NUCLEAR DIVISION

RN-DR-0165

FINAL TEST REPORT
NOZZLE-COOLANT-CHANNEL
END-CAP EVALUATION

NERVA Program

Contract SNP-1

October 1969

MASTER

NUCLEAR ROCKET OPERATIONS

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.

RN-DR-0165

FINAL TEST REPORT
NOZZLE-COOLANT-CHANNEL
END-CAP EVALUATION

NOTICE

THIS REPORT IS THE PROPERTY OF THE UNITED STATES GOVERNMENT. IT IS TO BE DISTRIBUTED TO THE BEST AVAILABLE SOURCE AT THE TIME OF THE REPORT; POSSIBLE AVAIL-

NERVA PROGRAM

CONTRACT SNP-1

NUCLEAR ROCKET OPERATIONS

SEPTEMBER 1969

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or 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.

CLASSIFICATION CATEGORY

UNCLASSIFIED

J. H. Sutton
CLASSIFYING OFFICER

9-18-69
DATE

AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

DISTRIBUTION

Saw

PAGE BLANK

RN-DR-0165

FINAL TEST REPORT

NOZZLE-COOLANT-CHANNEL
END-CAP EVALUATION.

R. B. Wright

L. A. Shurley for
L. A. Shurley
Manager, Thrust Chamber Section
Engineering Department
Nuclear Rocket Operations

I. L. Odgers for
I. L. Odgers, Manager
Engineering Department
Nuclear Rocket Operations

R. V. Evleth for
R. V. Evleth, Manager
NERVA Program Office
Nuclear Rocket Operations

PAGE BLANK

ABSTRACT

This report documents test results on the effectiveness of nozzle-coolant-channel end caps with respect to pressure drop and flow stagnation.

Part I describes the results obtained by using plastic-model end caps (with water flow) to determine their effect on pressure loss at the nozzle inlet and outlet and comparing the pressure drops and flow patterns of special end caps with those for a flat end cap of the type used on NERVA technology nozzles.

Because visual observations of air bubbles and high-speed motion pictures did not show the flow pattern well enough to demonstrate adequate cooling of the tube end, a second series of tests was performed to demonstrate the relative cooling ability of the reduced-pressure-drop end caps. Part II of this report documents results of heat-transfer tests made with full-scale metal end caps brazed into actual NERVA-type U-tubes. The tubes were heated with either hot nitrogen or quartz lamps, and the rate of tube-surface cool-down while cold nitrogen was flowing was monitored with thermocouples and liquid crystal.

PAGE BLANK

Part I

TABLE OF CONTENTS

	<u>Page</u>
I. Introduction	1
II. Test Objectives	1
III. Description of Test Components	1
IV. Test Procedures	3
V. Discussion of Test Results	7
VI. Conclusions and Recommendations	23

Part II

I. Introduction	35
II. Objectives	35
III. Hardware Description	35
IV. Test Procedure	36
V. Discussion of Test Results	42
VI. Conclusions and Recommendations	50

Appendix A Data Sheets for Exit-End-Cap Tests Showing
Individual Pressures

Appendix B Plots of Temperature Data from Test HT-12-112

Part I

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
1	Description of the 16 End-Cap Configurations Tested	5
2	Instrumentation List for Entrance-End-Cap Tests	12
3	Instrumentation List for Exit-End-Cap Tests	13
4	Comparison of Flow Areas with 1/4 in. Radius on Test Fixture	15
5	Comparison of Losses in Static and Total Pressure for Various Exit End Caps	16
6	Percent Improvement in Pressure Drop of Various Exit End Caps	18
7	Nozzle End Cap Kw Tabulation	20
8	Pressure Drop and Velocity Head Comparison of Exit End Caps at 15 lb/sec	21
9	Comparison of Entrance End Cap Pressure Drop	22

Part II

10	Summary of Ten Tests Where Tube Wall Temperatures were Monitored with Liquid Crystal	43
11	Summary of Eight Tests with Tube Wall Temperatures Monitored with Thermocouples	45
12	Comparative Pressure Drop of Flat End Cap (P/N 1134995-2), and Two Reduced ΔP End Caps (P/N 1136178-1 and P/N 1135860-1)	48

Part I

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1	Test Fixture P/N 1134717	2
2	Cross Sectional View of End Caps 1134728-1 and 1135496-1	4
3	Flow Schematic and Instrumentation Diagram for Entrance-End-Cap Tests	8
4	Flow Schematic and Instrumentation Diagram for Exit-End-Cap Tests	9
5	Test Installation for Entrance-End-Cap Tests	10
6	Test Installation for Exit-End-Cap Tests	11
7	Velocity Pressure Correction 0.61 U-Tube to 1.0 in. dia Tube	17
8	Flow Pattern, P/N 1134728-1, 5 lb/sec, 3/8 in. Radius	25
9	Flow Pattern, P/N 1134728-1, 10 lb/sec, 3/8 Radius	26
10	Flow Pattern, P/N 1134728-1, 15 lb/sec, 3/8 Radius	27
11	Flow Pattern, P/N 1135495-1, 5 lb/sec, 3/8 Radius	28
12	Flow Pattern, P/N 1135495-1, 10 lb/sec, 3/8 Radius	29
13	Flow Pattern, P/N 1135495-1, 15 lb/sec, 3/8 Radius	30
14	Flow Pattern, P/N 1135496-1, 5 lb/sec, 3/8 Radius	31
15	Flow Pattern, P/N 1135496-1, 10 lb/sec, 3/8 Radius	32
16	Flow Pattern, P/N 1135496-1, 15 lb/sec, 3/8 Radius	33

Part II

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
17	U-Tube Entrance and Exit Configuration	37
18	Heat-Transfer Test Setup in Physics Lab	38
19	Cross Sectional View of End Caps P/N 1134995-2, 1135860-1, and 1136178-1	39
20	Location of Thermocouples on Tube Crown	41

Part I

I. INTRODUCTION

The flow rate is reduced in those nozzle coolant tubes which are in line with the hot bleed port because of the additional flow impedance created by the hot-bleed-port manifold. Sources of pressure loss are: (1) where the coolant enters and leaves the bleed-port bypass manifold; (2) at the entrance to the coolant channels; and (3) at the point where the coolant discharges into the reflector-inlet plenum. Changes in flow direction, compounded by sudden changes in the direction of momentum at these locations, are the primary sources of energy loss. Special coolant-channel end caps of 16 different configurations were designed and tested for their effectiveness in minimizing such losses.

II. TEST OBJECTIVES

The objectives of the test program were to determine: (1) whether the use of turning vanes or special end caps reduced pressure loss in tubes, which are in line with the hot-bleed port; and (2) the configuration which is most effective in reducing pressure loss without adversely affecting heat transfer at the coolant-tube end region.

III. DESCRIPTION OF TEST COMPONENTS

Test fixture P/N 1134717, as shown in Figure 1, was constructed of clear acrylic plastic for ease of flow observation. A U-shaped cross section simulated at nozzle U-tube. Pressure taps were located both upstream and downstream of an end cap to measure pressure drop.

For ease of fabrication and better observance of flow conditions, the fixture and sample end caps were designed with a diameter little more than twice that of the nozzle U-tube. The sample end caps were constructed of clear acrylic plastic, and 16 end-cap configurations were tested.

Figure 1 -- Test Fixture P/N 1134717

Part I

A typical flow-streamlining end cap (P/N 1135461-1), and a flat end cap (P/N 1134728-1), which is representative of NERVA technology end caps, are shown in Figure 2.

Test results of the 16 end caps are compared in Table I. The significant differences in various end caps are: (1) the relative flow area in front of the deflecting surface; (2) the relative flow area, which bypasses the main deflector, as shown by dimensions B, C, and D in Table I; (3) the deflecting radius " R_2 "; and (4) the entrance radius to the exit hole.

IV. TEST PROCEDURES

Because of the added expense and safety problems involved with hydrogen flow, the tests were performed with water as the flow medium. The Reynolds number associated with hydrogen in the nozzle tubes could not be duplicated with water because the flow rate and resulting pressure drop would make it impractical. The Reynolds number for water at an equivalent pressure was sufficient to give a fully developed turbulent flow, and tests were performed with water at a pressure drop equivalent to that expected with hydrogen in the actual nozzle tubes. Water flow tests were also performed at flow rates approximately 30% above and below the nominal value to compare the effect of the changing Reynolds number.

Tests were performed at flow rates of 10, 15, and 20 lb/sec of water and gave Reynolds numbers of 2.2×10^5 , 3.3×10^5 , and 4.4×10^5 respectively, whereas, the Reynolds number at the nozzle tube exit with hydrogen flowing in the 75K NERVA engine is approximately 3.3×10^6 .

A total of 15 flow-streamlining end-cap configurations were tested with water flowing in both directions to compare them with the standard flat end-cap for improvement in flow streamlining at both the entrance and exit.

TYPICAL SPECIAL END CAP
PROPOSED FOR NERVA
P/N 1135496-1

NERVA TECHNOLOGY
END CAP
P/N 1134728-1

Figure 2 -- Cross Sectional View of End Caps 1134728-1 and 1135496-1

TABLE 1
DESCRIPTION OF THE 16 END-CAP-CONFIGURATIONS TESTED

<u>Part No.</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>Bypass Hole "D"</u>	<u>R₁</u>	<u>R₂</u>	<u>θ</u>	<u>Description</u>
1134728-1	0.20	---	---		---	---	---	Flat end cap to simulate NERVA tech. condition
1134689-1	1.50	0.450	0.64	0.31 x 0.50 slot	0.03	0.875	75°	Conical, curved face, and elongated bypass hole
113469-1	1.50	0.450	0.64	0.31 annular groove	0.03	0.875	75°	Similar to 1134689-1 except for annular bypass
1134691-1	1.40	0.450	0.65	0.31 dia hole	0.10	0.875	75°	Similar to 1134689-1 except for round bypass hole.
1134691-4	1.40	0.450	0.50	0.31 dia hole	0.10	0.875	75°	Same as Dash 1 except flat face and "C" decreased
1134696-1	1.40	0.450	0.65	0.31 dia hole	0.03	0.875	30°	Similar to 1134691-1 except bypass hole angle changed.
1134697-1	1.25	0.450	0.55	0.20 wide slot	0.03	0.875	30°	Same as 1134696-1 except open slot 0.20 wide
1134697-3	1.25	0.450	0.65	0.20 wide slot	0.03	0.875	30°	Same as 1134697-1 except for a flat face in the lateral plane

TABLE 1 (cont.)

<u>Part No.</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>Bypass Hole "D"</u>	<u>R₁</u>	<u>R₂</u>	<u>θ</u>	<u>Description</u>
1134729-1	1.40	0.550	0.65	0.31 dia hole	0.10	0.875	75°	Same as 1134691-1 except "B" dim. increased by 0.10
1135461-1	1.50	0.450	0.75	0.40 x 0.80 slot	0.25	0.875	75°	Cylindrical, curved face and elongated bypass slot
1135461-2	1.50	0.450	0.75	0.40 x 0.80 slot	0.03	0.875	75°	Same as Dash 1 except "R ₁ " decreased to 0.03 in.
1135462-1	1.50	0.450	0.75	0.31 annular groove	0.03	0.875	75°	Similar to 1135461-2 except for annular bypass groove
1135495-1	1.50	0.450	0.52	0.40 x 0.80 slot	0.25	1.020	75°	Similar to 113546-1 except flat face, "C" decreased, and "R ₂ " increased
1135496-1	1.10	0.450	0.335	0.31 x 0.50 slot	0.03	1.020	75°	Similar to 1134689-1 except "A" decreased, "C" decreased and "R ₂ " increased
1135496-2	1.10	0.450	0.335	0.31 x 0.50 slot	0.03	1.020	75°	Same as 1135496-1 except flat face
1135495-3	1.25	0.450	0.335	0.31 x 0.50 slot	0.03	1.020	75°	Same as 1135496-2 except "A" increased to 1.25

Part I

Pressures were measured both upstream and downstream of the sample end cap and compared with those of the standard flat end cap to determine the reduction in pressure.

The dynamic pressure behind the deflector was measured, and the flow pattern behind the deflector was observed to determine whether adequate heat transfer could be expected at the tube end. Nitrogen bubbles were introduced into the water upstream of the end cap to allow observation of the flow pattern and photographs were taken. Motion pictures (4000 frame/sec), were also taken of the flow pattern around the standard-flat end cap and two of the more favorable end caps.

The flow schematics and the instrumentation diagrams for the entrance end cap-tests and exit end cap tests are shown in Figures 3 and 4. The test installation for entrance-end-cap tests is shown in Figure 5, and Figure 6 shows the test installation for exit-end-cap tests.

The instrumentation list for entrance-end-cap tests is shown in Table 2, and Table 3 shows the instrumentation list for exit-end-cap tests.

Pressures were measured with Bourdon type pressure gages; and for better accuracy delta gages were used where practical. The flow rate was monitored with two vane-type flowmeters and the inlet temperature was monitored with a copper-constantan thermocouple.

V. DISCUSSION OF TEST RESULTS

The ten original end caps were tested and compared with the standard flat-end-cap configuration and resulted in little or no improvement in reducing the overall pressure loss. This result was attributed to a loss in the cross-sectional flow area caused by inserting the special end caps. This loss in the cross-sectional flow area was overcome primarily by decreasing the "C" dimension

Figure 3 -- Flow Schematic and Instrumentation Diagram for Entrance-End-Cap Tests

Figure 4 -- Flow Schematic and Instrumentation Diagram for Exit-End-Cap Tests

Figure 6 -- Test Installation for Exit-End-Cap Tests

Part I

TABLE 2
INSTRUMENTATION LIST FOR ENTRANCE END-CAP TESTS

<u>Parameter</u>	<u>Type of Instrumentation</u>	<u>Range</u>	<u>Description</u>
$\dot{w}$	Flowmeter	0 - 30 lb/sec	Inlet Water Flow
T_I	Thermocouple	50 - 100°F	Inlet Temperature
P_I	Pressure Gage	0 - 200 psig	Inlet Pressure
P_5	Pressure Gage	0 - 200 psig	See Figure 3
P_{T1}	Pressure Gage	0 - 200 psig	Dynamic Pressure 3/4 in. Immersion
P_{T2}	Pressure Gage	0 - 200 psig	Dynamic Pressure 3/8 in. Immersion
P_{T3}	Pressure Gage	0 - 200 psig	Dynamic Pressure 1/16 in. Immersion
P_o	Pressure Gage	0 - 100 psig	Outlet Pressure
P_1	Pressure Gage	0 - 100 psig	See Figure 3
$\Delta(P_5 - P_2)$	Delta Pressure Gage	0 - 25 psid	End Cap ΔP (See Figure 3)
$\Delta(P_4 - P_3)$	Delta Pressure Gage	0 - 25 psid	See Figure 3
$\Delta(P_3 - P_2)$	Delta Pressure Gage	0 - 25 psid	See Figure 3
$\Delta(P_2 - P_1)$	Delta Pressure Gage	0 - 15 psid	See Figure 3
$\Delta(P_T - P_2)$	Delta Pressure Gage	0 - 25 psid	See Figure 3

Part I

TABLE 3
INSTRUMENTATION LIST FOR EXIT-END CAPS

<u>Parameter</u>	<u>Type of Instrumentation</u>	<u>Range</u>	<u>Description</u>
$\dot{w}$	Flowmeter	0 - 30 lb/sec	Inlet Water Flow
T_I	Thermocouple	50 - 100°F	Inlet Temperature
P_1	Pressure Gage	0 - 200 psig	Inlet Pressure
P_2	Pressure Gage	0 - 200 psig	See Figure 4
P_{T_1}	Pressure Gage	0 - 200 psig	Dynamic Pressure 3/4 in. Immersion
P_{T_2}	Pressure Gage	0 - 200 psig	Dynamic Pressure 3/8 in. Immersion
P_{T_3}	Pressure Gage	0 - 200 psig	Dynamic Pressure 1/16 in. Immersion
P_5	Pressure Gage	0 - 100 psig	See Figure 4
P_6	Pressure Gage	0 - 100 psig	Outlet Pressure
$\Delta(P_1 - P_2)$	Delta Pressure Gage	0 - 10 psid	See Figure 4
$\Delta(P_3 - P_2)$	Delta Pressure Gage	0 - 25 psid	See Figure 4
$\Delta(P_4 - P_3)$	Delta Pressure Gage	0 - 15 psid	See Figure 4
$\Delta(P_T - P_2)$	Delta Pressure Gage	0 - 25 psid	See Figure 4
$\Delta(P_2 - P_5)$	Delta Pressure Gage	0 - 25 psid	See Figure 4
$\Delta(P_5 - P_6)$	Delta Pressure Gage	0 - 50 psid	See Figure 4

Part I

and increasing radius " R_2 " as shown in Table I. Increasing the radius at the entrance to the outlet hole in the test fixture from 1/4 to 3/8 in. allowed an increase in flow area and provided for a smoother flow pattern in the 90° turn, which further reduced the pressure loss.

Flow areas with the various end caps are compared in Table 4. Only end caps P/N 1134729-1, 1134691-4, 1135495-1, and 1135496-1 had cross-sectional flow areas greater than the upstream area when tested in the fixture with a 1/4-in. radius. Increasing the radius on the flow mixture to 3/8 in. resulted in an increase in cross-sectional area of approximately 0.060 in.².

Static and total pressure losses for various exit end caps with 1/4-in. and 3/8-in. radius at the entrance to the exit hole of the test fixture are compared in Table 5.

Because the cross-sectional flow area of the downstream section of the test fixture was larger than the upstream section, there is some pressure recovery caused by a decrease in velocity head. In order to more clearly define the pressure loss caused by the flow directing inserts, static-pressure measurements were converted to total pressure by adding the velocity head. Figure 7 shows the correction for velocity head caused by the change in area from the 0.61 in. radius U-tube to the 1.0 in. ID exit tube.

One test with a 1/8-in. radius at the entrance to the exit hole in the test fixture was performed with flat end cap P/N 1134728-1. This resulted in pressure losses approximately 10% higher than when the flat end cap was tested with a 1/4-in. radius in the test fixture.

The percent of improvement for the various exit end caps is shown in Table 6.

Part I

TABLE 4
COMPARISON OF FLOW AREAS
WITH 1/4 in. RADIUS ON TEST FIXTURE

Cross Sectional Flow Area (A_c) =
 $A_1 + (\text{The smaller of } A_2 \text{ or } A_3)$

<u>End Cap P/N</u>	<u>A_1 (in.²)</u>	<u>A_2 (in.²)</u>	<u>A_3 (in.²)</u>	<u>A_c (in.²)</u>	<u>A_u (in.²)</u>
1134689-1	0.455	0.258	0.136	0.591	0.635
1134690-1	0.455	0.258	0.136	0.591	0.635
1134691-1	0.455	0.258	0.110*	0.565	0.635
1134696-1	0.455	0.258	0.032*	0.487	0.635
1134697-1	0.455	0.258	0.032*	0.487	0.635
1134697-3	0.460	0.258	0.032*	0.492	0.635
1134729-1	0.545	0.150	0.110*	0.655	0.635
1135461-1	0.286	0.240	0.280	0.526	0.635
1135461-2	0.286	0.240	0.280	0.526	0.635
1135462-1	0.286	0.240	0.136	0.422	0.635
1134691-4	0.555	0.258	0.110*	0.665	0.635
1135495-1	0.485	0.240	0.280	0.725	0.635
1135496-1	0.537	0.258	0.136	0.673	0.635

* Includes bypass along side of cone.

TABLE 5

COMPARISON OF LOSSES IN STATIC AND
TOTAL PRESSURE FOR VARIOUS EXIT END CAPS

End Cap Part No.	1/4 in. Radius on Test Fixture						3/8 in. Radius on Test Fixture					
	10 lb/sec		15 lb/sec		20 lb/sec		10 lb/sec		15 lb/sec		20 lb/sec	
	ΔP	ΔP_T	ΔP	ΔP_T	ΔP	ΔP_T	ΔP	ΔP_T	ΔP	ΔP_T	ΔP	ΔP_T
1134728-1	7.5	10.5	14.5	21.3	28.2	40.5	4.2	7.2	10.4	17.2	19.1	31.4
1134689-1	4.1	7.1	8.7	15.5	22.6	34.9	0.4	3.4	3.9	10.7	10.3	22.6
1134690-1	4.9	7.9	8.8	15.6	23.5	35.8						
1134691-1	4.8	7.8	9.7	16.5	20.8	33.1						
1134696-1	6.4	9.4	10.9	17.7	31.0	45.4						
1134697-1	6.4	9.4	11.0	17.8	25.2	37.5						
1134697-3	6.4	8.4	10.2	17.0	23.0	35.8						
1134729-1	4.5	7.5	8.8	15.6	19.2	31.5						
1135461-1	6.0	9.0	11.3	18.1	23.9	36.2						
1135461-2	5.4	8.4	11.5	18.3	23.4	35.7						
1135462-1	7.5	10.5	14.8	21.6	45.6	57.9						
1134691-4	1.4	4.4	3.6	10.4	8.9	21.2	0.8	3.8	3.8	10.6	8.2	20.5
1135495-1	2.0	5.0	2.6	9.4	5.7	18.0	-0.5	2.5	1.8	8.6	4.2	16.5
1135496-1	1.3	4.3	3.5	10.3	5.8	18.1	0.4	3.4	2.1	8.9	8.1	20.4
1135496-2							1.4	4.4	4.7	11.5	9.5	21.8
1135496-3							1.7	4.7	4.4	11.2	8.6	20.9

Figure 7 -- Velocity Pressure Correction 0.61 U-Tube to 1.0 in. dia Tube

TABLE 6

PERCENT IMPROVEMENT IN PRESSURE DROP OF VARIOUS END CAPS
OVER FLAT END CAP WITH 1/4 in. RADIUS ON TEST FIXTURE

Part No.	1/4 in. Radius on Test Fixture							3/8 in. Radius on Test Fixture						
	10 lb/sec		15 lb/sec		20 lb/sec		Avg. %	10 lb/sec		15 lb/sec		20 lb/sec		Avg. %
	ΔP_T	% Red.	ΔP_T	% Red.	ΔP_T	% Red.		ΔP_T	% Red.	ΔP_T	% Red.	ΔP_T	% Red.	
1134728-1	10.5	--	21.3	--	40.5	--	0	7.2	31.4	17.2	19.2	31.4	22.5	24.4
1134689-1	7.1	32.4	15.5	27.2	34.9	13.8	24.5	3.4	67.6	10.7	49.8	22.6	44.2	53.9
1134690-1	7.9	24.7	15.6	26.8	35.8	11.6	21.0							
1134691-1	7.8	25.7	16.5	22.5	33.1	18.3	22.2							
1134696-1	9.4	10.5	17.7	16.9	45.4	-12.1*	5.1							
1134697-1	9.4	10.5	17.8	16.4	37.5	7.4	11.4							
1134697-3	8.4	20.0	17.0	20.2	35.8	11.6	17.3							
1134729-1	7.5	28.6	15.6	26.8	31.5	22.2	25.9							
1135461-1	9.0	14.3	18.1	15.0	36.2	10.6	13.3							
1135461-2	8.4	20.0	18.3	14.1	35.7	11.9	15.3							
1135462-1	10.5	0	21.6	-1.4*	57.9	-43.0*	-14.8*							
1134691-4	4.4	58.1	10.4	51.2	21.2	47.7	52.3	3.8	63.8	10.6	50.2	20.5	49.4	54.5
1135495-1	4.4	58.1	9.4	55.9	18.0	55.6	56.5	2.5	76.2	8.6	59.6	16.5	59.3	65.0
1135496-1	4.3	59.0	10.3	51.6	18.1	55.3	55.3	3.4	67.6	8.9	58.2	20.4	49.6	58.5
1135496-2								4.4	58.1	11.5	46.0	21.8	46.2	50.1
1135496-3								4.7	55.2	11.2	47.4	20.9	48.4	50.3

* A negative percent reduction of pressure indicates an increase in pressure drop.

Part I

A Kw value for use in determining pressure drop from the equation $\Delta P_T = \left(\frac{Kw}{\dot{w}}\right)^2 \times \frac{1}{S.G.}$ (where ΔP_T is the loss in total pressure) was calculated for each end cap and is shown in Table 7. These Kw values were obtained with water and previous test experience has shown that Kw values for hydrogen are 5 to 7% lower than the water Kw values.

The results of an attempt to measure the velocity head with a dynamic probe in the flow-bypass region near the tube crown behind the end-cap deflector are shown in Table 8. This data does not represent a true velocity head measurement because of heavy turbulence and complex-flow patterns, but it does give an indication of flow direction and velocity. For example, negative readings at $\Delta (P_{T3} - P_4)$ show a reversal of flow in this local area. This turbulence and reversal of flow can be seen in high-speed motion pictures and still photos by introducing N_2 bubbles.

Individual pressures for exit-end-cap tests adjusted for a constant inlet pressure are shown in Appendix A.

When the original ten end caps were tested, with water flowing in the reverse direction, as entrance end caps, all ten showed an increase in pressure loss over the standard flat end cap.

Only modified end caps P/N 1134691-9, 1135495-1, and 1135496-1 showed a reduction in pressure loss when tested as entrance end caps, and they only gave a 10 to 15% improvement. Entrance-end-cap pressure losses are compared in Table 9.

Results of introducing N_2 bubbles upstream of the sample end caps indicated that flow velocities and turbulence near the tube ends were probably as good with flow-streamlining end caps as with the standard flat end cap. Figures 8 through 16 show the flow pattern of the two more favorable end caps and the standard flat end cap at 5, 10, and 15 lb/sec flow rates.

Part I

TABLE 7
NOZZLE END CAP K_w TABULATION*

<u>P/N</u>	<u>Flow Rate (lb/sec)</u>	<u>1/4 in. Radius on Fixture</u>		<u>3/8 in. Radius on Fixture</u>	
		<u>ΔP_T</u>	<u>K_w</u>	<u>ΔP_T</u>	<u>K_w</u>
1134728-1 Flat End Cap	10	10.5	3.08	6.6	3.89
	15	21.2	3.26	16.9	3.65
	20	39.2	<u>3.19</u>	29.3	<u>3.69</u>
			3.18		3.74
1134689-1 Cone with 0.31 x 0.50 Bypass Slot	10	7.1	3.75	3.4	5.42
	15	15.5	3.81	10.1	4.72
	20	32.9	<u>3.48</u>	20.6	<u>4.41</u>
			3.68		4.85
1134691-4 Cone with 0.31 Bypass Hole and Flat Face	10	4.15	4.91	3.8	5.13
	15	10.5	4.63	10.0	4.74
	20	20.5	<u>4.42</u>	19.4	<u>4.54</u>
			4.65		4.80
1135495-1 Cyl. with 0.40 x 0.80 Bypass Slot	10	3.4	5.42	2.4	6.45
	15	9.0	5.00	7.8	5.37
	20	17.6	<u>4.77</u>	15.7	<u>5.05</u>
			5.06		5.62
1135496-1 Cone with 0.31 x 0.50 Bypass Slot	10	4.0	5.00	3.4	5.42
	15	9.7	4.82	9.0	5.00
	20	17.9	<u>4.73</u>	17.7	<u>4.75</u>
			4.85		5.06
1135496-2 Same as -1 except 0.4 shorter and Flat Face	10			4.4	4.77
	15			11.1	4.50
	20			20.6	<u>4.40</u>
					4.56
1135496-3 Same as -3 except 0.25 longer	10			4.7	4.61
	15			10.7	4.59
	20			20.4	<u>4.43</u>
					4.54

$$* K_w = \frac{w}{\sqrt{\Delta P} \times S.G.}$$

TABLE 8
PRESSURE DROP AND VELOCITY HEAD
COMPARISON OF EXIT END CAPS AT 15 lb/sec

End Cap P/N	Radius on Test Fixture (in.)	Description of End Cap	$\Delta(P_2 - P_6)$ psid	Velocity Head in Longitudinal Direction		
				$\Delta(P_{T1} - P_3)$	$\Delta(P_{T2} - P_3)$	$\Delta(P_{T3} - P_4)$
1134728-1	1/8	Flat End Cap	30.6	10.2	2.5	-2.8
1134728-1	1/4	Flat End Cap	28.6	9.3	3.2	-3.9
1134728-1	3/8	Flat End Cap	24.2	7.4	5.3	-5.4
1134689-1	1/4	Cone with Slotted Hole	22.8	8.9	6.9	-1.9
1134689-1	3/8	Cone with Slotted Hole	17.4	8.3	6.3	-2.1
1134691-4	1/4	Cone with Round Hole	17.8	5.8	3.8	-0.1
1134691-4	3/8	Cone with Round Hole	17.3	6.7	4.2	-1.1
1135495-1	1/4	Cyl. with Slotted Hole	16.6	7.8	3.4	0.1
1135495-1	3/8	Cyl. with Slotted Hole	15.0	6.9	1.9	0
1135496-1	1/4	Cone with Slotted Hole	21.7	6.4	4.1	-0.3
1135496-1	3/8	Cone with Slotted Hole	15.6	3.2	3.4	-0.1

TABLE 9

COMPARISON OF ENTRANCE END CAP PRESSURE DROP

End Cap P/N	1/4 in. Radius at Fixture Inside Corner						3/8 in. Radius at Fixture Inside Corner					
	10 lb/sec		15 lb/sec		20 lb/sec		10 lb/sec		15 lb/sec		20 lb/sec	
	ΔP	ΔP_T^*	ΔP	ΔP_T	ΔP	ΔP_T	ΔP	ΔP_T	ΔP	ΔP_T	ΔP	ΔP_T
1134728-1	6.1	3.1	13.3	6.5	24.2	11.9	6.2	3.2	13.7	6.9	24.6	12.3
1135495-1	6.4	3.4	13.4	6.6	23.5	11.2	5.6	2.6	12.4	5.6	22.3	10.0
1135496-1	8.0	5.0	13.2	6.4	21.7	9.4	5.7	2.7	12.6	5.8	23.0	10.7
1134691-4	6.7	3.7	14.1	7.3	24.9	12.6	5.9	2.9	13.0	6.2	23.0	10.7
1134689-1	6.9	3.9	15.3	8.5	27.5	15.2	6.6	3.6	14.6	7.8	26.0	13.7
1134729-1	7.1	4.1	15.8	9.0	26.4	14.1						
1134691-1	7.8	4.8	17.0	10.2	30.0	17.7						
1134690-1	7.9	4.9	17.3	10.5	30.8	18.5						
1135461-1	6.1	3.1	14.8	8.0	35.9	23.6						
1134697-3	8.2	5.2	17.3	10.5	32.6	20.3						
1134697-1	8.6	5.6	20.1	13.3	36.2	23.9						
1135461-2	7.8	4.8	17.6	10.8	32.2	19.9						
1134696-1	9.3	6.3	20.2	13.4	35.9	23.6						
1135462-1	10.5	7.5	23.5	16.7	43.1	30.8						

* ΔP_T shows drop in total pressure flowing from 1 in. dia. (0.785 in.²) to 0.635 in.² U-tube.

Part I

The amount of N_2 being introduced into the flow stream, while photographing the flow pattern, was measured and determined to be approximately 3.5% by volume with 5 lb/sec of water, 2% by volume with 10 lb/sec of water, and 1% by volume with 20 lb/sec of water. N_2 bubbles were introduced only to observe or photograph the flow pattern and were not used while measuring pressure losses.

The flow pattern around the end caps was observed while introducing a water-soluble red dye and the results were inconclusive. When the dye was introduced upstream of the end cap, it dispersed and thoroughly mixed with the water resulting in no indication of the flow pattern. When the dye was introduced at the P_3 or P_4 pressure taps near the tube end, the dye would propagate some distance upstream giving an indication of the flow pattern and turbulence. When the lowest pressure-drop end cap (P/N 1135495-1) was tested with the red dye introduced at P_3 or P_4 pressure taps, the dye continued downstream with little color observed upstream of the point of introduction. When dye was introduced at the P_4 tap of end cap P/N 1135496-3, the red color extended upstream from the point of introduction to near the forward tip of the end cap. Less color extended upstream with flat end cap P/N 1134728-1 indicating more turbulence with these two end caps than with P/N 1135495-1. It is not known whether the increased turbulence of P/N 1135496-3 or the possible higher velocity with reduced turbulence of P/N 1135495-1 would provide better cooling at the tube end.

VI. CONCLUSIONS AND RECOMMENDATIONS

Three of the 15 nozzle-coolant-channel end caps tested (P/N 1134691-4, 1135495-1, and 1135496-1), were effective in reducing the pressure loss 50% or more when tested in test fixture P/N 1134717-14, which has a 1/4 in. radius at the inside corner of the 90° turn.

Part I

End caps P/N 1135495-1 and 1135496-1 appeared to have the best flow pattern for cooling the tube end behind the flow-deflecting member, and end caps of this design are recommended for further heat-transfer evaluation as exit end caps into the bleed-port manifold, and at the tube exit into the nozzle-outlet manifold of tubes which are intercepted by the hot-bleed-port manifold.

Coolant-channel end caps of this design are not recommended for use at tube entrance regions because of little improvement in reducing pressure loss.

High-speed motion pictures and still photographs were taken while introducing N_2 bubbles into the flow stream, and indicated a coolant-flow pattern at the tube end at least as good as the flat end cap used in NERVA technology nozzles. However, it is recommended that additional heat-transfer tests be made using tube samples with full-scale end caps and measuring the heat-transfer coefficient with thermocouples, temperature-sensitive paint, or liquid crystal.

Figure 8 -- Flow Pattern, P/N 1134728-1, 5 lb/sec, 3/8 in. Radius

Figure 9 -- Flow Pattern, P/N 1134728-1, 10 lb/sec, $3/8$ Radius

Figure 10 -- Flow Pattern, P/N 1134728-1, 15 lb/sec, 3/8 Radius

Figure 11 -- Flow Pattern, P/N 1135495-1, 5 lb/sec, 3/8 Radius

Figure 12 -- Flow Pattern, P/N 1135495-1, 10 lb/sec, 3/8 Radius

Figure 13 -- Flow Pattern, P/N 1135495-1, 15 lb/sec, 3/8 Radius

31

Figure 14 -- Flow Pattern, P/N 1135496-1, 5 lb/sec, 3/8 Radius

Figure 15 -- Flow Pattern, P/N 1135496-1, 10 lb/sec, 3/8 Radius

Figure 16 -- Flow Pattern, P/N 1135496-1, 15 lb/sec, 3/8 Radius

PAGE BLANK

PAGE BLANK

Part II

I. INTRODUCTION

Prior to heat-transfer tests, special flow deflecting end caps were tested with water and they reduced the pressure loss at the tube outlet by as much as 50%. However, flow conditions at the tube end as determined from dynamic-pressure measurements and visual observation were inconclusive in determining how heat transfer may be affected because of change in propellant turbulence near the tube end. This test program was performed to demonstrate the ability of special reduced- ΔP end caps to cool the tube crown near the exit end.

II. OBJECTIVES

The primary objective of these tests was to determine the relative heat transfer through the NERVA U-tube crown near the tube end as affected by flat end cap P/N 1134995-2, and special reduced-pressure-drop end caps P/N 1135860-1, and P/N 1136178-1. This objective was accomplished by heating the tube crowns and monitoring the rate of cooldown while cold GN₂ flowed through the tubes.

A secondary objective was to verify the improvement in pressure drop of the low- ΔP end caps when fabricated from steel to full-scale size and installed in actual nozzle U-tubes.

III. HARDWARE DESCRIPTION

The test article was made from a U-tube braze-evaluation sample (P/N 1136177), consisting of eight U-tubes brazed into a steel plate 48-in.-long. Each U-tube had one of the test-end-caps brazed into the exit end. Steel tubes

Part II

with a 3/8-in.-radius were installed at 90° to the U-tubes at both entrance and exit ends to simulate entrance and exit from a U-tube nozzle as shown in Figure 17. A sonic orifice of 0.141 in. dia was installed in a straight section of 3/8-in.-radius tubing upstream of each nozzle tube and downstream of a common manifold to assure uniform flow to each tube. A photograph of the test setup is shown in Figure 18.

A cross section of the three end caps tested is shown in Figure 19. The flat end cap P/N 1134995-2 is similar to end caps used on NERVA technology nozzles. This flat end cap was used at the entrance to all tubes and at the exit of tubes No. 2 and 5. End cap P/N 1135860-1 has the same shape as plastic end cap P/N 1135496-2, used in tests with water, and was installed at the exit of tubes No. 1, 4, 7, and 8. End Cap P/N 1136178-1 has the same shape as plastic end cap P/N 1135495-1, used in tests with water, and was installed at the exit of tubes No. 3 and 6.

IV. TESTS PROCEDURE

A. PHASE I - HEATED-GN₂ TEST MONITORING TUBE-WALL TEMPERATURE WITH LIQUID CRYSTAL

The eight tube crowns were coated with liquid crystal, which changes color at 95°F. Heated GN₂ was flowed through the tubes until tube crowns were well above the 95°F temperature, the heaters were then turned off and tubes were cooled with cold GN₂. Color changes in the liquid crystal were monitored with color film in 64- and 200-frame/sec motion-picture cameras, and a 20 frame/sec sequence camera.

The tests were performed with pressures of 800, 1200, and 1600 psia upstream of the sonic orifices to provide flow rates of approximately 0.20, 0.30, and 0.40 lb/sec per tube. These flow rates were selected to give pressure drops at tube exits comparable to those in previous water-flow tests and to give a Reynolds No. varying from 0.9×10^6 to 1.3×10^6 , which approaches the Reynolds No. of 3.3×10^6 at the exit of NERVA nozzle tubes.

Figure 17 -- U-Tube Entrance and Exit Configuration

Figure 18 -- Heat-Transfer Test Setup in Physics Lab

End Cap Configuration
for Tubes 3 and 6

End Cap Configuration
for Tubes 1,4,7 & 8

End Cap Configuration
for Tubes 2 and 5

Figure 19 -- Cross Sectional View of End Caps P/N 1134995-2, 1135860-1,
and 1136178-1

Part II

B. PHASE II - COLD GN_2 TESTS, HEATING-TUBE CROWNS WITH QUARTZ LAMPS AND MONITORING TUBE-WALL TEMPERATURE WITH LIQUID CRYSTAL

The original plan for this phase was to heat tubes, while GN_2 was flowing, with quartz lamps to a temperature above 100°F and then turn off the quartz lamps and monitor liquid crystal colors as the tubes cool down through 95°F . However, because the quartz lamps would not maintain a temperature above 95°F , while flowing unheated GH_2 , the GN_2 heaters were used to supplement quartz lamps. Because this type of test was similar to Phase I testing, only one test was made at the nominal flow rate of 0.318 lb/sec.

C. PHASE III - COLD GN_2 TESTS, HEATING TUBE CROWNS WITH QUARTZ-LAMPS AND MONITORING TUBE WALL TEMPERATURES WITH THERMOCOUPLES

These tests were performed similar to Phase II tests except that tube crowns were preheated to a higher temperature (approximately 700°F) and hot-gas-side-tube-wall temperatures were measured in four places on each tube with thermocouples as shown in Figure 20.

The quartz lamp used during this phase consisted of a parabolic reflector containing five 1000-watt elements approximately 12-in.-long. The lamp elements were mounted 90° to the longitudinal axis of the tubes extending past tubes No. 1 and 8 for approximately 3 in. on each end and provided a uniform heating of each tube over a width of approximately 2 in. from the exit end of each tube.

A total of eight tests were performed during this phase. For the first three tests the quartz lamps were turned off at the start of flow. During the remaining five tests quartz lamps were left on until flow shutdown. The flow rate was varied among the tests by setting different pressures upstream of the sonic orifices.

Figure 20 -- Location of Thermocouples on Tube Crown

Part II

V. DISCUSSION OF TEST RESULTS

A. PHASE I TESTS

A tabulated summary of the ten tests where tube-wall temperatures were monitored with liquid crystal is shown in Table 10. The first three tests were successful only from the standpoint of pressure-drop data because movie film was underexposed and color changes of the liquid crystal could not be determined.

During Test 104 the back-pressure valve partially closed causing the flow through the sonic orifices to become subsonic. This did not permit accurate flow determination and could allow some tubes to flow more than others.

Color changes in the liquid crystal, during Tests 105 and 106, were inconclusive because of improper camera exposure.

Tests 107, 108, and 109 were satisfactorily performed at flow rates of 0.422, 0.324, and 0.318 lb/sec, respectively. Color changes of liquid crystal as analyzed from motion pictures showed the end cap in Tube No. 7 cooled the best followed by No. 4, 6, 2, 5, and 3, respectively. Tubes 4 and 7 both have end cap P/N 1135860-1, and this end cap appears to cool better. However, no conclusion can be drawn with respect to the relative advantage of the other two, because Tubes 6 and 3, which have end cap P/N 1136178-1, rated 3rd and 6th compared with flat end cap P/N 1134995-2, which rated 4th and 5th.

The variation in end-cap pressure drop among tests at approximately the same flow rate is the result of tests performed with different back pressures at the exit plenum, resulting in density changes of N_2 at the end cap.

TABLE 10

SUMMARY OF TESTS WHERE TUBE WALL TEMPERATURE WAS MONITORED WITH LIQUID CRYSTAL

Test No.	Inlet Pressure	Inlet Temperature	Flow Rate lb/sec	End Cap ΔP (psi) at Tube No.						Order of End Cap Rating by Tube No. (Best Cooling Listed First)					
				2	3	4	5	6	7						
HT-12-101	833	69	0.223	35	28	29	38	28	31					*	
-102	1204	66	0.322	51	40	41	54	40	46					*	
-103	1592	51	0.430	62	49	50	65	49	55					*	
-104	1480	217	**	40	32	32	41	31	34	7	4	2	6	5	3 (**)
-105	1205	65	0.323	83	69	69	86	68	75					*	
-106	810	70	0.217	40	33	33	41	33	36					*	
-107	1578	70	0.422	64	52	53	68	51	56	4	6	7	2	5	3
-108	1212	72	0.324	35	28	28	36	28	30	7	4	6	2	5	3
-109	837	67	0.224	24	19	20	25	20	21	7	4	2	6	5	3
-110	1188	70	0.318	45	36	37	47	37	40	7	6	4	2	5	3

*Movie film was too dark to distinguish color changes.

**Flow invalid due to subsonic flow through sonic orifices. Results of liquid crystal are questionable due to possibility of non-uniform flow in tubes.

NOTE: Flat end cap P/N 1134995-2 in Tubes No. 2 and 5.
Reduced ΔP end cap P/N 1136178-1 in Tubes No. 3 and 6.
Reduced ΔP end cap P/N 1135860-1 in Tubes No. 4 and 7.

Part II

B. PHASE II TESTS

Only Test 110 was performed during this phase. Quartz lamps did not have enough heating capacity to maintain a tube-wall temperature above the 95°F needed to change the color of liquid crystal while cold GN_2 was flowing. Therefore, GN_2 heaters were used to maintain the tube-crown temperature above 95°F until steady-flow conditions were achieved. This resulted in test conditions and results that were similar to Phase I tests as seen in Table 10. Photographs that show the color changes taking place during Test 110 are presented at the end of Part II. Colors change from blue through green to red as the tubes cool down.

These photographs show the colors to be changing faster on the upper side of each tube crown than below the crown. This is thought to be caused by the effect of the camera lights being mounted slightly below the level of the tubes and either heating the lower side more, or changing the color because of more reflected light, or both.

C. PHASE III TESTS

A tabulated summary of the eight tests performed during this phase, while monitoring tube-wall temperatures with thermocouples, is shown in Table 11. During Tests 111, 112, and 113, tubes were preheated with quartz lamps to approximately 600°F and then turned off prior to cold GN_2 flow, to minimize any non-uniformity of heat input. Quartz lamps were left on, while cold GN_2 flowed, during Tests 114 through 118 and the fact that variations in tube crown temperatures were less pronounced on these tests seemed to verify that differences in tube-wall temperatures were caused by flow conditions and heat transfer rather than variation in heat input.

TABLE 11

SUMMARY OF TESTS WHERE TUBES WERE HEATED WITH QUARTZ LAMPS
AND TUBE WALL TEMPERATURE MONITORED WITH THERMOCOUPLES

Test No.	Tube No.	End Cap Part No.	Inlet Pressure (psia)	Inlet Temperature (°F)	Tube Flow (lb/sec)	End Cap ΔP (psi)	Fluid Temperature (°F)	Tube Wall Temp. (°F) at			
								A	B	C	D
45 HT-12-111	2	1134995-2	1568	57	0.425	60	42	58	60	65	66
	3	1136178-1				48	42	--	79	75	69
	4	1135860-1				49	42	60	67	--	--
	5	1134995-2				62	42	78	97	73	73
	6	1136178-1				--	42	64	--	69	63
	7	1135860-1				--	42	70	109	71	66
HT-12-112	2	1134995-2	1017	44	0.278	39	36	46	49	51	54
	3	1136178-1				32	35	--	51	59	57
	4	1135860-1				33	36	50	54	--	--
	5	1134995-2				40	36	59	76	61	64
	6	1136178-1				--	35	52	--	55	51
	7	1135860-1				--	35	53	84	55	55
HT-12-113	2	1134995-2	691	41	0.190	27	38	48	50	52	56
	3	1136178-1				22	38	--	52	59	60
	4	1135860-1				23	38	52	57	--	--
	5	1134995-2				28	38	62	80	63	70
	6	1136178-1				--	37	55	--	56	55
	7	1135860-1				--	38	54	80	55	59

Part II

TABLE 11 (cont.)

Test No.	Tube No.	End Cap Part No.	Inlet Pressure (psia)	Inlet Temperature (°F)	Tube Flow (lb/sec)	End Cap P (psi)	Fluid Temperature (°F)	Tube Wall Temp. (°F) at			
								A	B	C	D
HT-12-114	2	1134995-2	393	37	0.117	16	39	85	98	97	104
	3	1136178-1				13	39	--	100	123	119
	4	1135860-1				13	39	102	110	--	--
	5	1134995-2				16	40	126	157	127	123
	6	1136178-1				--	40	116	--	132	126
	7	1135860-1				--	40	113	171	114	121
HT-12-115	2	1134995-2	830	37	0.230	32	31	47	54	53	61
	3	1136178-1				26	30	--	57	76	68
	4	1135860-1				27	31	60	69	--	--
	5	1134995-2				33	31	73	96	73	75
	6	1136178-1				--	30	61	--	70	61
	7	1135860-1				--	31	67	108	68	62
HT-12-116	2	1134995-2	1203	38	0.332	48	26	56	64	65	79
	3	1136178-1				38	24	--	63	91	81
	4	1135860-1				38	25	68	73	--	--
	5	1134995-2				48	25	82	123	90	86
	6	1136178-1				--	24	70	--	85	76
	7	1135860-1				--	25	74	135	76	76
HT-12-117	2	1134995-2	1628	40	0.447	62	22	42	52	52	65
	3	1136178-1				50	21	--	51	83	70
	4	1135860-1				51	22	50	59	--	--
	5	1134995-2				64	21	68	104	72	67
	6	1136178-1				--	21	54	--	68	58
	7	1135860-1				--	21	59	116	60	57
HT-12-118	2	1134995-2	1191	48	0.325	46	35	61	71	70	82
	3	1136178-1				37	35	--	71	99	89
	4	1135860-1				37	36	59	66	--	--
	5	1134995-2				47	35	85	99	74	69
	6	1136178-1				--	35	66	--	88	76
	7	1135860-1				--	35	67	105	67	78

Part II

Part II

The data in Table 11 shows that the greatest variation in temperatures takes place at Position B, 3/8 in. upstream of the tube end. At this point, reduced ΔP end cap P/N 1136178-1 appeared to cool the better followed by flat end cap P/N 1134995-2 and reduced ΔP end cap P/N 1135860-1, respectively. At points C and D, 1/4 and 1/8 in. upstream of the tube end, respectively, the trend appeared to reverse, and reduced ΔP end cap P/N 1135860-1 appeared to cool better followed by flat end cap P/N 1134995-2 and the reduced ΔP end cap P/N 1136178-1. See Figure 20 for the thermocouple-location diagram.

However, the differences in tube-surface temperature between two tubes with the same end cap were frequently greater than the differences between those with different end caps. The conclusion is that the variance in the cooling capacity of the three different end caps was less than could be measured with this test method.

Plots of temperature data from Test 112, which is a typical test at nominal flow rate, are shown in Appendix B.

Comparative pressure drops of the three different type end caps are shown in Table 12. A limited number of instrumentation channels are available in the laboratory where the tests were performed; therefore, it was not practical to measure the pressure immediately upstream and downstream of each end cap. The pressure drop was measured from a point just upstream of the end cap to the exit plenum, and includes the loss through approximately 18 in. of 3/8 in. diameter flexible hose and the expansion loss into the outlet plenum. In order to obtain a better comparison of end cap only pressure losses, an assumption had to be made regarding exit losses downstream of the end caps. Because all exit lines were of the same size and length and emptied into a common plenum, this loss was assumed to be 50% of the total. This value agrees fairly well with the calculated value of pressure drop for the flat end cap with GN_2 flowing at 0.34 lb/sec and 60°F. Table 12 shows the percent of improvement of each reduced ΔP end cap over the flat end cap, assuming exit losses to be equal and 50% of the total loss with the flat end-cap configuration.

TABLE 12

COMPARATIVE PRESSURE DROP OF FLAT END CAP P/N 1134995-2 AND
TWO REDUCED ΔP END CAPS P/N 1136178-1 AND P/N 1135860-1

Test No.	Flow Rate (lb/sec)	Flat End Cap P/N 1134995-2		Low ΔP End Cap P/N 1136178-1			Low ΔP End Cap P/N 1135860-1		
		Average Total Exit Loss (psi)	End Cap Only Pressure Drop Assuming 50% of Total (psi)	Average Total Exit Loss (psi)	End Cap Only Pressure Drop (psi)	Percent Improvement Over Flat End Cap	Average Total Exit Loss (psi)	End Cap Only Pressure Drop (psi)	Percent Improvement Over Flat End Cap
HT-12-101	0.223	36.5	18.3	28	9.7	47	30	11.7	36
-102	0.322	52.0	26.0	40	14.0	46	43	17.0	35
-103	0.430	63.5	31.8	49	17.2	46	52.5	20.7	35
-104	--	Questionable Data							
-105	0.323	84.5	42.3	68.5	26.2	38	72	29.7	30
-106	0.217	40.5	20.3	33	12.7	37	34.5	14.2	30
-107	0.422	66.0	33.0	51.5	18.5	44	54.5	21.5	35
-108	0.324	35.5	17.8	28	10.2	43	29	11.2	37
-109	0.224	24.5	12.3	19.5	7.2	41	20.5	8.2	33
-110	0.318	46.0	23.0	36.5	13.5	41	38.5	15.5	33
-111	0.425	61.0	30.5	48	17.5	43	49	18.5	39
-112	0.278	39.5	19.8	32	12.2	38	33	13.2	33
-113	0.190	27.5	13.8	22	8.2	41	23	9.2	33
-114	0.117	16.0	8.0	13	5.0	38	13	5.0	38
-115	0.230	32.5	16.3	26	9.7	40	27	10.5	34
-116	0.332	48.0	24.0	38	14.0	42	38	14.0	42
-117	0.447	63.0	31.5	50	18.5	41	51	19.5	38
-118	0.325	46.5	23.3	37	13.7	41	37	13.7	41
AVERAGE IMPROVEMENT OVER FLAT END CAP						41.6%	33.4%		

Part II

To verify that all sonic orifices were controlling the flow rate uniformly in all tubes, a flow calibration was performed on the flow of each tube individually with a flow-measuring orifice upstream of the sonic orifice. The results of this flow calibration showed a total variation in flow among the six tubes to be less than 3%, or $\pm 1\text{-}1/2\%$ from the nominal.

The exit configuration downstream of the end cap was modified from that used during water flow tests and from that which would normally be used for flat end cap.

The exit holes in test fixture P/N 1136177 were milled flat on the downstream side and round on the upstream side to facilitate installation of the special end caps; whereas the plastic test fixture, for water flow tests and previous nozzles with flat end caps, have had round holes downstream of the end cap.

Another difference affecting exit losses on these tests relative to water-flow tests and NERVA technology configuration was the lack of a radius on the inside corner at the entrance to the exit hole. No radius was called out on the fixture drawing, and it is assumed that the actual radius was from 0.005 to 0.015 in. A 0.125-in. radius as used in NERVA technology nozzles would have been comparable to the 0.250-in. radius on double-size plastic fixtures for water flow tests. As shown during water flow tests, a larger radius on the inside corner of the entrance to the exit hole would favor the modified end caps more than the flat end caps because it increases the minimum flow area under the flow-deflecting member.

End cap pressure loss data of these tests tend to substantiate the data from previous water flow tests but should be considered less reliable, and actual pressure drop comparisons should be made on the basis of the water flow tests.

Part II

VI. CONCLUSIONS AND RECOMMENDATIONS

Test data were not conclusive in showing one type of end cap to be better than another from the standpoint of heat transfer.

There was as much variation in measured tube-crown temperatures between end caps of the same type as there was among the different end caps. The measured tube-crown temperature varied as much as 30°F, which if a true temperature reading would represent a 38% change in the liquid side heat transfer coefficient. Computer output with a 38% change in liquid side heat transfer coefficient at full nuclear power conditions gave a 300°F change in predicted maximum hot-gas-side tube-wall temperature. This is pointed out to show the lack of accuracy in determining the relative heat transfer by this method.

In spite of the lack of confidence in the accuracy of heat-transfer data, there were no indications, from either liquid-crystal data or measured-temperature data, that the two types of reduced ΔP end caps did not cool as well as the flat end caps.

Because the indicated improvement, in the cooling ability of reduced ΔP end cap P/N 1135860-1 over P/N 1136178-1, is less than the accuracy obtainable by testing methods, P/N 1136178-1 is recommended as the best candidate for replacing flat end caps P/N 1139995-2 because of its better pressure drop characteristics as noted in Table 12 and in Table 5. For comparison with water flow test data from Part I it must be noted that end cap P/N 1135860-1 is similar to plastic end cap P/N 1135496-2; P/N 1136178-1 is similar to plastic end cap P/N 1135495-1; and P/N 1134995-2 is similar to plastic end cap P/N 1134728-1.

Appendix A

EXIT END CAP DATA AT 10 LB/SEC
WITH 1/4 IN. RADIUS ON TEST FIXTURE
DATA NORMALIZED FOR $P_1 = 100$ PSIG

End Cap P/N	Probe Immersion in.	P_I psig	P_1 psig	P_2 psig	P_3 psig	P_4 psig	P_5 psig	P_6 psig	P_T psig
1134728-1	3/4	110	100	98.9	101.6	103.0	96.9	85	107
	3/8	111	100	98.8	101.7	103.1	96.8	85	104
	1/16	110	100	99.2	101.7	103.5	96.9	85	103
1134689-1	3/4	105	100	98.9	103.2	104.5	95.9	89	107
	3/8	105	100	98.9	103.2	104.4	95.4	88	106
	1/16	106	100	98.9	103.6	104.8	95.9	88	104
1134690-1	3/4	107	100	98.9	103.6	105.0	95.4	87	107
	3/8	107	100	98.9	103.6	105.0	95.4	87.5	107
	1/16	106	100	98.9	103.6	104.7	95.4	88	105
1134691-1	3/4	106	100	98.9	103.2	104.3	95.4	87.5	107
	3/8	106	100	98.9	103.4	104.5	95.9	87	106
	1/16	106	100	98.9	103.4	104.5	95.9	87	104
1134696-1	3/4	106	100	99.0	103.7	105.3	95.5	86	106
	3/8	107	100	98.9	103.6	105.4	95.4	86	104
	1/16	106	100	98.9	103.6	105.4	95.4	86	106
1134697-1	3/4	107	100	98.9	103.2	106.4	95.4	86	104
	3/8	106	100	98.9	102.9	105.4	94.4	86	104
	1/16	106	100	98.9	102.9	105.6	94.4	86	107
1134697-3	3/4	106	100	98.9	102.9	105.8	94.4	87	104
	3/8	106	100	98.9	103.2	106.4	94.9	87	106
	1/16	106	100	98.9	103.2	106.8	94.9	87	109
1134729-1	3/4	107	100	98.9	102.7	98.4	94.9	87.5	107
	3/8	106	100	98.9	102.7	98.7	94.4	88	107
	1/16	106	100	98.9	102.7	98.7	94.4	87.5	102
1135461-1	3/4	106	100	98.8	97.7	100.6	91.8	86	107
	3/8	106	100	98.8	97.7	101.0	91.8	86	106
	1/16	106	100	98.8	97.7	99.5	92.8	87	101
1135461-2	3/4	107	100	98.9	99.6	101.8	93.4	87	107
	3/8	106	100	98.9	98.9	101.6	93.4	87	106
	1/16	106	100	98.9	98.9	100.7	93.4	87	102
1135462-1	3/4	106	100	99.0	103.0	104.8	91.0	85	106
	3/8	107	100	99.0	102.6	104.4	91.0	85	107
	1/16	107	100	99.0	102.6	104.0	91.0	85	105
1134691-4	3/4	106	100	98.9	103.6	105.0	98.3	91	107
	3/8	106	100	98.9	103.4	104.8	98.3	91	105
	1/16	106	100	98.8	103.3	104.7	98.2	91	104
1135495-1	3/4	106	100	98.8	103.1	103.9	97.7	91	107
	3/8	105	100	98.8	103.1	103.9	97.5	91	105
	1/16	105	100	98.9	103.2	103.8	97.5	92	104
1135496-1	3/4	104	100	98.8	103.5	105.3	98.8		107
	3/8	106	100	98.8	103.9	105.7	98.8	91	107
	1/16	106	100	98.8	103.9	105.6	98.8	91	106

Appendix A

EXIT END CAP DATA AT 10 LB/SEC
WITH 3/8 IN. RADIUS ON TEST FIXTURE
DATA NORMALIZED FOR $P_1 = 100$ PSIG

End Cap P/N	Probe Immersion in.	P_I psig	P_1 psig	P_2 psig	P_3 psig	P_4 psig	P_5 psig	P_6 psig	P_T psig
1134728-1	3/4	106	100	98.8	102.2	103.4	97.7	88	106
	3/8	106	100	98.7	102.0	103.3	97.6	88	104
	1/16	105	100	98.6	102.0	103.3	97.5	88	101
1134689-1	3/4	105	100	99.0	103.9	105.3	98.1	92	107
	3/8	105	100	98.9	103.7	105.1	98.0	92	106
	1/16	106	100	98.9	103.6	104.9	98.0	92	104
1134691-4	3/4	106	100	99.0	104.1	105.9	99.0	91.5	107
	3/8	106	100	99.0	104.1	105.7	99.0	91.5	106
	1/16	105	100	99.0	103.7	105.1	99.0	92	105
1135495-1	3/4	105	100	99.0	103.5	104.1	99.4	93	107
	3/8	106	100	99.0	103.7	104.2	99.4	93	105
	1/16	105	100	99.0	103.7	104.2	99.4	93	104
1135496-1	3/4	105	100	98.9	103.5	105.3	99.6	92	106
	3/8	106	100	98.9	103.6	105.3	99.6	92	106
	1/16	106	100	98.9	103.4	105.2	99.4	92	105
1135496-2	3/4	107	100	98.9	102.9	104.7	99.6	91	106
	3/8	107	100	98.9	103.2	105.0	99.4	91	106
	1/16	106	100	98.9	103.2	105.1	99.4	91	106
1135496-3	3/4	107	100	98.9	103.2	104.8	99.4	91	107
	3/8	107	100	98.8	103.5	105.2	99.4	90	107
	1/16	106	100	98.8	103.5	105.2	99.4	91	106

Appendix A

EXIT END CAP DATA AT 15 LB/SEC
WITH 1/4 IN. RADIUS ON TEST FIXTURE
DATA NORMALIZED FOR $P_1 = 95$ PSIG

End Cap P/N	Probe Immersion in.	P_I psig	P_1 psig	P_2 psig	P_3 psig	P_4 psig	P_5 psig	P_6 psig	P_T psig
1134728-1	3/4	115	95	92.8	99.5	102.5	88.8	65	109
	3/8	115	95	92.6	99.4	102.3	88.9	64	102
	1/16	115	95	93.3	99.8	103.4	89.2	64	100
1134689-1	3/4	107	95	92.8	102.9	106.0	87.8	70	112
	3/8	107	95	92.9	103.0	105.9	86.9	70	110
	1/16	107	95	92.8	103.3	106.2	87.3	70	105
1134690-1	3/4	107	95	92.8	103.3	106.4	87.8	70	111
	3/8	108	95	92.9	103.4	106.6	87.9	70	110
	1/16	107	95	92.9	103.4	106.3	87.9	70	107
1134691-1	3/4	107	95	92.8	102.9	105.1	88.3	69	111
	3/8	108	95	92.8	103.3	105.8	88.3	69	109
	1/16	109	95	92.8	103.1	105.6	88.3	69	104
1134696-1	3/4	108	95	92.8	103.3	106.9	87.3	68	108
	3/8	107	95	92.8	102.9	106.3	87.8	68	103
	1/16	107	95	92.9	103.4	107.7	87.4	67.5	108
1134697-1	3/4	108	95	92.9	101.6	106.7	86.9	67.5	102
	3/8	108	95	92.9	101.9	107.7	86.4	68	106
	1/16	108	95	92.9	101.8	107.9	86.4	68	111
1134697-3	3/4	107	95	92.8	101.7	107.5	86.3	69	103
	3/8	108	95	92.8	102.2	109.1	86.3	68	108
	1/16	108	95	92.8	102.2	109.8	86.3	68.5	114
1134729-1	3/4	107	95	92.9	101.9	94.3	85.9	70	110
	3/8	107	95	92.9	101.9	92.1	86.4	70	111
	1/16	107	95	92.9	101.6	92.2	85.7	70	101
1135461-1	3/4	108	95	92.7	92.0	97.8	79.7	67	112
	3/8	108	95	92.7	91.6	98.1	80.2	67	107
	1/16	108	95	92.7	90.9	94.9	80.7	68	99
1135461-2	3/4	107	95	92.8	94.6	99.3	81.8	67	113
	3/8	107	95	92.8	93.9	99.7	81.8	67.5	110
	1/16	108	95	92.8	93.9	99.0	81.8	67	102
1135462-1	3/4	107	95	93.0	101.3	104.5	76.0	64	111
	3/8	107	95	93.0	99.9	103.5	76.0	64	112
	1/16	107	95	92.9	99.8	103.0	75.9	64	108
1134691-4	3/4	106	95	92.8	103.0	106.3	92.1	75	109
	3/8	107	95	92.7	102.9	106.1	91.9	75	107
	1/16	107	95	92.7	102.8	105.8	91.9	75	106
1135495-1	3/4	107	95	92.8	102.5	103.9	91.0	76	111
	3/8	107	95	92.7	102.3	103.6	90.7	76	106
	1/16	107	95	92.7	102.5	103.6	91.1	76	104
1135496-1	3/4	105	95	92.7	103.3	107.2	92.7		110
	3/8	108	95	92.6	103.5	107.1	92.6	75	108
	1/16	107	95	92.6	103.4	106.9	92.6	75	107

Appendix A

EXIT END CAP DATA AT 15 LB/SEC
WITH 3/8 IN. RADIUS ON TEST FIXTURE
DATA NORMALIZED FOR $P_1 = 95$ PSIG

End Cap P/N	Probe Immersion in.	P_I psig	P_1 psig	P_2 psig	P_3 psig	P_4 psig	P_5 psig	P_6 psig	P_T psig
1134728-1	3/4	107	95	92.6	100.2	102.9	90.3	69	108
	3/8	105	95	91.9	99.1	101.9	89.2	67	105
	1/16	105	95	91.9	99.1	102.3	89.4	67	97
1134689-1	3/4	106	95	93.0	103.7	106.4	89.6	75	112
	3/8	106	95	93.0	103.7	106.4	89.7	75	110
	1/16	106	95	92.9	103.4	106.0	89.3	75	104
1134691-4	3/4	106	95	92.9	103.7	107.2	92.9	75	111
	3/8	106	95	92.9	103.7	107.1	92.9	75	108
	1/16	106	95	92.9	103.1	106.0	92.9	75	105
1135495-1	3/4	106	95	92.9	103.0	104.3	92.9	77	110
	3/8	106	95	92.9	103.0	104.2	92.9	77	105
	1/16	106	95	93.0	103.1	104.0	92.8	77	104
1135496-1	3/4	106	95	93.0	102.8	106.3	94.1	78	106
	3/8	106	95	92.9	103.0	106.8	94.0	76	107
	1/16	106	95	92.8	102.9	106.4	94.1	76	107
1135496-2	3/4	108	95	92.8	102.6	106.2	94.2	74	108
	3/8	109	95	92.8	102.4	106.2	94.1	74	107
	1/16	108	95	92.8	102.4	106.2	94.0	74	107
1135496-3	3/4	108	95	92.8	102.7	106.3	93.8	75	110
	3/8	108	95	92.8	102.3	105.9	93.7	74	107
	1/16	107	95	92.8	102.7	106.1	93.8	74	107

Appendix A

EXIT END CAP DATA AT 20 LB/SEC
WITH 1/4 IN. RADIUS ON TEST FIXTURE
DATA NORMALIZED FOR $P_1 = 85$ PSIG

End Cap P/N	Probe Immersion in.	P_I psig	P_1 psig	P_2 psig	P_3 psig	P_4 psig	P_5 psig	P_6 psig	P_T psig
1134728-1	3/4	119	85	81.1	93.0	98.4	73.0	28	109
	3/8	119	85	81.0	92.9	98.3	73.9	29	101
	1/16	118	85	82.5	94.4	100.5	75.6	30	94
1134689-1	3/4	106	85	81.5	99.5	104.6	70.5	38	116
	3/8	109	85	81.2	91.8	97.8	65.2	33	116
	1/16	108	85	81.0	101.6	107.4	65.5	32	104
1134690-1	3/4	106	85	81.5	99.9	105.3	69.5	37	114
	3/8	109	85	81.2	102.2	108.3	66.7	32	116
	1/16	109	85	81.2	102.2	107.4	66.7	31.5	110
1134691-1	3/4	107	85	81.7	99.7	104.0	70.7	37	114
	3/8	107	85	81.6	99.6	104.3	71.1	36.5	109
	1/16	106	85	81.5	99.9	103.5	70.5	36	102
1134696-1	3/4	107	85	81.5	100.3	106.4	59.0	25	109
	3/8	106	85	81.5	100.3	106.4	60.5	26	98
	1/16	107	85	81.5	99.9	106.8	60.5	27.5	109
1134697-1	3/4	106	85	81.5	97.5	107.3	66.5	31	100
	3/8	106	85	81.5	97.8	107.2	65.0	33	105
	1/16	105	85	81.5	97.5	108.0	66.0	32	111
1134697-3	3/4	106	85	81.5	97.5	108.0	64.0	33	101
	3/8	106	85	81.4	97.3	107.4	64.9	33.5	105
	1/16	107	85	81.4	97.3	108.5	66.9	36	115
1134729-1	3/4	107	85	81.5	97.0	84.4	66.0	38	113
	3/8	107	85	81.5	97.0	84.4	66.0	38	113
	1/16	106	85	81.5	97.0	84.4	66.5	38	95
1135461-1	3/4	106	85	81.2	80.1	85.9	57.7	32	117
	3/8	105	85	81.2	79.4	91.0	57.7	32	109
	1/16	106	85	81.2	78.0	85.0	59.2	35	93
1135461-2	3/4	105	85	81.4	84.3	93.3	61.4	33	117
	3/8	107	85	81.4	83.2	93.7	61.4	34	112
	1/16	106	85	81.4	83.4	91.2	61.9	34	95
1135462-1	3/4	107	85	81.6	94.6	102.5	29.6	13	117
	3/8	105	85	81.6	94.6	102.5	29.1	11	116
	1/16	106	85	81.6	94.2	101.4	28.6	11	108
1134691-4	3/4	104	85	81.2	99.3	104.9	79.8	48	114
	3/8	104	85	81.2	99.3	104.9	79.6	48	109
	1/16	105	85	81.3	99.4	104.6	79.7	48	108

Appendix A

EXIT END CAP DATA AT 20 LB/SEC
WITH 1/4 IN. RADIUS ON TEST FIXTURE
DATA NORMALIZED FOR $P_1 = 85$ PSIG

End Cap <u>P/N</u>	Probe Immersion <u>in.</u>	P_I <u>psig</u>	P_1 <u>psig</u>	P_2 <u>psig</u>	P_3 <u>psig</u>	P_4 <u>psig</u>	P_5 <u>psig</u>	P_6 <u>psig</u>	P_T <u>psig</u>
1135495-1	3/4	103	85	81.3	98.1	100.6	75.9	51	113
	3/8	103	85	81.3	98.0	100.3	76.2	52	104
	1/16	104	85	81.3	98.1	100.0	75.5	51	101
1135496-1	3/4	104	85	81.2	99.6	105.6	81	50	109
	3/8	103	85	81.1	99.5	105.7	80	50	107
	1/16	104	85	81.0	99.1	105.0	81	53	105

Appendix A

EXIT END CAP DATA AT 20 LB/SEC
WITH 3/8 IN. RADIUS ON TEST FIXTURE
DATA NORMALIZED FOR $P_1 = 85$ PSIG

End Cap P/N	Probe Immersion in.	P_I psig	P_1 psig	P_2 psig	P_3 psig	P_4 psig	P_5 psig	P_6 psig	P_T psig
1134728-1	3/4	104	85	81.2	94.4	98.2	77.6	37	108.2
	3/8	102	85	80.1	93.5	97.7	76.5	37	100.1
	1/16	103	85	79.8	93.2	97.5	76.4	37	89.8
1134689-1	3/4	105	85	81.5	100.3	105.0	71.6	47	114.5
	3/8	104	85	81.6	100.0	104.9	71.8	47	111.6
	1/16	104	85	81.6	100.2	105.0	72.4	47	101.6
1134691-4	3/4	104	85	81.5	100.3	106.0	81.1	50	111.5
	3/8	103	85	81.5	100.1	105.5	81.1	50	106.5
	1/16	104	85	81.5	99.9	105.0	81.0	50	104.5
1135495-1	3/4	103	85	81.5	99.2	101.3	80.1	53	112.5
	3/8	104	85	81.5	99.2	101.3	79.7	53	103.5
	1/16	104	85	81.6	99.3	100.9	79.8	53	101.6
1135496-1	3/4	104	85	81.6	99.3	105.7	82.7	50	106.6
	3/8	104	85	81.1	98.4	104.3	82.5	48	105.1
	1/16	104	85	81.4	99.1	105.1	82.8	49	105.4
1135496-2	3/4	107	85	81.4	98.6	104.7	83.5	47	107.4
	3/8	108	85	81.4	98.4	104.7	83.4	48	105.6
	1/16	107	85	81.5	99.2	106.1	83.5	48	106.8
1135496-3	3/4	107	85	81.4	99.5	105.6	82.8	48.5	111.4
	3/8	108	85	81.4	99.1	104.9	82.6	49	106.4
	1/16	108	85	81.5	99.2	105.0	82.8	48	106.0