	CLEAR VANE SEPARATOR
FIRST MADE FOR				PL ISSUED FEC 198F193

NOTE

1. P1, OUTER VANE ASM. TO BE USED ON TEST 1
P13, OUTER VANE ASM. TO BE USED ON TEST 2
2. POSITION & ALIGN VANES, P2, P3 (60 PIS) & AIR BOX, P4
AS A UNIT BEFORE TIGHTENING BOLTS, P8.

Figure C-5. Clear Vane Separator

8												9												GENERAL ELECTRIC												846D880											
UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:-																								REV. 0				TITLE																			
APPLIED PRACTICES						SURFACES						TOLERANCES ON DIMENSIONS						846D880																													
1A: A548L						125 ✓						FRACTIONS + 1/64 - — ANGLES + 0°30'																																			
CONT. ON SHEET																								FIRST MADE FOR CLEAR VANE SEPARATOR																							
SHEET NO.												PART NO.												DRAWING NO., DESCRIPTION, MATERIAL, WEIGHT																							
57

FCF 237E983

NOTE:
1. ALL WELDS TO BE VISUAL INSPECTED.

Figure C-6. Stand Assembly

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:		8		9		GENERAL ELECTRIC		846D881	
APPLIED PRACTICES	SURFACES	FRACTIONS	DECIMALS	ANGLES	TITLE				
145A5981	125	$\frac{1}{32}$	-	$0^{\circ}30'$	846D881				
CONT. ON SHEET					FIRST MADE FOR CLEAR VANE SEPARATOR TEST				
REV. NO.					PART NO.				
NAME					DRAWING NO., DESCRIPTION, MATERIAL, WEIGHT

- NOTE
- 1. TWO 1/4" THK. SHEETS MAY BE BONDED TOGETHER TO MAKE UP 1/2" THK. PLATE.
 - 2. USE PS, METHYLENE CHLORIDE TO BOND ALL PARTS TOGETHER. REFER TO GENERAL ELECTRIC TECHNICAL REPORT COL-502 REV. B FOR MORE FABRICATION DATA.
 - 3. SURFACE "A" OF PTS. 2 & 3 TO BE IN SAME PLANE WITHIN ±.010.

Figure C-7. Outer Vane Assembly

8		9		GENERAL ELECTRIC		846D893	
UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:				REV 0			
APPLIED PRACTICES	SURFACES	TOLERANCES ON MEASURED DIMENSIONS		TITLE		DRAWING NO., DESCRIPTION, MATERIAL, WEIGHT	
145A5+81	250	FRACTIONS	DECIMALS	846D893		RETURN DUCT	
		+	-	CONT. ON SHEET		FIRST MADE FOR CLEAR VANE SEPARATOR TEST	
				PART NO.		NAME

1 1/4 THK. (STK.)

2 1/4 THK. (STK.)

5 1/2 DIA.

NOTE

1. ALL WELDS TO BE VISUAL INSPECTED.
2. SURFACES A-A & B-B TO BE IN SAME PLANE WITHIN 1/32".

Figure C-9. Return Duct

APPENDIX D

DRAWINGS FOR MODIFICATION OF LARGE AIR-WATER TEST FACILITY

This appendix consists of the drawings for the Large Air-Water-Test Facility modification, and the following drawings are included.

<u>Figure No.</u>	<u>Drawing No.</u>	<u>Title</u>
D-1	706E202	Large Air-Water Loop Modification
D-2	706E203	Excavating and Paving
D-3	706E208	Test Tank

Figure D-2. Excavating and Paving

Figure D-3. Test Tank

REFERENCES

1. Moen, R. H. , "Nuclear Superheat, Project Internal Steam Separation, Development of Radial Vane Steam Separators," GEAP-4272, May 31, 1963.
2. Robbins, C. H. , "Analysis of the Radial Separator," GEAP-4012, February 1962.

Approved:

D. H. Imhoff, Manager
Engineering Development

C. H. Robbins, Manager
Mechanical and Process Development

R. H. Moen, Project Engineer
Radial Vane Steam Separator Development Project

DISTRIBUTION LISTNo. Copies

United States Atomic Energy Commission San Francisco Operations Office Berkeley, California Attention: Director, Reactor Division	24
United States Atomic Energy Commission Division Reactor Development Washington 25, D. C. Attention: Chief, Water Reactors Branch	2
Attention: Assistant Director, Office of Foreign Activities	1
United States Atomic Energy Commission Oak Ridge Operations Office Oak Ridge, Tennessee Attention: Director, Reactor Division	1
DTIE Oak Ridge, Tennessee Attention: R. L. Metter	3
Allis-Chalmers Manufacturing Company Nuclear Power Department-Greendale Post Office Box 512 Milwaukee, Wisconsin Attention: G. Johnson	1
Babcock and Wilcox Company Atomic Energy Division Post Office Box 1260 Lynchburg, Virginia Attention: Librarian	1
Combustion Engineering, Inc. Nuclear Division Prospect Hill Road Windsor, Connecticut Attention: Business Manager	1
Northern States Power Company Minneapolis, Minnesota Attention: E. C. Ward	1
Argonne National Laboratory Post Office Box 299 Lamont, Illinois Attention: A. V. Crewe	1
General Nuclear Engineering Corporation Post Office Box 245 Dunedin, Florida Attention: J. M. West	1
Westinghouse Electric Corporation Atomic Power Department Post Office Box 355 Pittsburg, Pennsylvania Attention: J. M. Wright	1