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Nickel-Iron Battery System Safety

Final Report

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NICKEL-IRON BATTERY SYSTEM SAFETY

FINAL REPORT

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Abstract

Eagle-Picher Industries, under contract to JPL/DOE, conducted a literature search and experimental tests to characterize the generated flow rates of gaseous hydrogen (GH_2) and gaseous oxygen (GO_2) from an electrical vehicle (EV) nickel-iron battery system. The resulting gassing rates were used to experimentally evaluate the flame quenching capabilities of several candidate devices to prevent the propagation of flame within batteries having central watering/venting systems. The battery generated hydrogen (GH_2) and oxygen (GO_2) gasses were measured for a complete charge and discharge cycle. The data correlates well with accepted theory during strong overcharge conditions indicating that the measurements are valid for other portions of the cycle. Tests have confirmed that the gas mixture in the cells is always flammable regardless of the battery status.

Research of flame arrestor literature yielded little information regarding their operation with hydrogen-oxygen mixtures. It was indicated that a conventional flame arrestor would not be effective over the broad spectrum of gassing conditions presented by a nickel-iron battery. Four different types of protective devices were evaluated. A foam-metal arrestor design was successful in quenching GH_2-GO_2 flames, however; the application of this flame arrestor to individual cell or module protection in a battery is problematic..

A possible rearrangement of the watering/venting system to accept the partial protection of simple one-way valves is presented. This in combination with the successful foam-metal arrestor as main vent protection, could result in a significant improvement in battery protection. This concept was not tested.

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1.0 Introduction

Recent testing of the nickel-iron battery system has demonstrated several positive attributes when assessing its viability as a near-term power source for an electric vehicle propulsion system. At the same time, it has exhibited gassing characteristics which are not desirable. The fact that high quantities of flammable gas are generated by this type of battery system presents a concern regarding its safety. The nickel-iron battery uses a relatively large amount of water in ordinary and deep cycle service. Typically a battery which is in daily use could require maintenance biweekly or even weekly when compact designs disallow excess electrolyte in each cell. The problem with electrolyte maintenance arises from the number of cells in a vehicle battery. Maintaining 80 to 90 or more cells on a weekly basis would be intolerable. Consequently, a maintenance aid which in effect reduces the time required, the tediousness of the job and increases the probability that each cell is properly filled, is practically mandatory. Such a watering system has been devised and it has been proved to be satisfactory for the interim. However, the same system which facilitates the watering of a cell, makes the whole battery more vulnerable to explosive conditions. As it is presently designed the vent/watering system manifolds the cells to a common point. One ignition incident propagates flame or detonation to all the cells on the manifold. It is the manifolding of cells which magnifies the seriousness of an accidental ignition; all the cells are in jeopardy and the volume of gas ignited is multiplied by the same factor. At the same time the nickel-iron battery may be safer in another respect by virtue of that same manifold. The battery generated atmosphere has been demonstrated to be flammable under normal conditions. Therefore, venting all cells to one safe location external to the vehicle is more desirable than individual cell vents to the battery compartment. In the latter case the whole battery compartment head space could become a large volume full of flammable gasses. In effect the problem is reduced to having a more desirable solution which is to devise a means of preventing flame from entering and propagating through the watering/vent manifold.

The purpose of this contracted effort was to determine the applicability of in-line flame arrestors to a common vent/watering manifold in a battery system. The work included the following appropriate subtasks:

1. A literature search of the flame arrestor technology.
2. Analyze the gassing characteristics of the nickel-iron battery.
3. Develop flame arrestors or other methods to quench or interrrupt flame propagation.
4. Evaluate alternative approaches to vent/watering manifold safety.

The literature search was directed toward papers and reports which exhibited the key words hydrogen, oxygen, and high-speed flames. The literature was not encouraging. High-velocity flames are the most difficult to quench and hydrogen-oxygen flames can accelerate to the point of detonation. Therefore, flame arrestor placement at the very exit of a vent line is the only location likely to be effective in quenching a low-velocity flash-back flame. This was demonstrated with foam-metal flame arrestors which successfully quenched repeated ignitions when positioned at the end of the vent tubing. With a "lead-in" vent line only 12 inches long the flame accelerated to a high-speed flame and they lost their effectiveness. However, these designs are a qualified success. An end of vent (exit) arrestor will quench a flash-back flame without consuming battery energy, as required by an air dilution fan.

Water traps are simple effective barriers to flame propagation in tubes and pipes. The flame arrestor test station flow tubing included one, to protect the gas generator battery during all tests. In a practical battery they are not appropriate because, low temperatures will freeze the water. Electrolyte or other antifreeze solutions cannot be used because these are in-line with the watering system.

A simple one-way valve in conjunction with a blow-out disc is a possible solution to in-line module protection. Flame arrestor consisting of a molded rubber flapper valve was effective for twelve repeated ignitions before a high-speed flames penetrated to the module side of the barrier.

Special gas collection cells were built to evaluate the gassing characteristics of the nickel-iron battery. Extra layers of separator and plastic barriers in the cell gas space served to isolate the gas from the test electrode from the other electrodes. Oxygen was collected from the central positive-nickel electrode of one cell. Another cell with a central negative-iron electrode was tested under identical charge and discharge conditions to collect the corresponding hydrogen which would be evolved in a battery cell. The data correlated well with the known stoichiometric, hydrogen to oxygen volume ratio of 2, conditions for full overcharge indicating that the collection cells were adequate in isolating the evolved gas of the test electrodes. The cell atmosphere shifts from hydrogen rich to oxygen rich, but it is always flammable. The data are presented in tabular and graphic form.

2.0 Technical Discussion

2.1 Literature Search

A literature search was conducted with the assistance of Missouri Southern State College of Joplin, Missouri. The key words used in the literature search were flame arrestors, hydrogen-oxygen gas mixture, high-speed flames, and combustion. The key word search thru the computer net resulted in a pertinent list of articles. Those publication that apparently would help in understanding flame arrestors were ordered. A list of the publications obtained from the computer search is included in the References, Section No. 6, of this report.

2.2 Nickel-Iron Cell Gassing Characteristic

A cell gassing study was initiated to determine the amount and composition of the gas being evolved during cell operation. Two specially designed cells were built. Each cell was constructed so that the oxygen and hydrogen gasses evolved were vented separately. Each of the three electrodes was completely enveloped with the micro porous PVC separator. At near zero pressure differential the wet separator is an effective gas barrier. The space above the plates was divided by thin plastic sheets into three compartments. The thin sheets were sealed to the cell cover and edges. They extended below the electrolyte level and the open tops of the separator envelopes in a manner to keep the gas from the central electrode separate from the rest. The gas produced by the central electrode was piped to the water displacement measuring apparatus. The gas produced by the two outer electrodes was vented to the atmosphere.

The gas volume measuring equipment is shown in Figure 1. It consisted of a graduated cylinder, an open water reservoir mounted on a height adjusting apparatus, the appropriate tubing, and valves to control the flow of gas and water. This test set-up was in an acrylic plastic protective enclosure.

In operation, the equipment collects the gas to be measured in the graduated cylinder under atmospheric temperature and pressure conditions. The adjustable water reservoir is used to compensate for the varying water level in the graduated cylinder as gas is accumulated. Each measurement was an accurately timed interval over which a volume of gas was collected. Gas collection and timing was initiated by closing the valve at the top of the cylinder. The equipment was reset by merely opening the valve to vent the gas while readjusting the water level to "0". Measurements were made at 30 minute intervals during the first three hours and at 15 minute intervals for the remainder of the six hour charge at the C/6 rate. The 15 minute measurements were continued for one hour after the end of charge. The frequency was then reduced to one per hour.

The gassing characteristic can be best interpreted from the results shown in Figures 2, 3 and 4. While charging, the gassing rate in effect changes from near the minimum stand rate to the maximum of 100% water dissociation in the final stages of overcharge. Early in the charge cycle the cell atmosphere is hydrogen rich. Later in the charge cycle as the positive electrode starts to gas, the atmosphere shifts to oxygen rich before becoming stoichiometric during the overcharge period. During stand, after discharge, the gassing rate is a minumum. The gassing during stand is somewhat complicated. Immediately after charge termination, both electrodes continue to evolve gas. The positive electrode yields more oxygen indicating the decomposition of some higher oxides of the active nickel compounds. However, even the iron electrode required four hours time to reach the quiescent level of 0.17 cc/min. This might indicate the occurence of a type of surface passivation. Again, the ratio of hydrogen to oxygen is below stoichiometric. The atmosphere is a hydrogen lean mixture as shown in Table I and Figure 5. These data can be recalculated to represent the gassing rates of a full size cell or battery. Two full size nickel-iron cells, VNF-150 and NIF-270, were run to measure the gas evolved by each cell. The gassing rate for all the nickel-iron cells (F-II, F-III, VNF-150 & NIF-270) displays the same shape curve and is dependent upon the charge rate. See Table II, and Figure 6, for the gassing rate of the VNF-150; Table III and Figure 7, for the NIF-270. The calculated gassing characteristic corresponds well with the actual measurements on the cells.

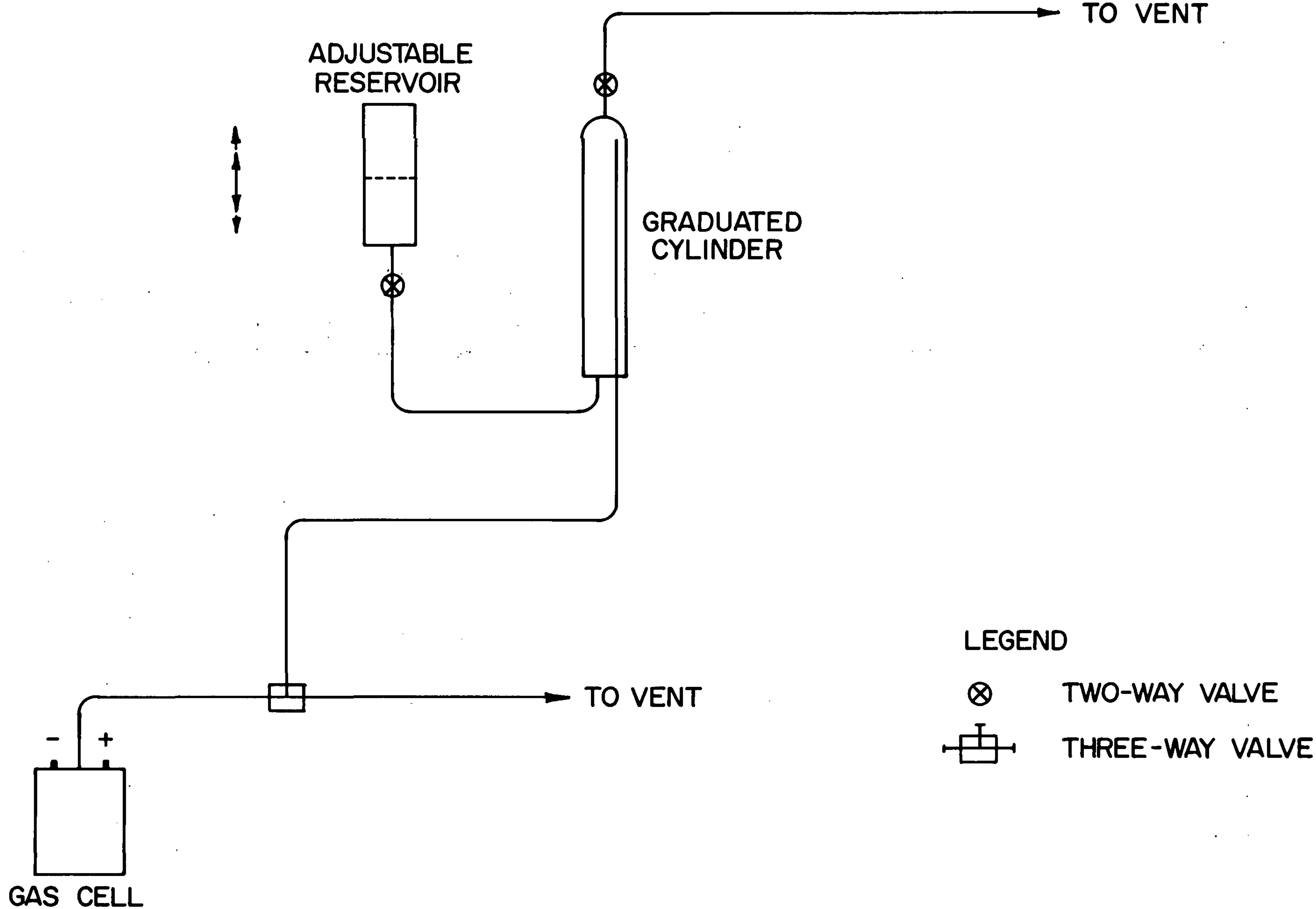
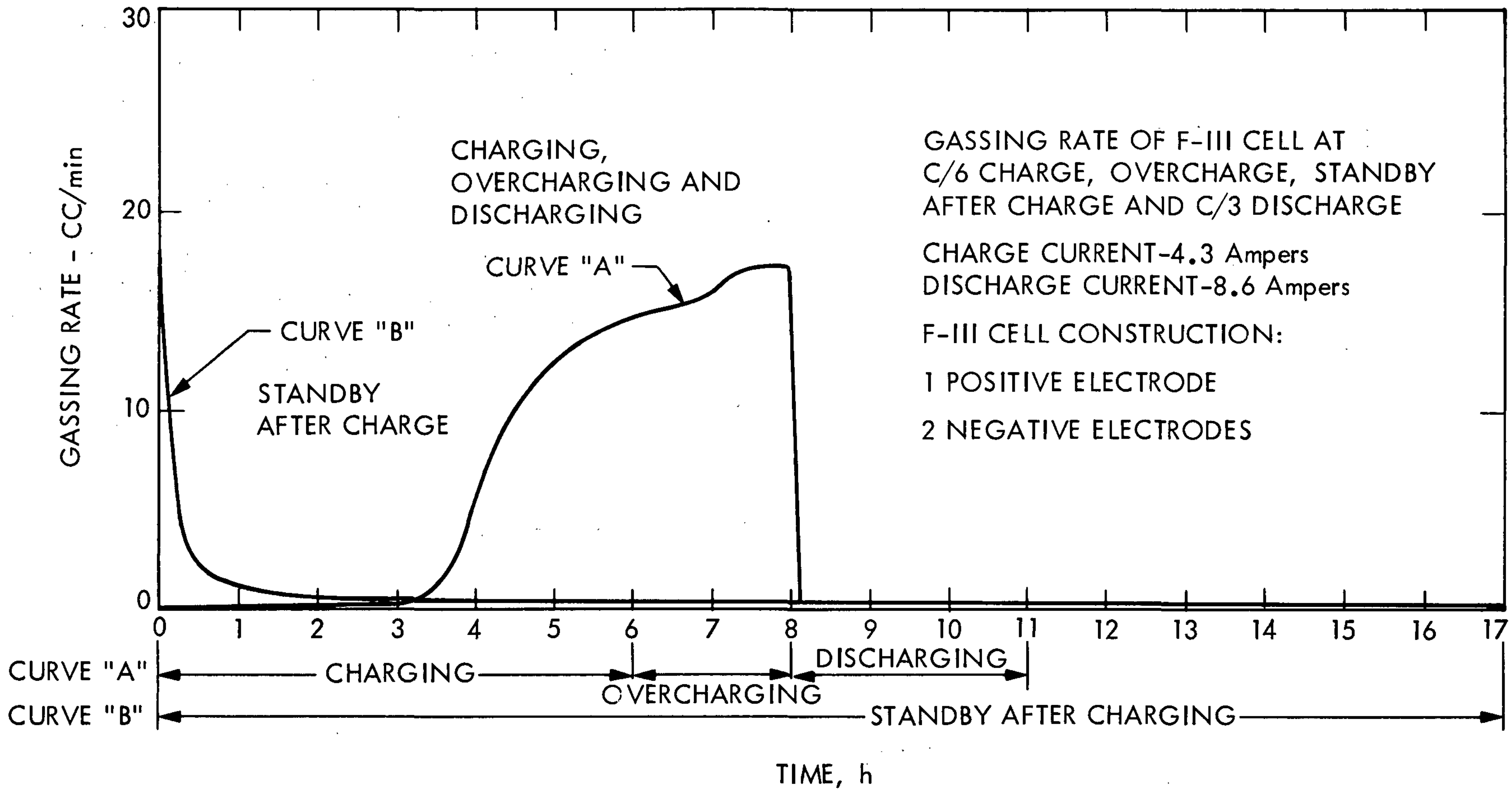
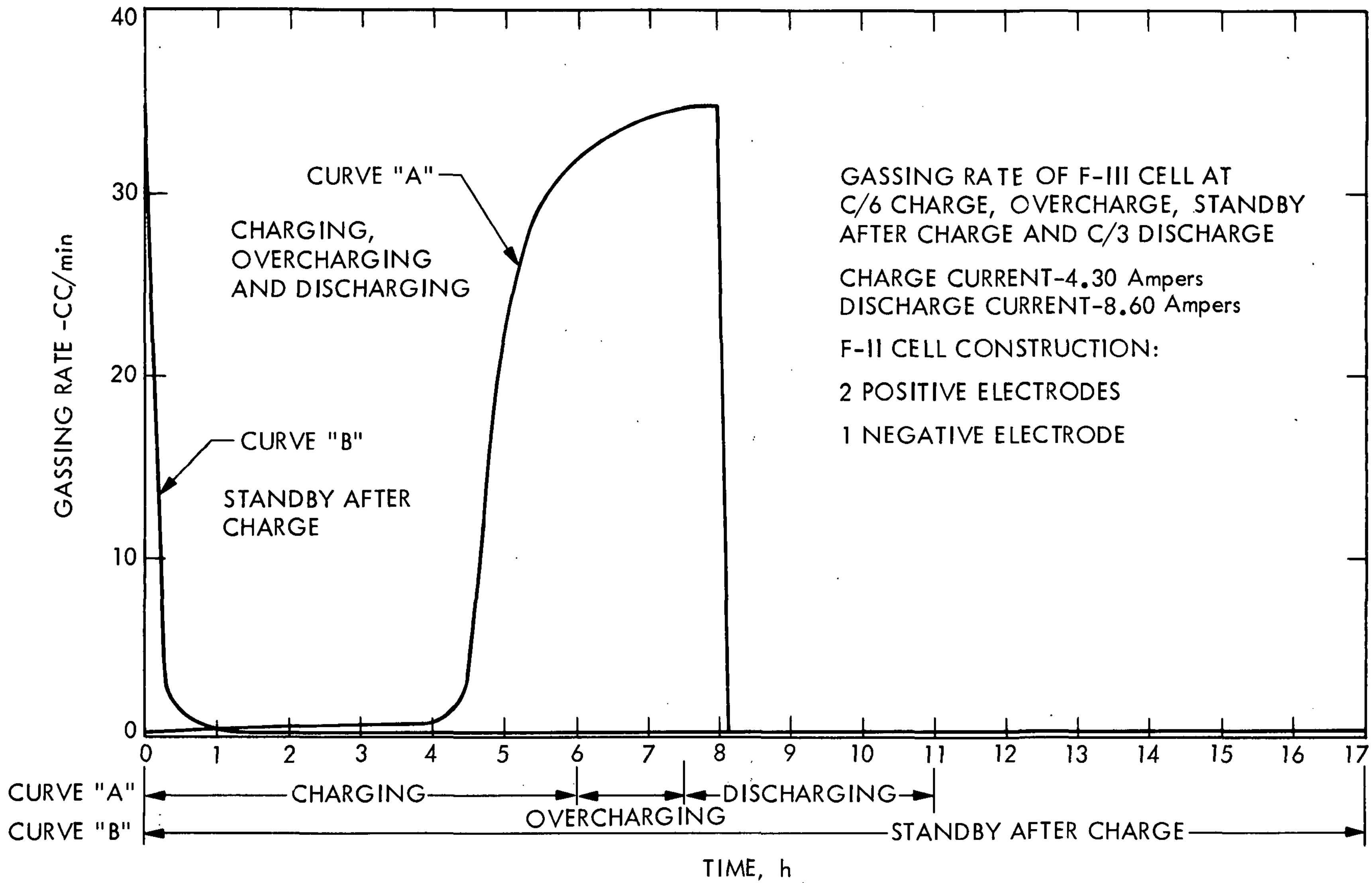


FIGURE I. CELL GAS MEASUREMENT SET-UP


GASSING RATE OF F-III CELL AT
C/6 CHARGE, OVERCHARGE, STANDBY
AFTER CHARGE AND C/3 DISCHARGE
CHARGE CURRENT-4.3 Ampers
DISCHARGE CURRENT-8.6 Ampers
F-III CELL CONSTRUCTION:
1 POSITIVE ELECTRODE
2 NEGATIVE ELECTRODES
CHARGING,
OVERCHARGING AND
DISCHARGING
CURVE "A"
CURVE "B"
STANDBY
AFTER CHARGE
GASSING RATE - CC/min
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
CURVE "A"
CHARGING
OVERCHARGING
DISCHARGING
CURVE "B"
STANDBY AFTER CHARGING
TIME, h


GASSING RATE OF F-III CELL AT
C/6 CHARGE, OVERCHARGE, STANDBY
AFTER CHARGE AND C/3 DISCHARGE
CHARGE CURRENT-4.30 Amperes
DISCHARGE CURRENT-8.60 Amperes
F-II CELL CONSTRUCTION:
2 POSITIVE ELECTRODES
1 NEGATIVE ELECTRODE
CURVE "A"
CHARGING,
OVERCHARGING
AND DISCHARGING
CURVE "B"
STANDBY AFTER
CHARGE
GASSING RATE -CC/min
0
10
20
30
40
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
CURVE "A"
CURVE "B"
CHARGING
OVERCHARGING
DISCHARGING
STANDBY AFTER CHARGE
TIME, h

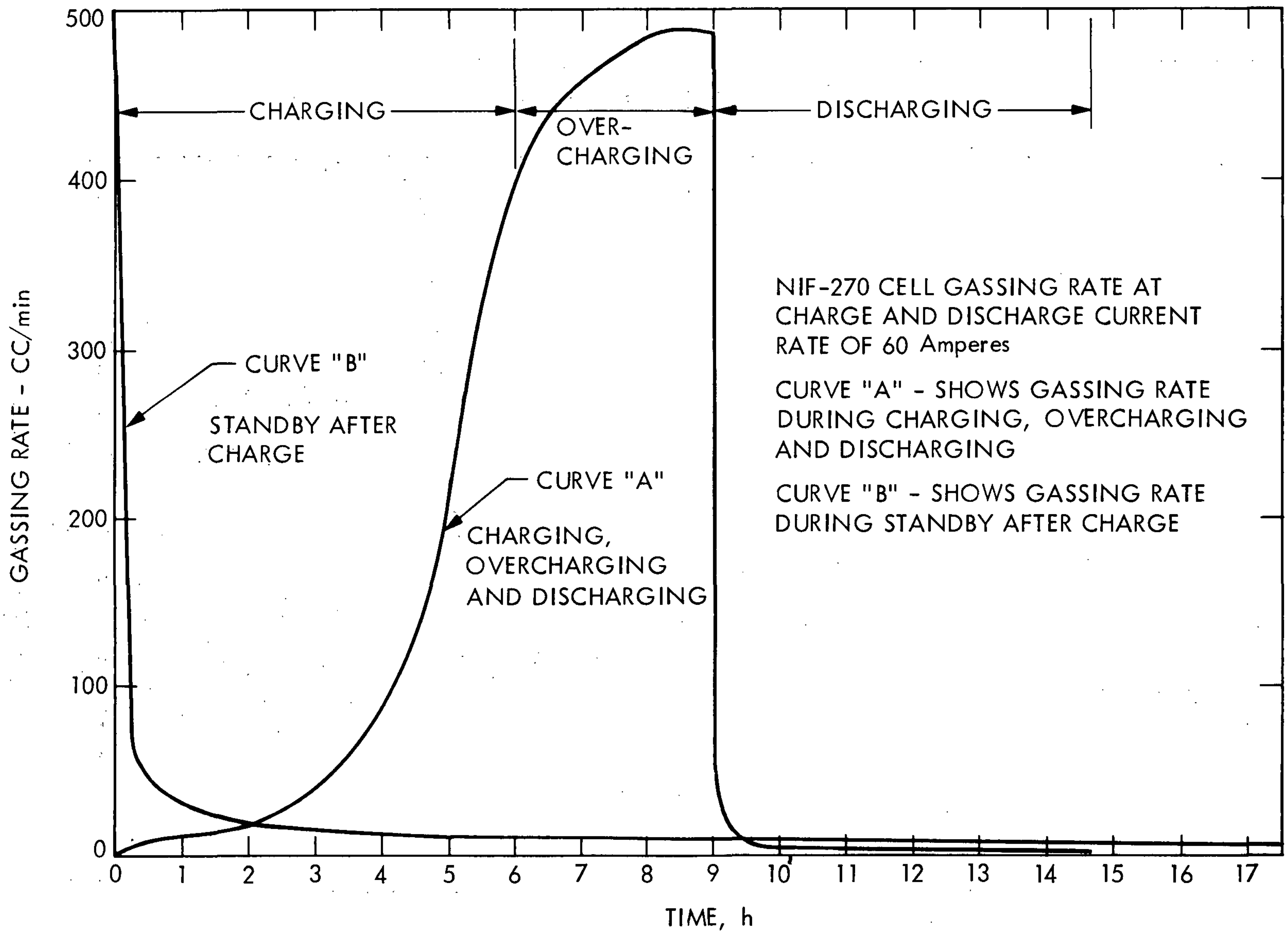

NIF-270 CELL GASSING RATE AT
CHARGE AND DISCHARGE CURRENT
RATE OF 60 Amperes
CURVE "A" - SHOWS GASSING RATE
DURING CHARGING, OVERCHARGING
AND DISCHARGING
CURVE "B" - SHOWS GASSING RATE
DURING STANDBY AFTER CHARGE
CHARGING
OVER-
CHARGING
DISCHARGING
CURVE "B"
STANDBY AFTER
CHARGE
CURVE "A"
CHARGING,
OVERCHARGING
AND DISCHARGING
GASSING RATE - CC/min
TIME, h
0
100
200
300
400
500
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

TABLE I

AVERAGE GASSING RATES

AND STOICHIOMETRIC ANALYSIS DATA

TIME ON CYCLE hrs	F-III CELL O_2 GAS RATE cc/min.	F-II CELL H_2 GAS RATE cc/min	TOTAL GASSING RATE cc/min.	RATIO OF H_2 TO O_2	CYCLE MODE & OBSERVATION
.50	0.00 *	0.37	0.37	____	CHARGING @ C/6 4.3 amp
1.00	0.00 *	0.50	0.50	____	
1.50	0.00 *	0.50	0.50	____	
2.00	0.00 *	0.50	0.50	____	
2.50	0.00 *	0.51	0.51	____	
3.00	0.02	0.55	0.57	27.50	
3.25	0.18	0.60	0.78	3.33	
3.50	1.04	0.65	1.69	0.63	
3.75	2.73	0.77	3.50	0.28	
4.00	4.85	0.93	5.78	0.19	
4.25	8.17	1.38	9.55	0.17	
4.50	9.99	4.15	14.14	0.42	
4.75	11.46	17.01	28.47	1.48	
5.00	12.99	23.01	36.00	1.77	
5.25	13.20	26.89	40.09	2.04	
5.50	13.80	29.39	43.19	2.13	
5.75	14.43	30.78	45.21	2.13	
6.00	14.71	31.61	46.32	2.15	
0.25	14.81	32.61	47.42	2.20	OVER-CHARGING C/6 @ 4.3 amp
0.50	15.15	33.15	48.30	2.19	
0.75	15.53	33.71	49.24	2.17	
1.00	15.83	33.71	49.54	2.13	
1.25	16.30	34.48	50.78	2.12	
1.50	17.15	34.68	51.83	2.02	
1.75	17.15	34.68	51.83	2.02	
2.00	17.20	34.68	51.88	2.02	

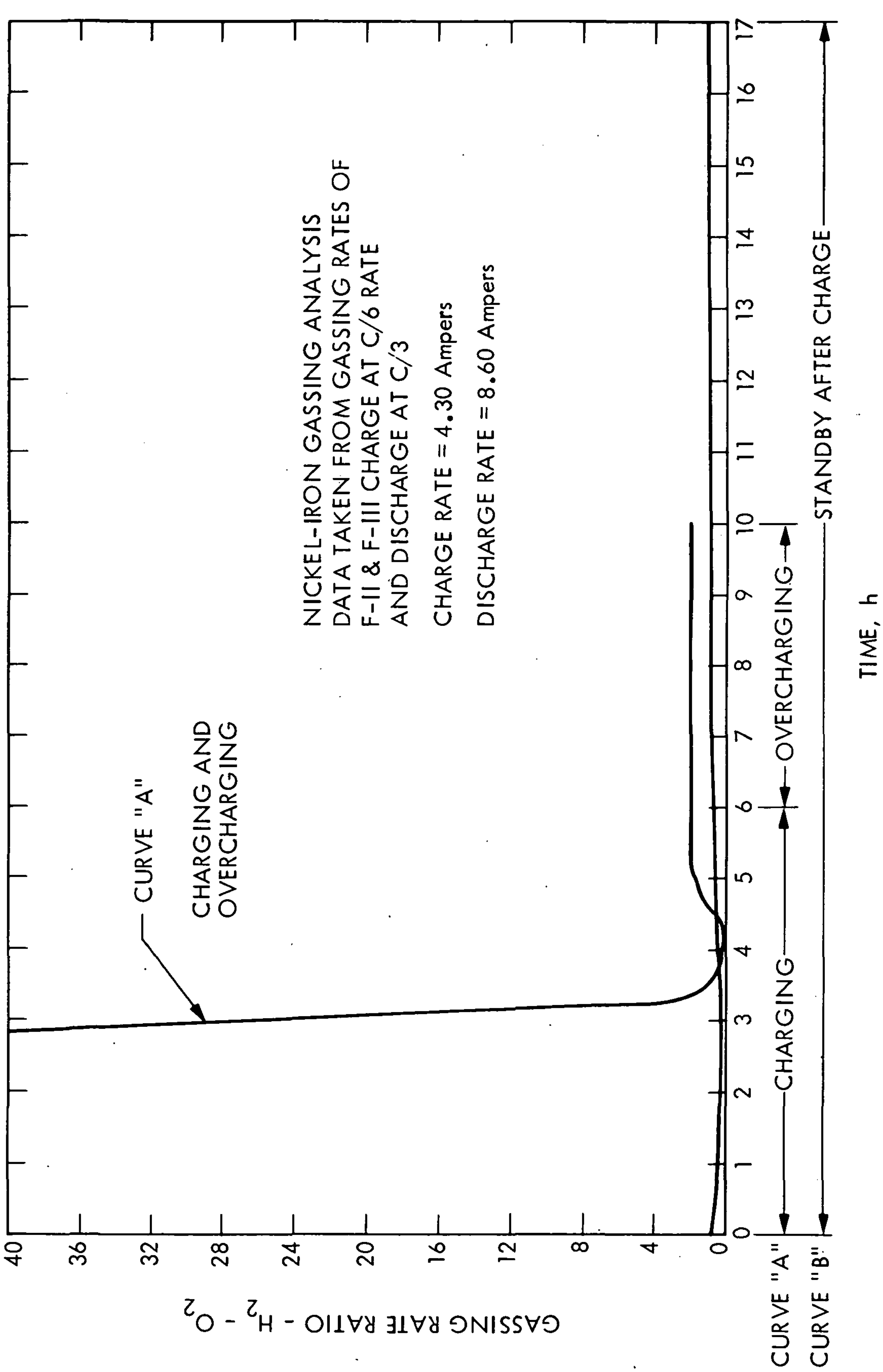
* GASSING IS EVIDENT, BUT NOT MEASUREABLE.

TABLE I (continued)

AVERAGE GASSING RATES
AND STOICHIOMETRIC ANALYSIS DATA

TIME ON CYCLE hrs	F-III CELL O_2 GAS RATE cc/min.	F-II CELL H_2 GAS RATE cc/min.	TOTAL GASSING RATE cc/min.	RATIO OF H_2 TO O_2	CYCLE MODE & OBSERVATION
0.25	4.89	2.95	7.84	0.60	STANDBY AFTER CHARGE. 0 amp
0.50	2.00	1.00	3.00	0.50	
0.75	1.53	0.66	2.19	0.43	
1.00	1.09	0.31	1.40	0.28	
2.00	0.60	0.31	0.91	0.52	
3.00	0.54	0.18	0.72	0.21	
4.00	0.38	0.17	0.55	0.45	
5.00	0.26	0.17	0.43	0.65	
6.00	0.23	0.17	0.40	0.74	
7.00	0.21	0.17	0.38	0.81	
8.00	0.19	0.17	0.36	0.89	
17.00	0.17	0.17	0.34	1.00	

NO SIGNIFICANT GASSING OCCURED DURING DISCHARGE CYCLE......



NICKEL-IRON GASSING ANALYSIS
DATA TAKEN FROM GASSING RATES OF
F-II & F-III CHARGE AT C/6 RATE
AND DISCHARGE AT C/3
CHARGE RATE = 4.30 Ampers
DISCHARGE RATE = 8.60 Ampers
CURVE "A"
CHARGING AND
OVERCHARGING
GASSING RATE RATIO - H2 - O2
40
36
32
28
24
20
16
12
8
4
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
CHARGING
OVERCHARGING
STANDBY AFTER CHARGE
CURVE "A"
CURVE "B"
TIME, h

TABLE II

TYPE OF TEST GAS MEASUREMENT

VNF-150 CELL GASSING RATE MEASUREMENT

DATE: 8 July 1983

SPECIMEN NO. VNF-150 (502-H2C)CELL

TIME OF DAY	TIME ON CYCLE hrs	CURRENT amp	VOLTAGE volts	GAS VOLUME IN "cc"	GAS COLLECTION TIME. mins.	GASSING RATE cc/min.	CYCLE MODE	COMMENTS
0800	0.00	30.00	1.400	0.00	0.00	0.00	Charge	Charging
0830	0.50	30.00	1.480	30.00	10.927	2.75	Charge	Charging
0900	1.00	30.00	1.508	35.00	9.48	3.69	Charge	Charging
0930	1.50	30.00	1.517	25.00	5.94	4.21	Charge	Charging
1000	2.00	30.00	1.524	35.00	7.44	4.70	Charge	Charging
1030	2.50	30.00	1.530	30.00	5.38	5.58	Charge	Charging
1100	3.00	30.00	1.537	30.00	4.245	7.07	Charge	Charging
1115	3.25	30.00	1.542	20.00	2.40	8.33	Charge	Charging
1130	3.50	30.00	1.545	35.00	3.965	8.83	Charge	Charging
1145	3.75	30.00	1.549	70.00	6.910	10.13	Charge	Charging
1200	4.00	30.00	1.553	25.00	1.796	13.92	Charge	Charging
1215	4.25	30.00	1.556	35.00	2.287	15.30	Charge	Charging
1230	4.50	30.00	1.560	50.00	2.763	18.09	Charge	Charging
1245	4.75	30.00	1.565	25.00	1.033	24.19	Charge	Charging
1300	5.00	30.00	1.569	50.00	1.740	28.74	Charge	Charging
1315	5.25	30.00	1.573	100.00	3.155	31.70	Charge	Charging

TABLE II (continued)

TYPE OF TEST GAS MEASUREMENT — VNF-150 CELL GASSING RATE MEASUREMENT — DATE: 8 July 1983

SPECIMEN NO. VNF-150 (502-H_2C)CELL

TIME OF DAY	TIME ON CYCLE hrs	CURRENT amp	VOLTAGE volts	GAS VOLUME IN "cc"	GAS COLLECTION TIME. mins.	GASSING RATE cc/min.	CYCLE MODE	COMMENTS
1330	5.50	30.00	1.577	100.00	2.53	39.47	Charge	Charging
1345	5.75	30.00	1.583	100.00	2.235	44.74	Charge	Charging
1400	6.00	30.00	1.588	100.00	1.845	54.20	Charge	Charging
1415	.25	30.00	1.597	100.00	1.578	63.37	Charge	Overcharge
1430	.50	30.00	1.605	100.00	1.390	71.94	Charge	Overcharge
1445	.75	30.00	1.615	100.00	1.178	84.83	Charge	Overcharge
1500	1.00	30.00	1.630	100.00	0.967	102.92	Charge	Overcharge
1515	1.25	30.00	1.639	100.00	0.872	114.72	Charge	Overcharge
1530	1.50	30.00	1.648	100.00	0.770	129.87	Charge	Overcharge
1545	1.75	30.00	1.654	100.00	0.677	147.78	Charge	Overcharge
1600	2.00	30.00	1.658	150.00	0.925	162.16	Charge	Overcharge
1615	2.25	30.00	1.659	100.00	0.568	175.95	Charge	Overcharge
1630	2.50	30.00	1.659	100.00	0.542	184.62	Charge	Overcharge
8-11-83 1030	START CHARGING 30 AMPS TILL E= 1.659 AND TAKE RD6 AFTER 15 MIN.							Continue Overcharge
1045	2.75	30.00	1.673	100.00	0.485	206.28	Charge	Overcharge
1100	3.00	30.00	1.671	100.00	0.433	230.76	Charge	Overcharge

TABLE II (continued)

TYPE OF TEST GAS MEASUREMENT

VNF-150 CELL GASSING RATE MEASUREMENT

DATE: 11 July 1983

SPECIMEN NO. VNF-150 (502-H_2 C)CELL

TIME OF DAY	TIME ON CYCLE hrs	CURRENT amp	VOLTAGE volts	GAS VOLUME IN "cc"	GAS COLLECTION TIME. mins.	GASSING RATE cc/min.	CYCLE MODE	COMMENTS
1115	3.25	30.00	1.670	100.00	0.445	224.72	Charge	Overcharge
1130	3.50	30.00	1.668	100.00	-.435	229.88	Charge	Overcharge
1145	3.75	30.00	1.666	100.00	0.425	235.29	Charge	Overcharge
1200	4.00	30.00	1.665	100.00	0.413	241.94	Charge	Overcharge
1310	5.17	30.00	1.662	100.00	0.390	256.41	End of Overcharge	Put on O.C. After C.
1315	0.083	00.00	1.506	100.00	1.197	83.56	O.C.	O.C.
1320	0.166	00.00	1.487	100.00	1.852	45.77	O.C.	O.C.
1325	0.25	00.00	1.475	50.00	1.098	45.52	O.C.	O.C.
1410	1.00	00.00	1.450	180.00	9.882	18.22	O.C.	O.C.
1510	2.00	00.00	1.442	25.00	2.000	12.05	O.C.	O.C.
1610	3.00	00.00	1.436	25.00	2.075	8.02	O.C.	O.C.
1710	4.00	00.00	1.433	20.00	3.117	7.50	O.C.	O.C.
1910	6.00	00.00	1.428	20.00	3.030	6.62	O.C.	O.C.
2110	8.00	00.00	1.424	10.00	1.750	5.71	O.C.	O.C.
2310	10.00	00.00	1.422	10.00	2.000	5.00	O.C.	O.C.
0810	19.00	00.00	1.414	30.00	8.178	3.67	O.C.	O.C.

ON NEXT RUN, CHARGE CELL TILL E= 1.659 VOLT AND START DISCHARGING. TAKE READING AFTER 5 MINS. - 10 MINS. - 15 MINS. THEN 30 MIN - 1 HR AND EVERY HOUR THEREAFTER.....

TABLE II (continued)

TYPE OF TEST GAS MEASUREMENT (H_2-O_2) VNF-150 CELL GASSING RATE MEASUREMENT

DATE: 7 July 1983

SPECIMEN NO. VNF-150 (H2C)

TIME OF DAY	TIME ON CYCLE hrs	CURRENT amps	VOLTAGE volts	GAS VOLUME IN "cc"	GAS COLLECTION TIME. mins.	GASSING RATE cc/min.	CYCLE MODE	COMMENTS
0935		30.00	1.674	100.00	0.352	284.36	Charging	
0940		30.00	1.674	100.00	0.345	289.85	Charging	
CELL WAS PUT TO DISCHARGE AFTER TAKING 2 SUCCESSIVE READINGS ON CHARGE								
0945	0.000	60.00	1.332	100.00	1.050	95.24	Discharge	
0950	0.083	60.00	1.313	15.00	1.185	12.65	Discharge	
0955	0.166	60.00	1.299	10.00	1.773	5.64	Discharge	
1000	0.25	60.00	1.283	5.00	1.907	2.62	Discharge	
1015	0.50	60.00	1.245	5.00	8.827	0.56	Discharge	
1045	1.00	60.00	1.221	10.00	21.173	0.47	Discharge	
1115	1.50	60.00	1.202	17.00	30.00	0.56	Discharge	
1145	2.00	60.00	1.181	19.00	30.00	0.63	Discharge	
1215	2.50	60.00	1.158	17.00	30.00	0.56	Discharge	
1245	3.00	60.00	1.127	12.00	30.00	0.40	Discharge	
1315	3.50	60.00	1.037	5.00	30.00	0.17	Discharge	

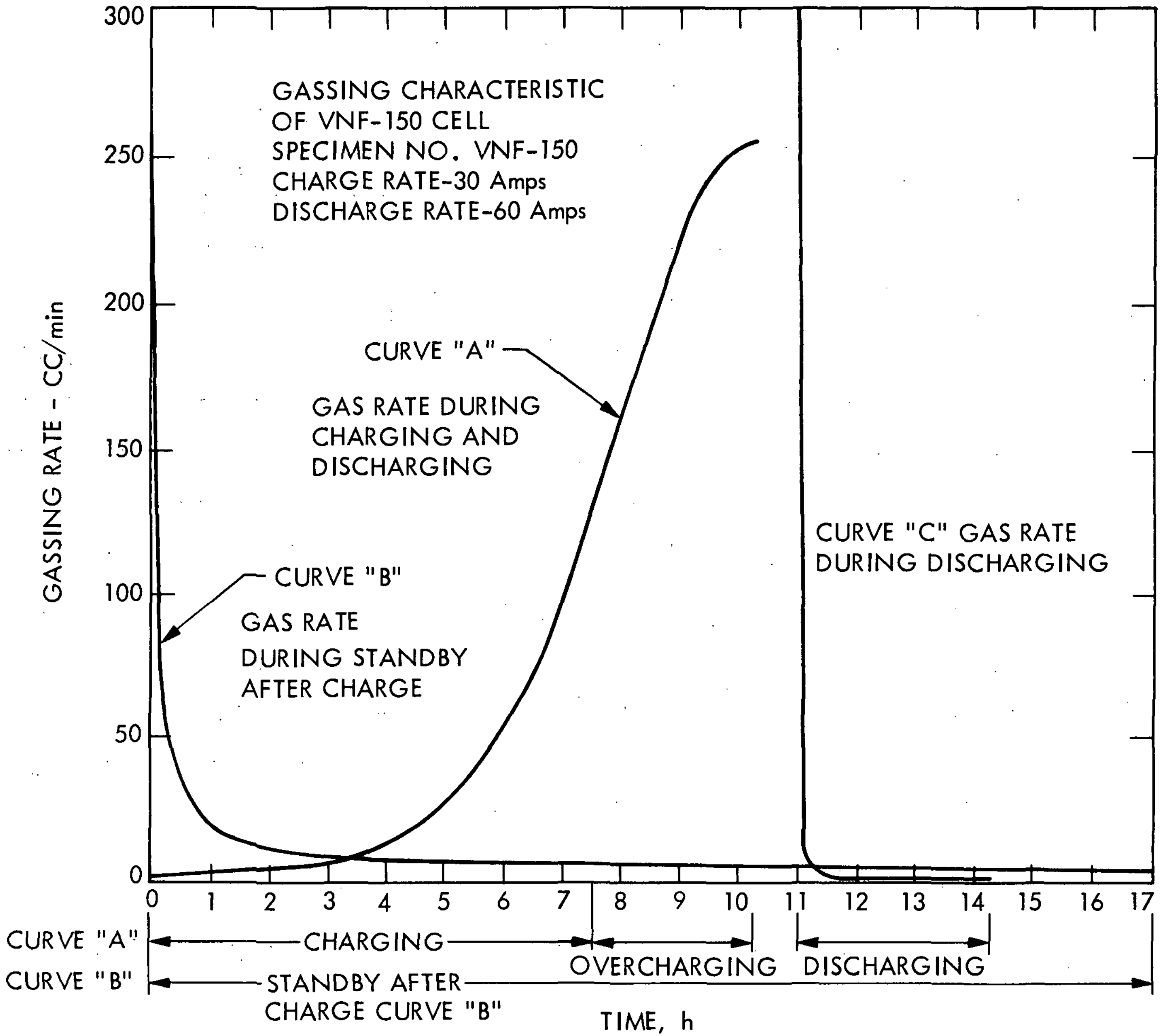

GASSING CHARACTERISTIC
OF VNF-150 CELL
SPECIMEN NO. VNF-150
CHARGE RATE-30 Amps
DISCHARGE RATE-60 Amps
CURVE "A"
GAS RATE DURING
CHARGING AND
DISCHARGING
CURVE "B"
GAS RATE
DURING STANDBY
AFTER CHARGE
CURVE "C" GAS RATE
DURING DISCHARGING
GASSING RATE - CC/min
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
CURVE "A"
CHARGING
OVERCHARGING
DISCHARGING
CURVE "B"
STANDBY AFTER
CHARGE CURVE "B"
TIME, h

TABLE III

NIF-270 CELL GASSING RATE MEASUREMENT

TYPE OF TEST GAS MEASUREMENT

DATE: 2 August 83

SPECIMEN NO. NIF - 270

TIME OF DAY	TIME ON CYCLE (HRS)	CURRENT AMP	VOLTAGE VOLTS	GAS VOLUME IN "CC"	GAS COLLECTION TIME. MINS.	GASSING RATE CC/MIN.	CYCLE MODE	COMMENTS
0800	0.00	60.00	1.460	0.00	0.00	0.00	START OF CHARGE	
0830	0.50	60.00	1.520	50.00	5.20	9.62	CHARGING	
0900	1.00	60.00	1.542	50.00	4.65	10.75	CHARGING	
0930	1.50	60.00	1.553	50.00	3.98	12.55	CHARGING	
1000	2.00	60.00	1.561	50.00	3.02	16.57	CHARGING	
1030	2.50	60.00	1.570	50.00	1.83	27.32	CHARGING	
1100	3.00	60.00	1.577	100.00	2.59	38.66	CHARGING	
1115	3.25	60.00	1.582	100.00	2.00	50.00	CHARGING	
1130	3.50	60.00	1.588	100.00	1.70	59.00	CHARGING	
1145	3.75	60.00	1.595	100.00	1.39	71.77	CHARGING	
1200	4.00	60.00	1.603	100.00	1.16	86.21	CHARGING	
1215	4.25	60.00	1.612	100.00	0.968	103.27	CHARGING	
1230	4.50	60.00	1.622	100.00	0.78	128.21	CHARGING	
1245	4.75	60.00	1.638	100.00	0.605	165.29	CHARGING	
1300	5.00	60.00	1.654	100.00	0.46	216.92	CHARGING	
1315	5.25	60.00	1.667	100.00	0.38	265.49	CHARGING	

TABLE III (con't)

NIF-270 CELL GASSING RATE MEASUREMENT

TYPE OF TEST GAS MEASUREMENT

DATE: 2 August 1983

SPECIMEN NO. NIF - 270

TIME OF DAY	TIME ON CYCLE (HRS)	CURRENT AMP	VOLTAGE VOLTS	GAS VOLUME IN "CC"	GAS COLLECTION TIME. MINS.	GASSING RATE CC/MIN.	CYCLE MODE	COMMENTS
1330	5.50	60.00	1.677	100.00	0.308	324.32	CHARGING	
1345	5.75	60.00	1.680	100.00	0.288	352.94	CHARGING	
1400	6.00	60.00	1.682	100.00	0.275	363.64	CHARGING	
1415	6.25	60.00	1.682	200.00	0.475	421.05	OVER-CHARGING	
1430	6.50	60.00	1.682	200.00	0.457	437.96	OVER-CHARGING	
1445	6.75	60.00	1.682	200.00	0.447	447.76	OVER-CHARGING	
1500	7.00	60.00	1.681	200.00	0.437	458.02	OVER-CHARGING	
1515	7.25	60.00	1.680	200.00	0.433	461.54	OVER-CHARGING	
1530	7.50	60.00	1.679	200.00	0.425	470.59	OVER-CHARGING	
1545	7.75	60.00	1.678	200.00	0.423	472.81	OVER-CHARGING	
1600	8.00	60.00	1.677	200.00	0.415	481.92	OVER-CHARGING	
1615	8.25	60.00	1.676	200.00	0.411	486.6	OVER-CHARGING	
1630	8.50	60.00	1.675	200.00	0.408	490.1	OVER-CHARGING	
1645	8.75	60.00	1.674	200.00	0.411	486.6	OVER-CHARGING	
1700	9.00	60.00	1.674	200.00	0.411	486.6	OVER-CHARGING	

TABLE III (con't)

NIF-270 CELL GASSING RATE MEASUREMENT

TYPE OF TEST GAS MEASUREMENT

DATE: 3 August 1983

SPECIMEN NO. NIF - 270

TIME OF DAY	TIME ON CYCLE(HRS)	CURRENT AMP	VOLTAGE VOLTS	GAS VOLUME IN "CC"	GAS COLLECTION TIME. MINS.	GASSING RATE CC/MIN.	CYCLE MODE	COMMENTS
CELL IS PUT TO OVERCHARGING FOR 3 HOURS THEN SWITCH TO OPEN CIRCUIT.								
1100	0.00	60.00	1.681	200.00	.408	490.20		
1115	0.25	00.00	1.462	50.00	.79	63.29	OPEN CIRCUIT	
1130	0.50	00	1.455	50.00	1.103	45.32	OPEN CIRCUIT	
1145	0.75	00	1.451	50.00	1.478	33.82	OPEN CIRCUIT	
1200	1.00	00	1.449	25.00	0.82	30.49	OPEN CIRCUIT	
1215	1.25	00	1.446	25.00	0.977	25.60	OPEN CIRCUIT	
1230	1.50	00	1.445	25.00	1.093	22.87	OPEN CIRCUIT	
1245	1.75	00	1.443	35.00	1.732	20.21	OPEN CIRCUIT	
1300	2.00	00	1.441	25.00	1.318	18.96	OPEN CIRCUIT	
1400	3.00	00	1.438	25.00	1.777	14.07	OPEN CIRCUIT	
1500	4.00	00	1.435	25.00	2.062	12.13	OPEN CIRCUIT	
1600	5.00	00	1.432	40.00	3.80	10.53	OPEN CIRCUIT	
1700	6.00	00	1.431	30.00	2.92	10.27	OPEN CIRCUIT	
2200	11.00	00	1.424	25.00	3.70	6.75	OPEN CIRCUIT	
0800	21.00	00	1.417	25.00	4.10	6.10		

TABLE III (con't)

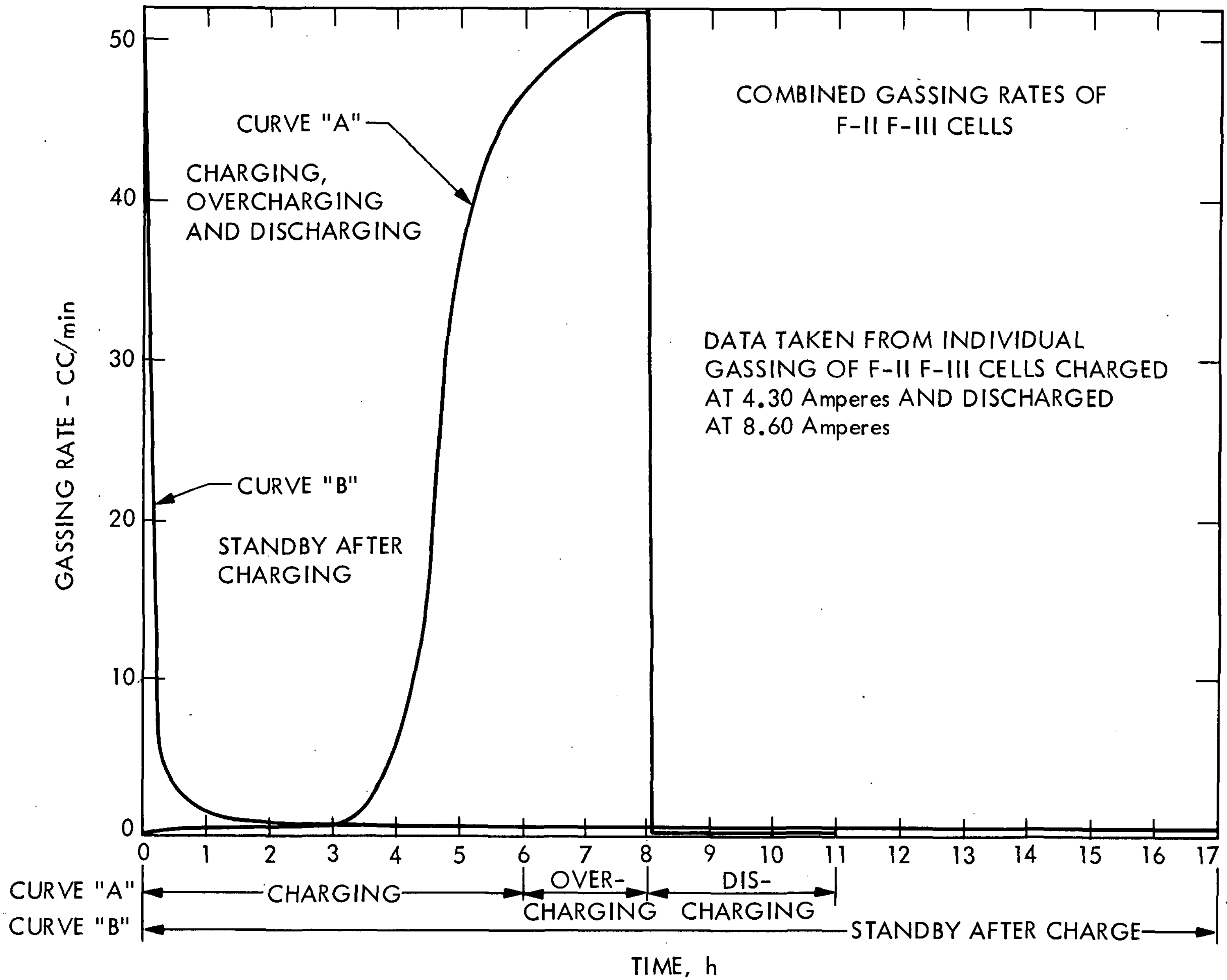
NIF-270 CELL GASSING RATE MEASUREMENT

TYPE OF TEST GAS MEASUREMENT

SPECIMEN NO. NIF - 270

DATE: 4 August 1983

TIME OF DAY	TIME ON CYCLE(HRS)	CURRENT AMP	VOLTAGE VOLTS	GAS VOLUME IN "CC"	GAS COLLECTION TIME. MINS.	GASSING RATE CC/MIN.	CYCLE MODE	COMMENTS
CELL WAS PUT TO OVERCHARGING FOR 3 HOURS THEN SWITCHED TO DISCHARGE								
1100	0.00	60.00	1.680	200.00	0.40	500.00	DISCHARGING	
1105	0.083	60.00	1.377	25.00	0.537	46.58	DISCHARGING	
1110	0.167	60.00	1.362	25.00	1.07	23.36	DISCHARGING	
1115	0.25	60.00	1.351	25.00	1.85	13.51	DISCHARGING	
1130	0.50	60.00	1.323	30.00	5.28	5.68	DISCHARGING	
1230	1.00	60.00	1.276	5.00	2.067	2.42	DISCHARGING	
1330	2.00	60.00	1.247	5.00	2.46	2.28	DISCHARGING	
1430	3.00	60.00	1.216	5.00	2.83	1.77	DISCHARGING	
1530	4.00	60.00	1.200	5.00	2.83	1.74	DISCHARGING	
1630	5.00	60.00	1.140	5.00	2.98	1.68	DISCHARGING	
1706	5.60	60.00	0.90	5.00	3.03	1.65	END OF DISCHARGING	



COMBINED GASSING RATES OF
F-II F-III CELLS
CURVE "A"
CHARGING,
OVERCHARGING
AND DISCHARGING
CURVE "B"
STANDBY AFTER
CHARGING
DATA TAKEN FROM INDIVIDUAL
GASSING OF F-II F-III CELLS CHARGED
AT 4.30 Amperes AND DISCHARGED
AT 8.60 Amperes
GASSING RATE - CC/min
0
10
20
30
40
50
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
CURVE "A"
CHARGING
OVER-
CHARGING
DIS-
CHARGING
CURVE "B"
STANDBY AFTER CHARGE
TIME, h

2.3 Flame Arrestor Testing

All flame arrestor testing was accomplished using the test station shown in Figure 8. The flame arrestor test station consisted of a gas generator, a water trap, an explosion protected site for the arrestor under test, a spark gap with its power source and Tygon tubing to pipe the gas to the arrestor. The gas generator provided a hydrogen-oxygen mixture by the dissociation of water. The five cells of the generator contained nickel-nickel plate groups so the gas mixture is always stoichiometric. The gas generation rate is proportional to the current passed through the generator. The water trap was a simple bubbler with a PVC body and a thin plastic cover. Its purpose was to protect the gas generator. Upon failure of an arrestor to quench an ignition, the thin polyethylene cover ruptured protecting the body of the water trap and the gas generator. It was placed in a safe remote location. An automotive spark plug and coil, firing once per second continuously, provided ignition for the tests.

The test procedure was to mount the arrestor in the protective enclosure, position the spark plug at the discharge, power the gas generator and after a moments purging of the system with the GH_2-GO_2 mixture, ignition was initiated. If the ignitions were quenched, the testing would continue as the generator current was increased from 5 to 80 amperes and decreased to zero. In this manner the arrestors were tested for effectiveness over a wide range of gassing rate from zero up to 4.3 liters per minute. Upon the failure of an arrestor to quench the flame, the water trap cover ruptured with a loud report. No flame arrestor developed in the course of this contact was tested with an actual nickel-iron battery.

Of the many types of flame arrestors described in the literature, only those which might work with GH_2-GO_2 mixtures were considered. A further restraint was their adapability to the water/vent system of the battery. The velocity type flame arrestors were eliminated due to varying gas flow rates from a nickel-iron battery. Crimped ribbon arrestors were not attempted because of difficulties in obtaining materials and their construction. In theory these arrestors are equivalent to tube bundles and cylindrical channels. Ref. 24 The Passage of Explosion Through Narrow Cylindrical Channels by H. G. Wolfhard and A. E. Bruszak. The four basic types of flame arrestors investigated were the one-way valve, foam metals, tube bundles and wet-bubbler flame arrestors. A tabulation, Table IV, describes all the arrestors which were tested, the results of the tests and their advantages and disadvantages. A drawing of each arrestor is included as Figures 9 to 23.

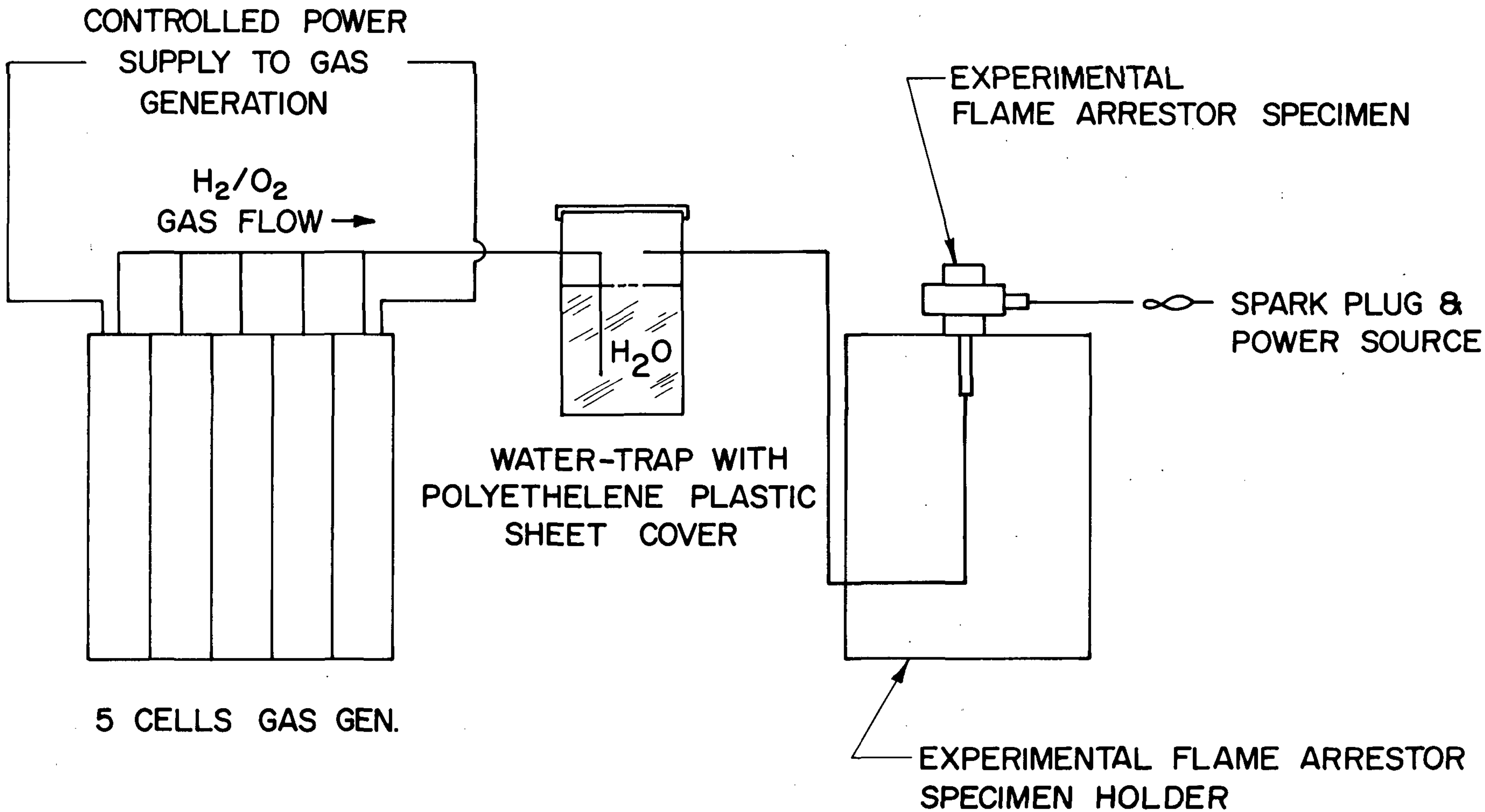


FIGURE 8. FLAME ARRESTOR TESTING-EQUIPMENT LAYOUT

2.4 One-Way Valve Flame Arrestor

The one-way valve flame arrestor -001, Figure 9 and 10 consisted of a Vernay Laboratory one-way valve of ethylene propylene rubber installed in a plastic casing. The valve allows the gas to pass through in one direction by lifting the lip of the valve. This same lip is supposed to stop flame propagation in the opposite direction by closing when the pressure created during an explosion reseats it. This type of flame arrestor performed inconsistently. It was effective for a few to ten trials then failed. Post-test examination of the flame arrestor indicated both distortion of the rubber valve in the mounting hole and deterioration of its sealing lip. With the deterioration of the lip, the valve loses its ability to seal against the mounting surface. In effect it is no longer a one-way valve and allows flame to transfer to the gas source. The valve is a mechanical device which has a limited life when subjected to explosive pressures. It should still be considered for module level protection in a revised watering system.

2.5 Foam-Metal Flame Arrestor

The next group of flame arrestors investigated, were those made of porous nickel material. Two different types were investigated. The two materials were the 1/8" thick nickel foam, Retimet 80, 50 μm pores, and .080" thick Brunswick, 40 μm pore nickel felt. These flame arrestors materials proved effective. Their effectiveness was dependent upon the number of stacked discs used. The greater the number of discs installed in the casing, the better the chance of quenching a high speed flame. There is a problem in increasing the thickness, or number of foam-metal disc elements. The back pressure created by gassing in the cell becomes higher as the number of foam-metal discs is increased. This increased pressure might cause the cell cases to crack. At this time the foam-metal type arrestors are the ones that are most adapable to the gas venting system.

2.6 Cylindrical-Channel Flame Arrestor

The cylindrical-channel flame arrestor was also investigated. Two different sizes of tubing were used for the experiments; Gage 22, 0.018 in. outside diameter x 0.00625 in. wall thickness x 2.00 in. long and gage 30, 0.012 in. outside diameter x 0.003 in. wall thickness x 2.00 in. long. It was demonstrated that the tube bundles with the smaller diameter tubing was more effective. This is attributed to its increases surface area as the results of higher length to hydraulic diameter ratio. In either case a need for a cooling system was indicated because of the tendency to establish a stable flame at the arrestor exit or inside the arrestor. At the start of a test, flames are extinguished, but after repeated ignitions the tube bundle heats up to the auto ignition temperature and becomes an ignition source itself. At a very low or critical gassing flow rate, the flame will flash-back through the arrestor into the cell and cause a detonation. These arrestors would not be appropriate for cell or module protection, because of the extreme range of gas evolution rates. The tube bundle flame arrestor creates less back pressure in the cell, but at this time successful performance is very dependent on keeping the tubes cool; a greater length to hydraulic diameter ratio, and a more consistent gassing rate.

2.7 Wet-Type Flame Arrestor

The most successful flame arrestor investigated was the wet-bubbler type or liquid-trap flame arrestor. The liquid used was water which is compatible with the electrolyte in a Ni-Fe cell. A crudely constructed water trap (bubbler) was always used as a safety device during flame arrestor testing. Not a single detonation propagated to the gas source. The water-trap principle was designed into the cell watering cap provided for watering and cell venting. This type of flame arrestor was designed to be expendable. If an explosion were to occur, it would be destroyed and would have to be replaced. The problems that would be encountered with this type flame arrestor are the increased head space to accommodate the water trap, the water freezing causing the cell to rupture during cold weather operation, and the danger of an unnoticed ignition which destroys a cell cap, filling the entire battery compartment with flammable gasses. However, because of its simplicity and compatability with the battery system, water traps deserve further consideration.

TABLE IV

FLAME ARRESTOR TESTING

FLAME ARRESTOR NO.	FLAME ARRESTOR DESCRIPTION	FLAME ARRESTOR TEST RESULTS	ADVANTAGE OR DISADVANTAGE
001	Vernay Laboratory one-way valve installed in a plastic casing.	Inconsistent performance. Works for approximately 10-15 trials then the next explosion could be a disaster.	Performance is very dependent on placement of one-way valve on the mounting hole. Not very easy to incorporate in a watering system.
002	Two layers of 1/8" Retimet 80, 50 μm foam metal and two perforated screens brazed in place inside the S.S. container.	Works at lower gassing rate with blow-out cap, but failed to stop flame propagation at higher gassing rate.	Difficult to construct by brazing the foam metal in place. It reduces the surface area exposed to the gas. Potential problem of clogging due to water freezing during cold weather operation.
003	Two layers of .080" - 42 μm Brunswick felt metal and two pieces perforated screens glued to the inside of the S.S. Container.	Works at lower gassing rate with blow-out cap, but failed to stop flame propagation at higher gassing rate.	Easy to construct. Potential problem of clogging due to water freezing during cold weather operation.
004	Two Layers of .080"- 42 μm Brunswick felt metal and two pieces perforated screen glued to the inside of the S.S. container. Smaller in diameter than flame arrestor 003.	Works at lower gassing rates with blow-out cap, but failed to stop flame propagation at higher gassing rate.	Easy to construct. Potential problem of clogging due to water freezing during cold weather operation.

TABLE IV (con't)

FLAME ARRESTOR TESTING

FLAME ARRESTOR NO.	FLAME ARRESTOR DESCRIPTION	FLAME ARRESTOR TEST RESULTS	ADVANTAGE OR DISADVANTAGE
005	Two Brunswicks .080 - 42 μm felt metal with two perforated screens incorporated into the NIF-270 watering cap.	Failed. Didn't stop flame propagation to the gas source.	Easy to construct, but it did not work.
006	Four Brunswick .080 -42 μm felt metal with four perforated screens incorporated into the NIF-270 watering cap.	Failed. Didn't stop flame propagation to the gas source.	Easy to construct, but it did not work.
007	Constructed with 10 each Brunswick felt metal with 6 each perforated screen. Felt metal and screens were glued together and held in place with the press fit aluminum spacer into the S.S. Metal container.	Positive result, self extinguishing ignitions occured at the gas exit without propagating to the gas source.	Creats back pressure on the cell. The pores of felt metal will be clogged with sediments and possible freezing of water in the pores during cold weather operation.
008	Constructed with 8 each Brunswick felt metal with 9 each perforated screen cut to press fit inside S.S. container. No. glue used during construction except during placing aluminum spacer.	Positive result, self extinguishing ignitions occured at the gas exit without flame propagation to the gas source.	Creats back pressure to the cell. Pores of felt metal will be clogged with sediments and possible freezing of water in the pores during cold weather operation.

TABLE IV (con't)

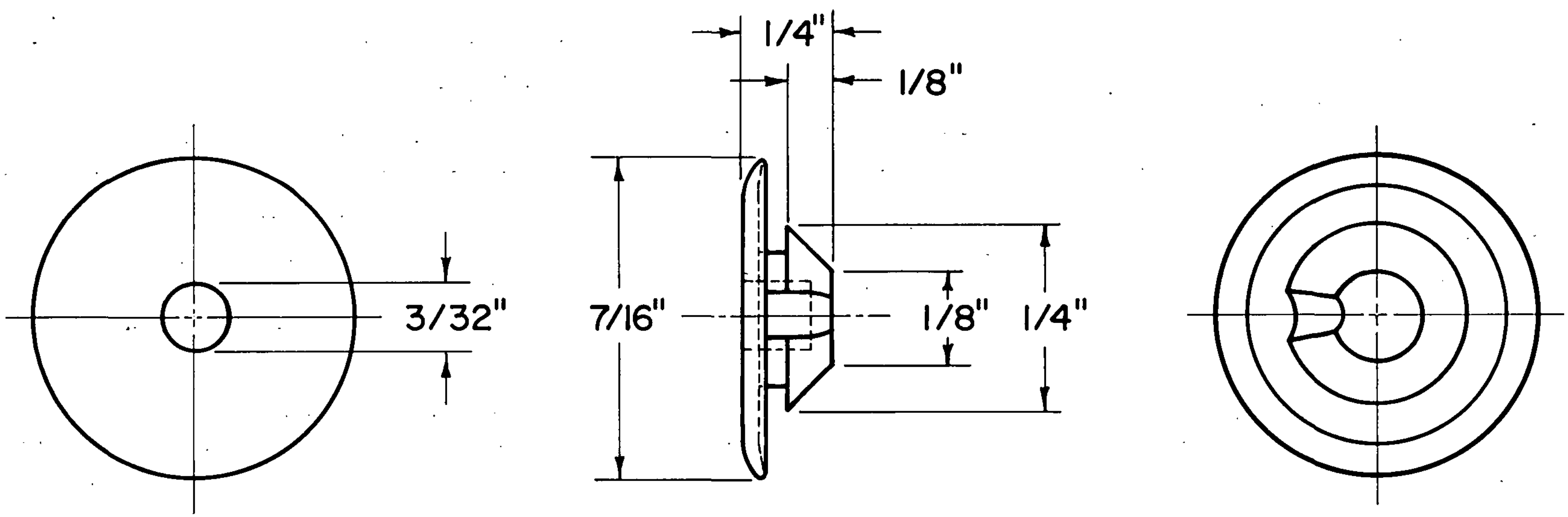
FLAME ARRESTOR TESTING

FLAME ARRESTOR NO.	FLAME ARRESTOR DESCRIPTION	FLAME ARRESTOR TEST RESULTS	ADVANTAGE OR DISADVANTAGE
009	Water-cooled tube bundle flame arrestor. Uses Ga. 30 x 2.00 S.S. tube bundled to around 3/8" Diameter	Positive results from 30 amps-80 amps charge to gas source. Self extinguishing explosion occured, but never propagated to the gas source.	Easy to construct, but tubes are expensive. Could be a problem during cold weather operation.
010	Wet-flame arrestor is made out of Plexiglas.	Positive result. Flame didn't Propagate to the gas source. Plexiglas top exploded.	Easy to construct. Freezing problem during cold weather operation. Unsafe due to flying debris if it explodes.
011	Tube bundle flame arrestor using GA 30 x 2.00 long S.S. tube bundled to around 3/4" dia. installed inside a S.S. container.	Failed. Explosion occured at the gas source.	Easy to construct, but tube are expensive. Could be a problem during cold weather operation.
012	8 discs of 1/8" Retiment 80 and 9 disc of S.S. perforated screen installed in S.S. tube.	Positive result from 10-80 amps then from 80 amps to "0"	Easy to construct and install into the system
013	7 discs of 1/8" Retiment 80 and 8 discs of S. S. perforated screen installed in S.S. tube.	Positive result from 10-80 amps then from 80 amps to "0"	Easy to construct and install into the system

TABLE IV (con't)

FLAME ARRESTOR TESTING

FLAME ARRESTOR NO.	FLAME ARRESTOR DESCRIPTION	FLAME ARRESTOR TEST RESULTS	ADVANTAGE OR DISADVANTAGE
014	6 discs of 1/8" Retimet 80 and 7 discs of S.S. perforated screen installed in S.S. tube.	Positive result from 10-80 Amps, then from 80 amps to "0"	Easy to construct and install into the system.
015	5 discs of 1/8" Retimet 80 and 6 discs of S.S. perforated.	Positive result from 10-80 amps then from 80 amps to "0"	Easy to construct and install into the system.
016	4 disc of 1/8" Retimet 80 and 5 disc of S.S. perforated screen installed in S.S. tube.	Failed at 10 amps setting.	Easy to construct, but proned to explosion.
017	Gage 22 tube bundle, soldered solid and installed into a 3/8" O. D. tubing, provided with a water cooling system.	Failed due to heat build-up and reduced ratio of the length to the hydraulic diameter.	Easy to construct. Tubes to expensive. Proned to failure as it became a heat flame source.
018	Heat exchange construction tube flame arrestor with water inlet and outlet for cooling system.	Failed, became a flame source. Failure is attributed to construction and design problem.	Hard to construct. Tube bundles too expensive.



MATERIAL: VL-1702M9 ETHYLENE PROPYLENE RUBBER

FIGURE 9. VERNAY ONE-WAY VALVE
PART NO. VA3206
FLAME ARRESTOR—001

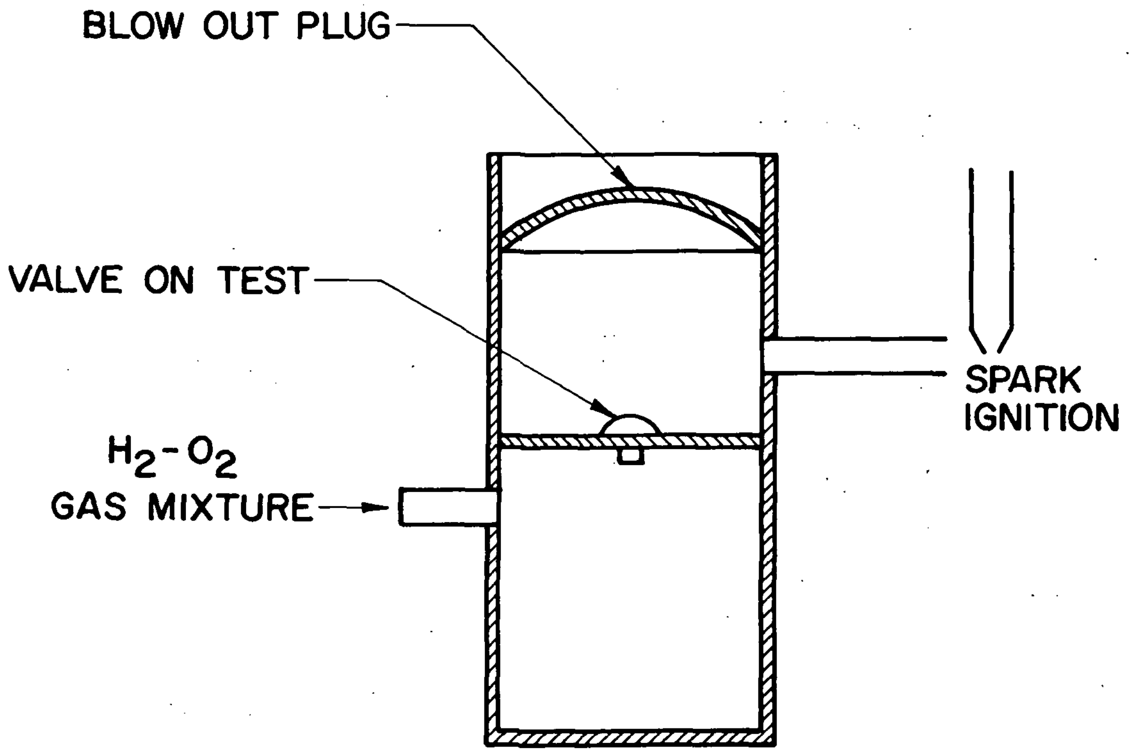


FIGURE 10. ONE-WAY VALVE INSTALLATION

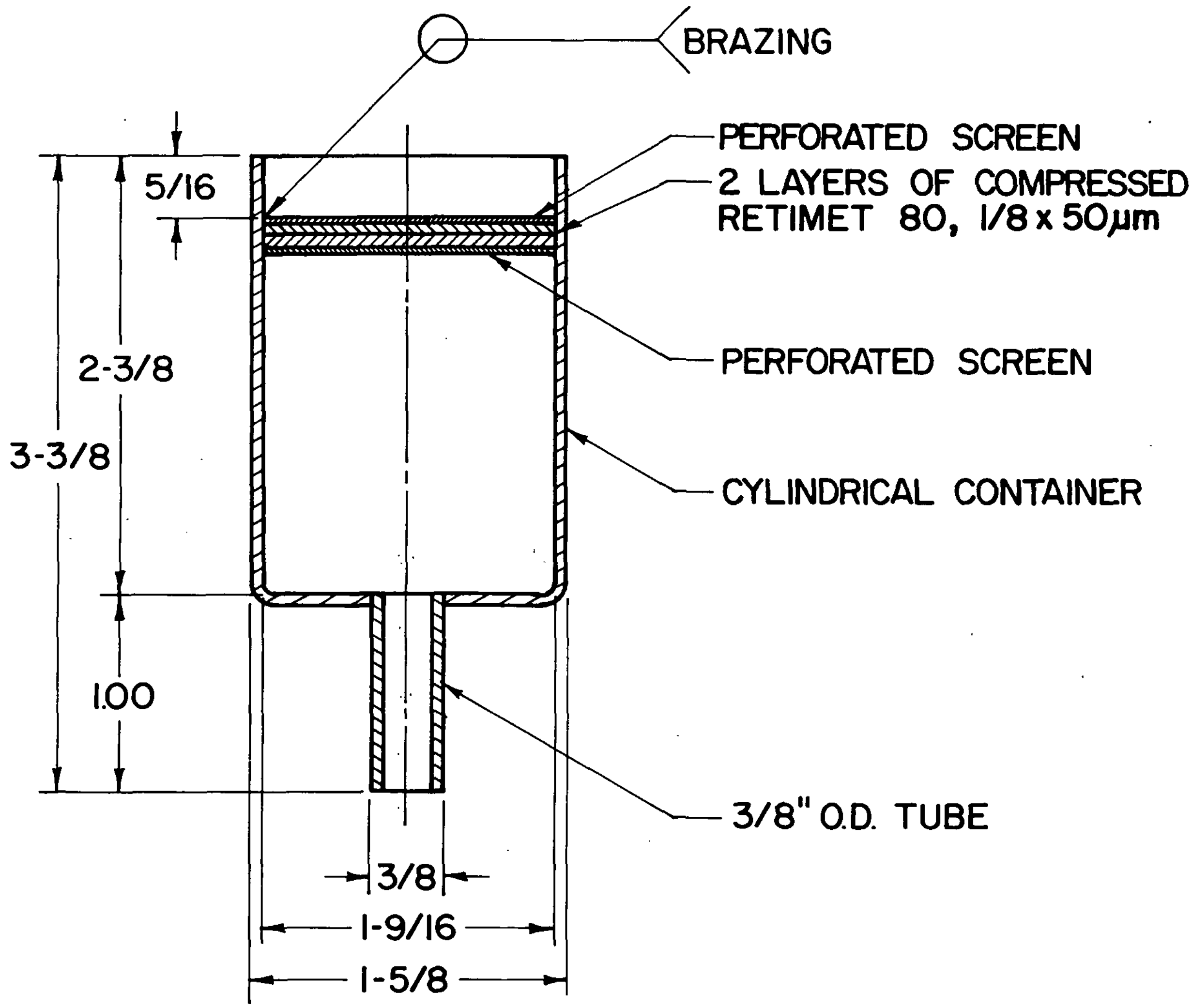


FIGURE 11. FLAME ARRESTOR — 002

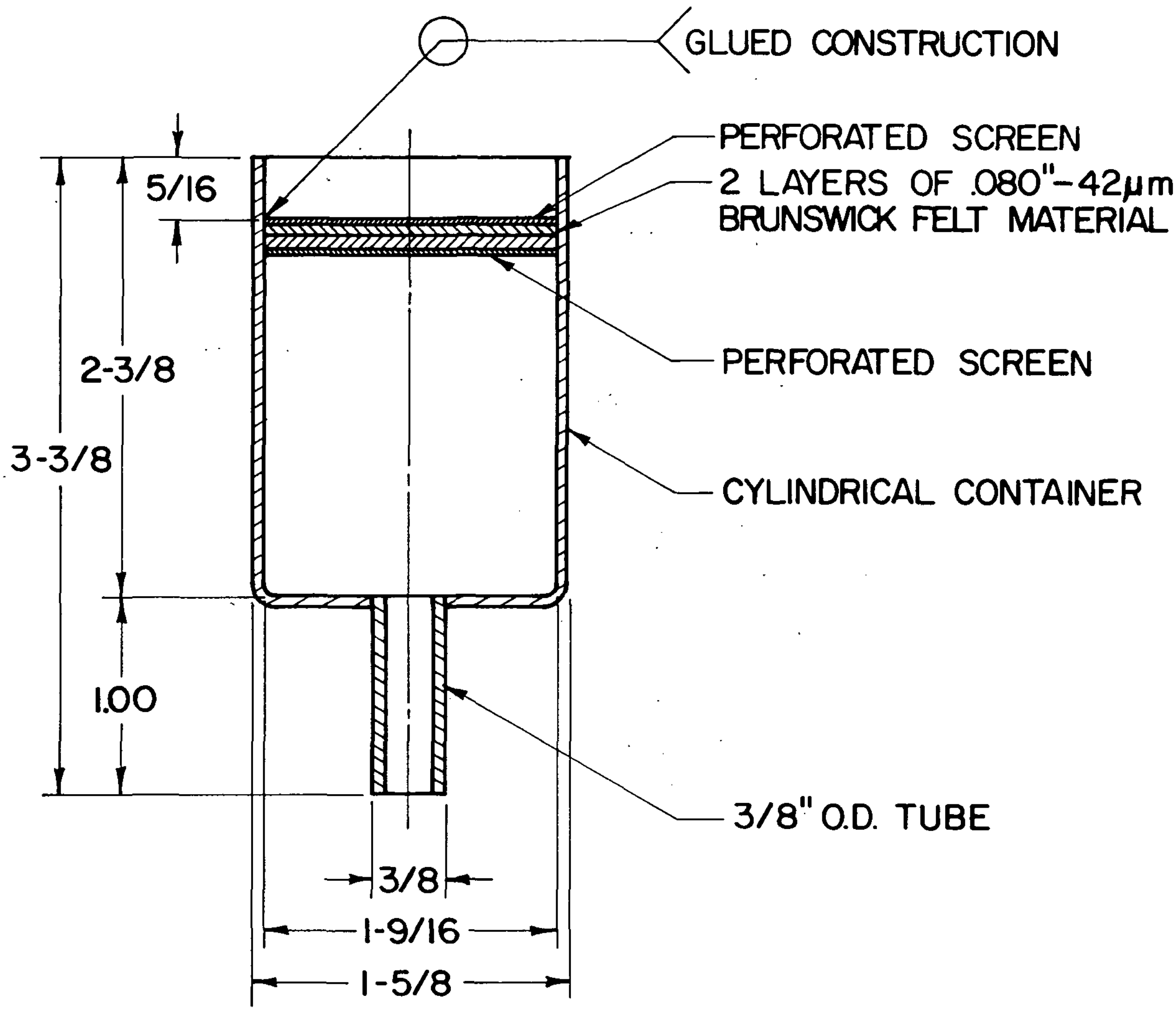


FIGURE 12. FLAME ARRESTOR—003

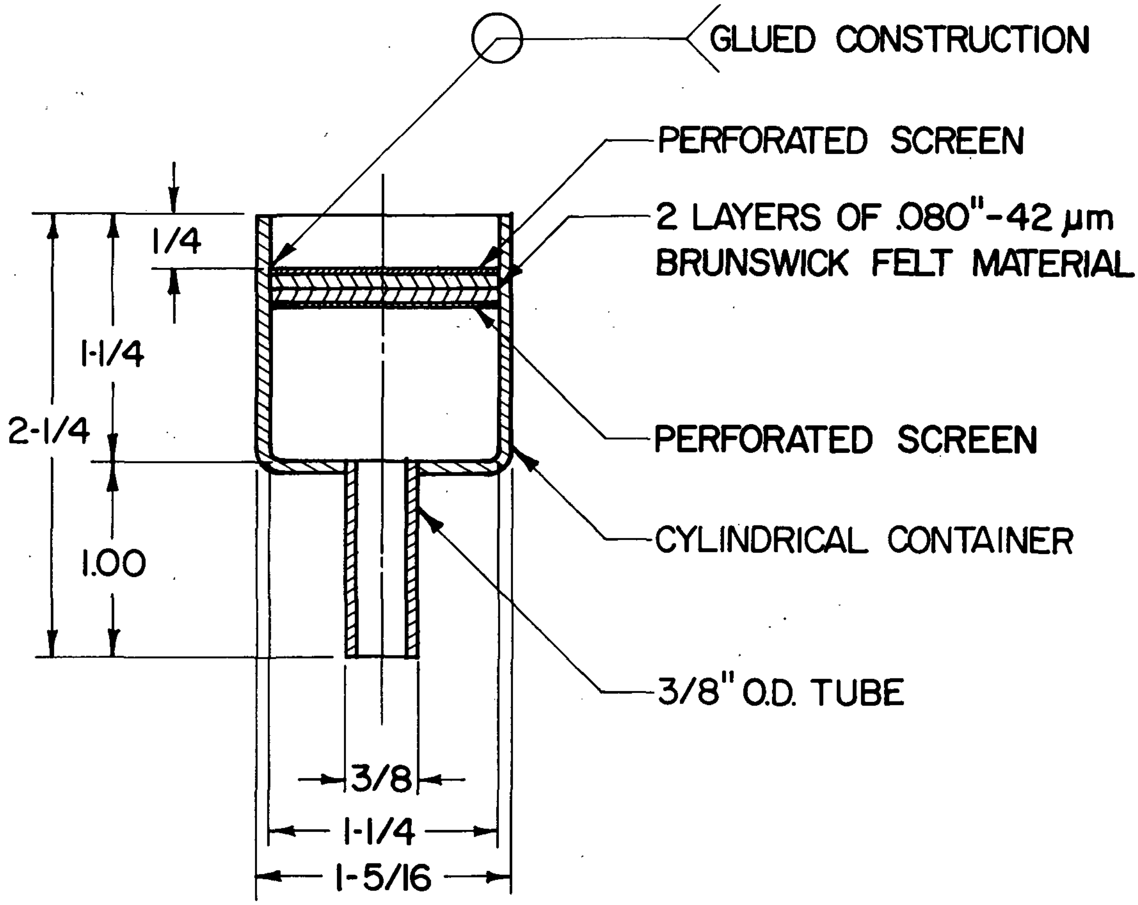


FIGURE 13. FLAME ARRESTOR — 004

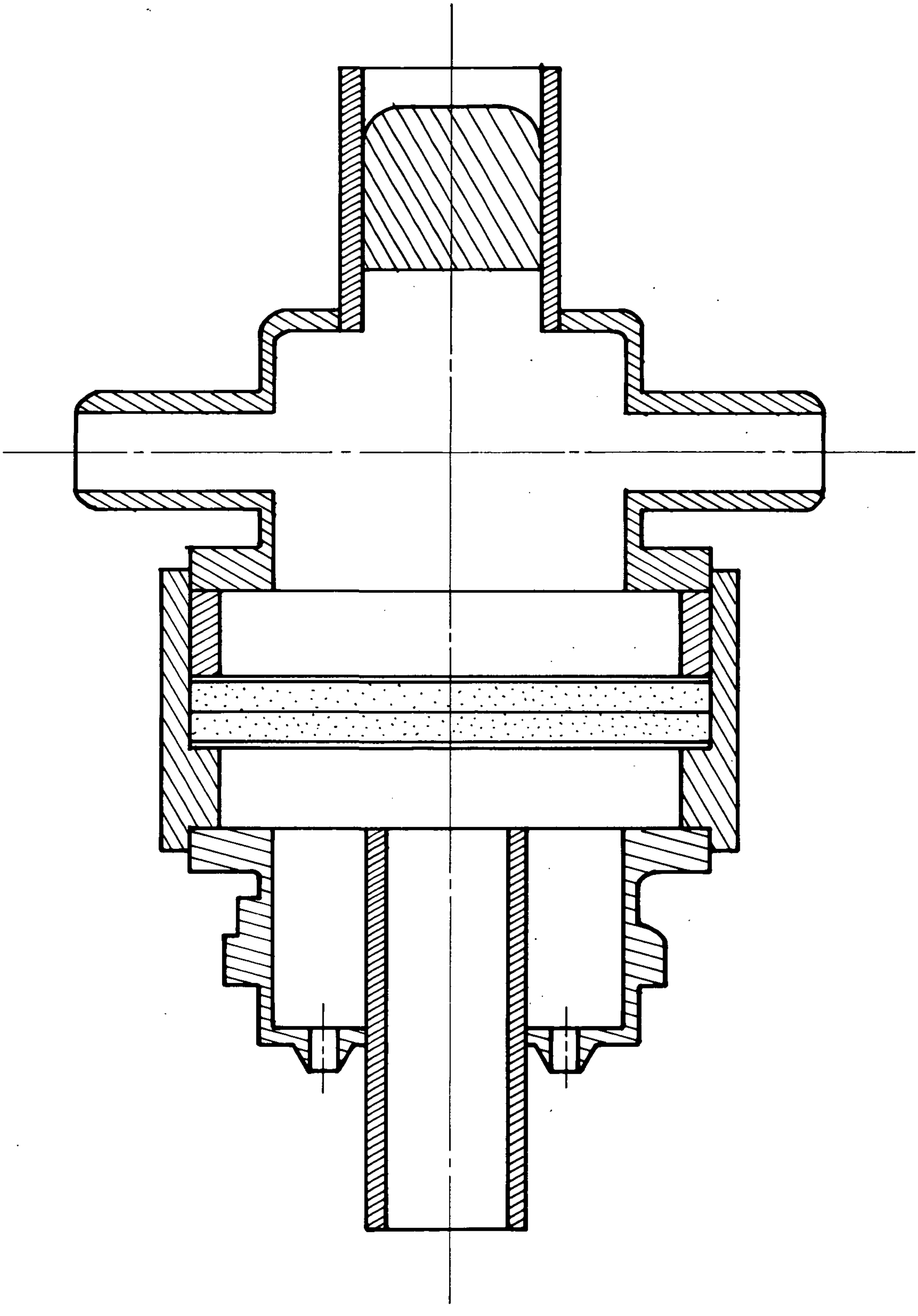


FIGURE 14. FLAME ARRESTOR — 005

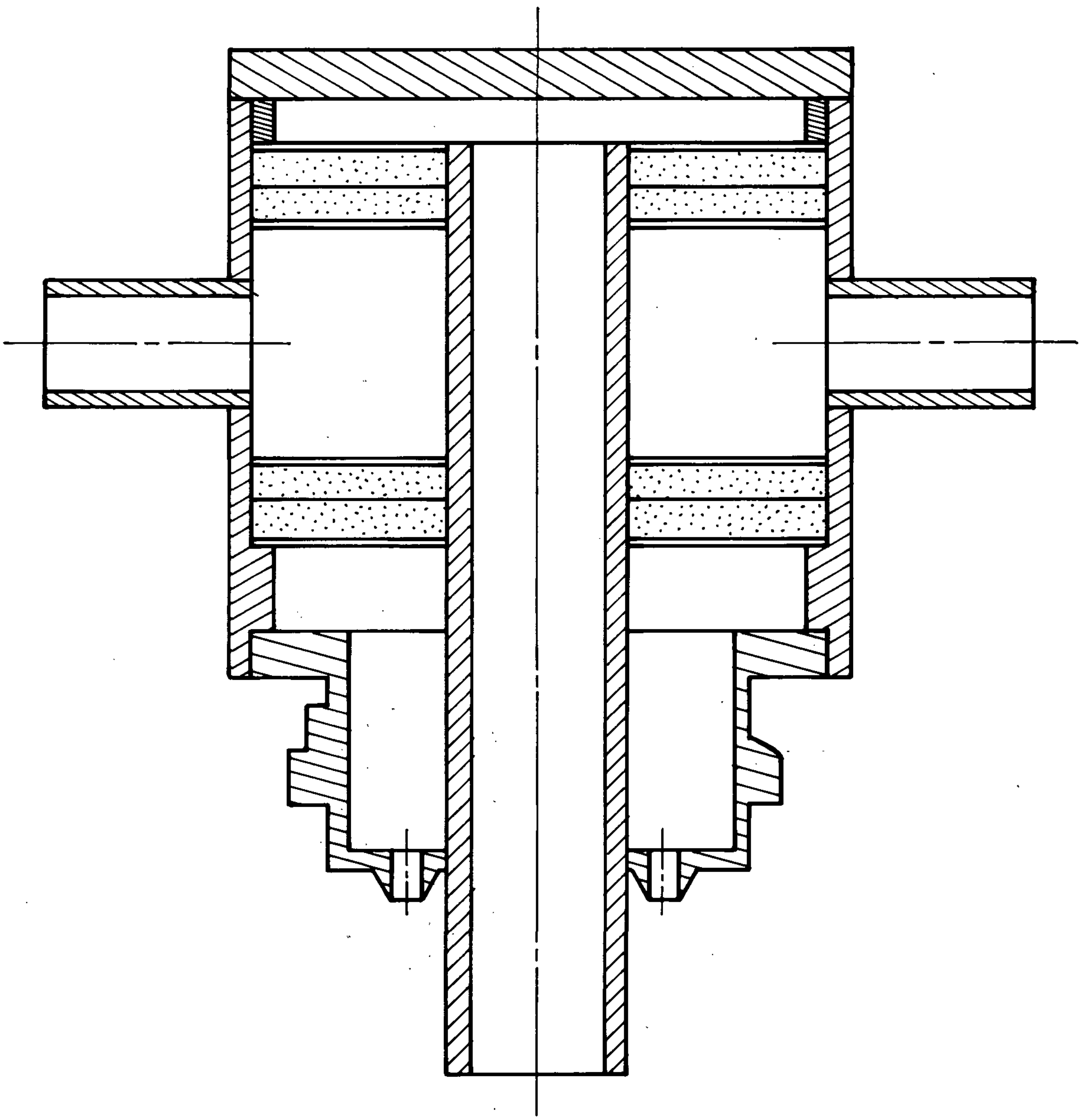


FIGURE 15. FLAME ARRESTOR—006

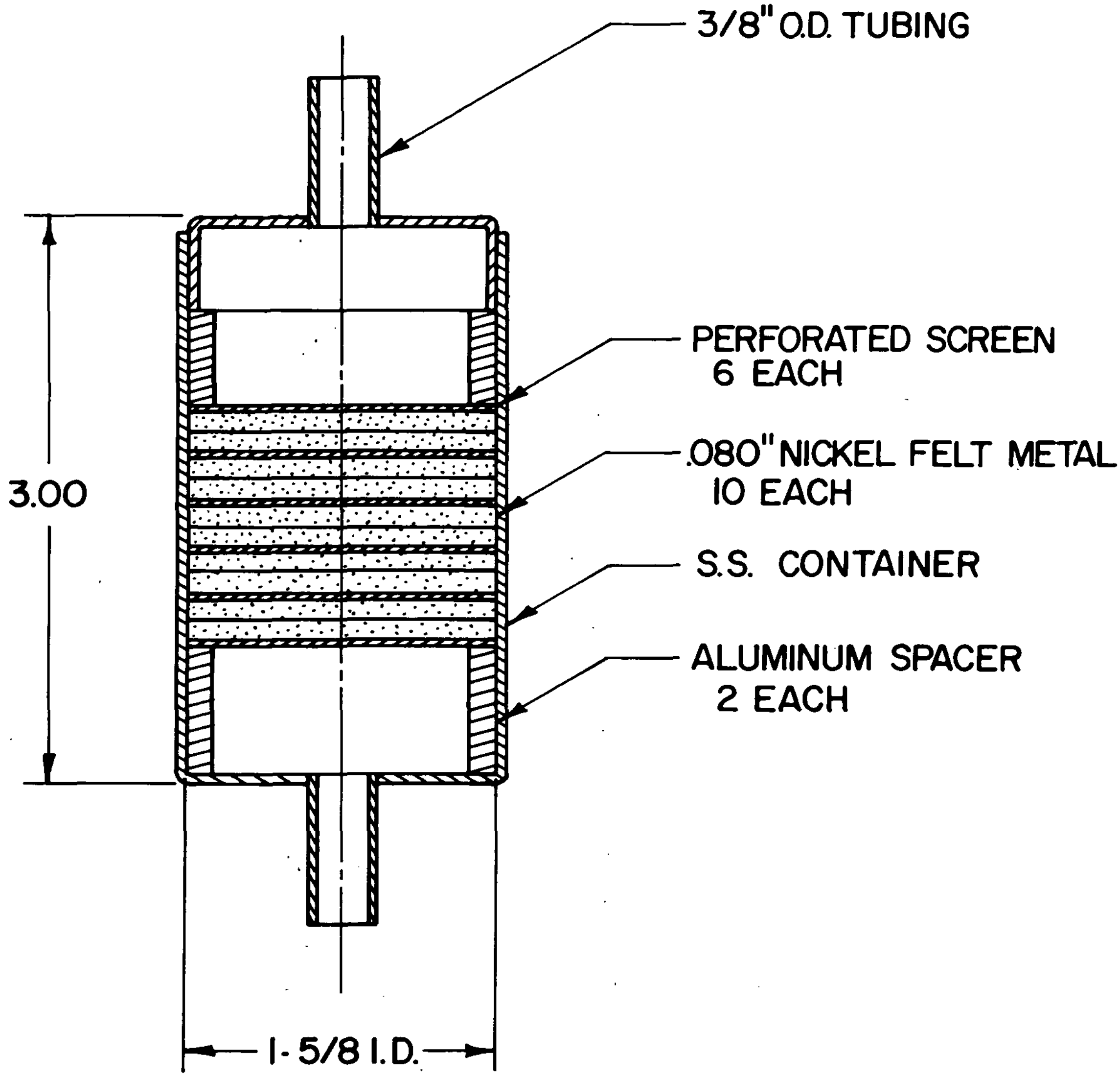


FIGURE 16. FLAME ARRESTOR — 007

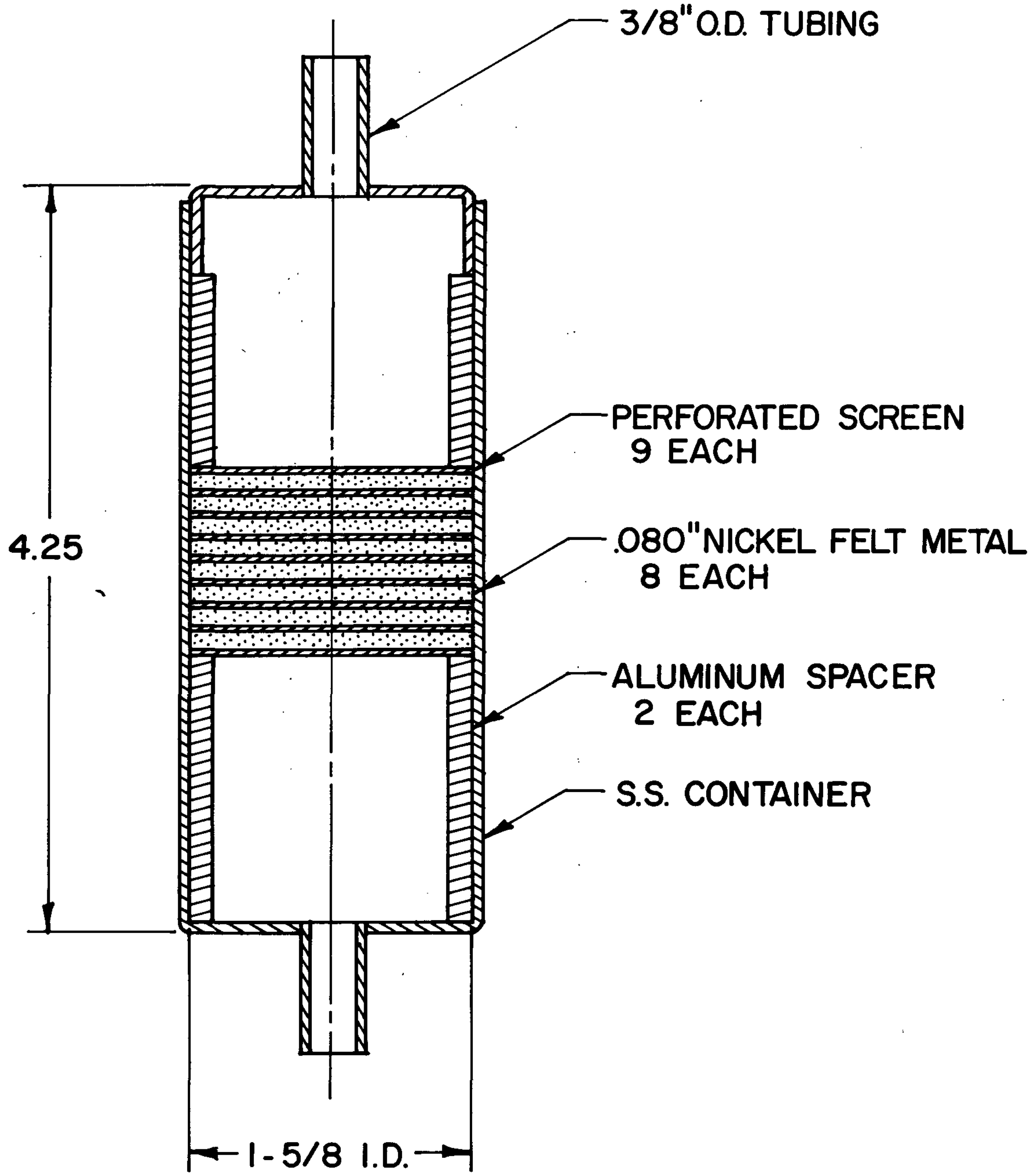


FIGURE 17. FLAME ARRESTOR — 008

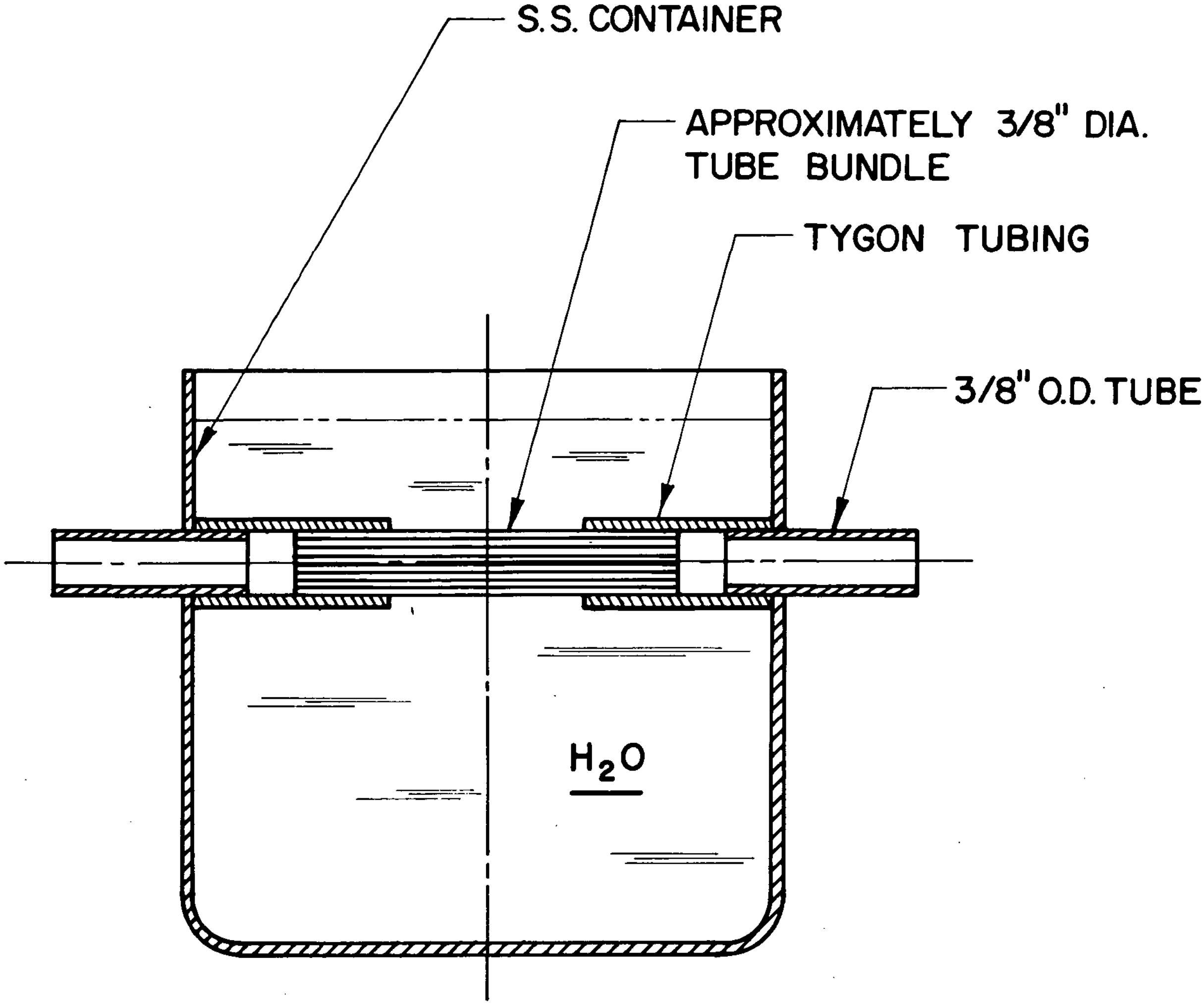


FIGURE 18. WATER-COOLED TUBE BUNDLE ARRESTOR

FLAME ARRESTOR — 009

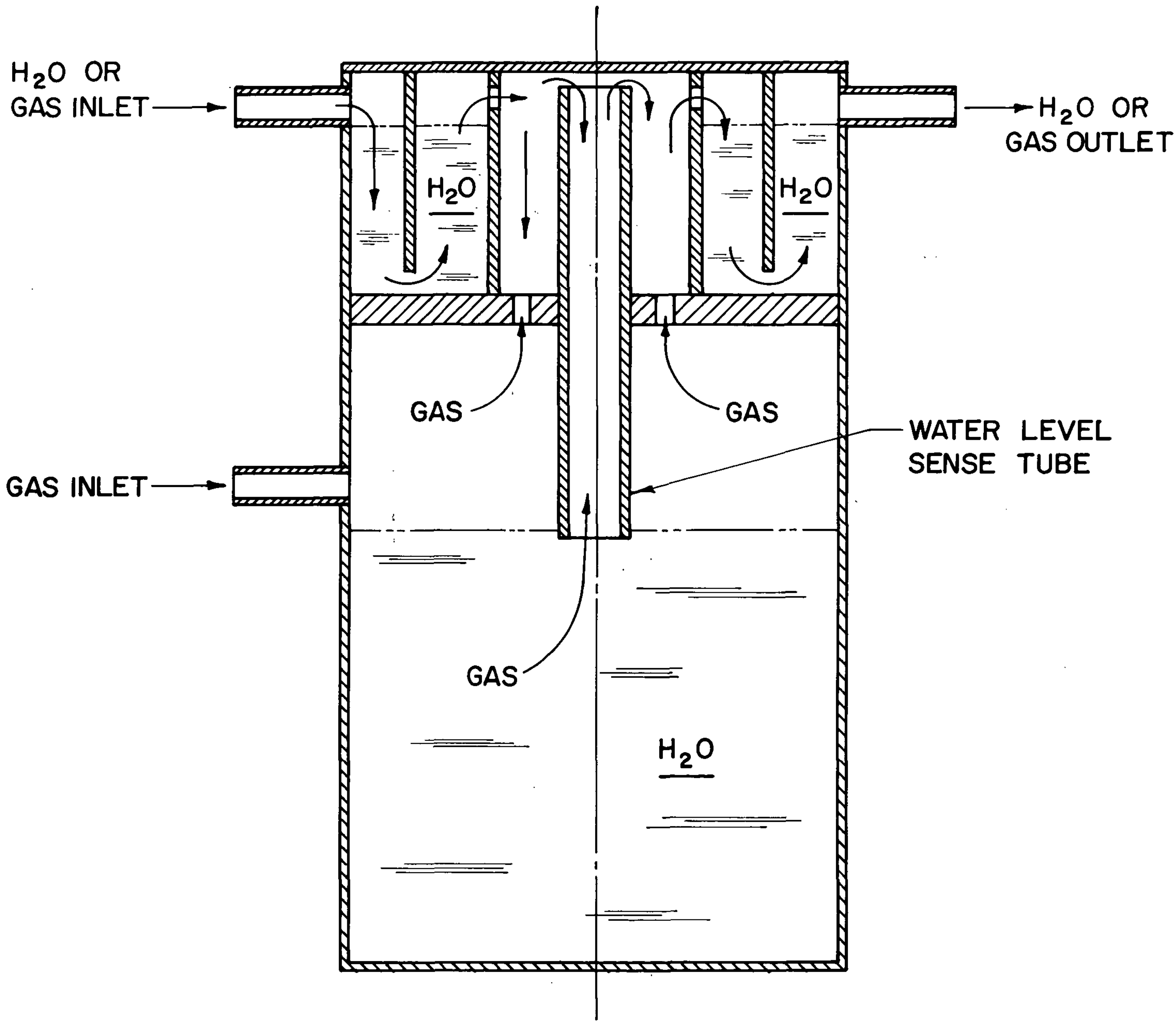


FIGURE 19. WATER-TRAP FLAME ARRESTOR

FLAME ARRESTOR — 010

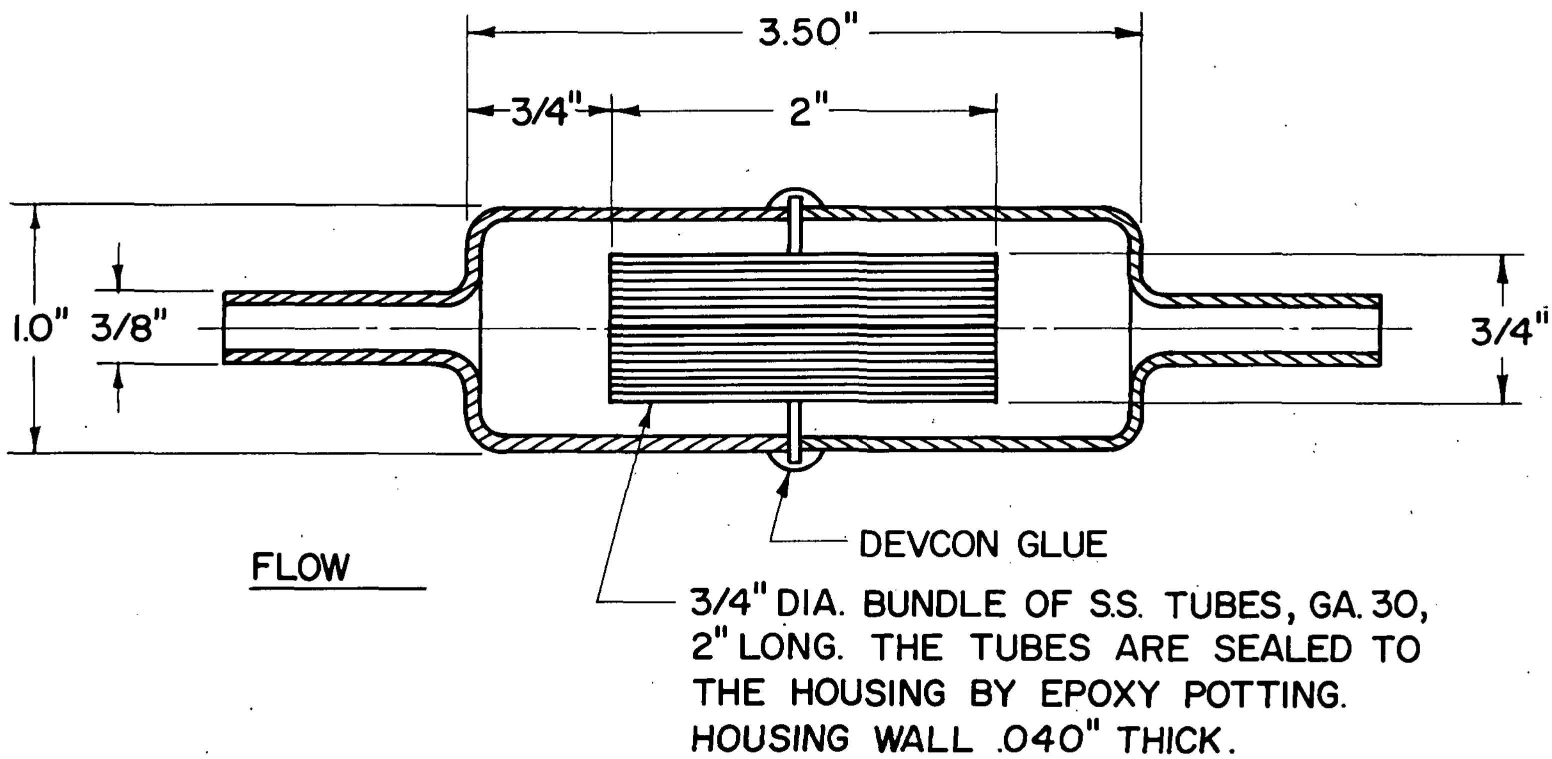


FIGURE 20. FLAME ARRESTOR—011

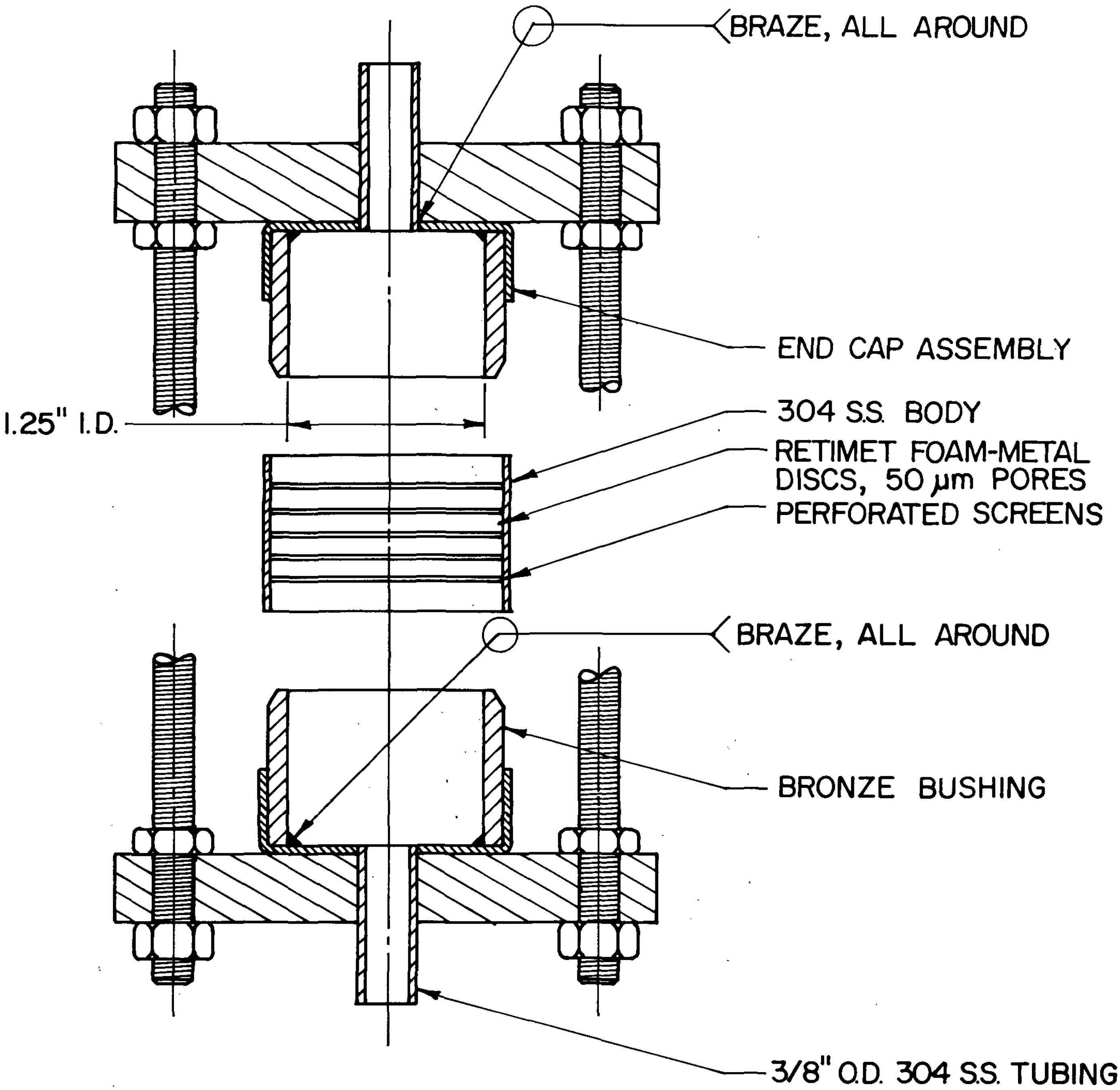


FIGURE 21. REPLACEABLE BODY FOAM-METAL ARRESTORS

ARRESTOR NO.	NO. OF DISCS *	NO. OF PERFORATED SCREENS
012	8	9
013	7	8
014	6	7
015	5	6
016	4	5

* NO. OF 1/8" THICK 50 µm RETIMET 80 FOAM-METAL DISCS

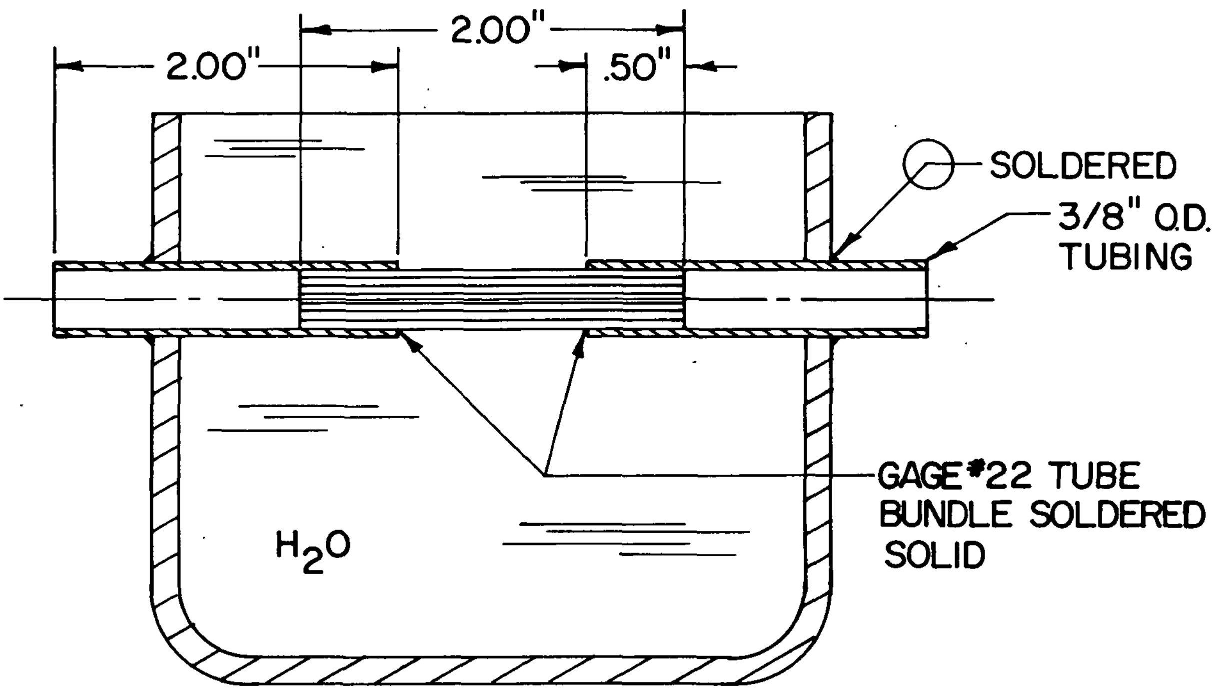
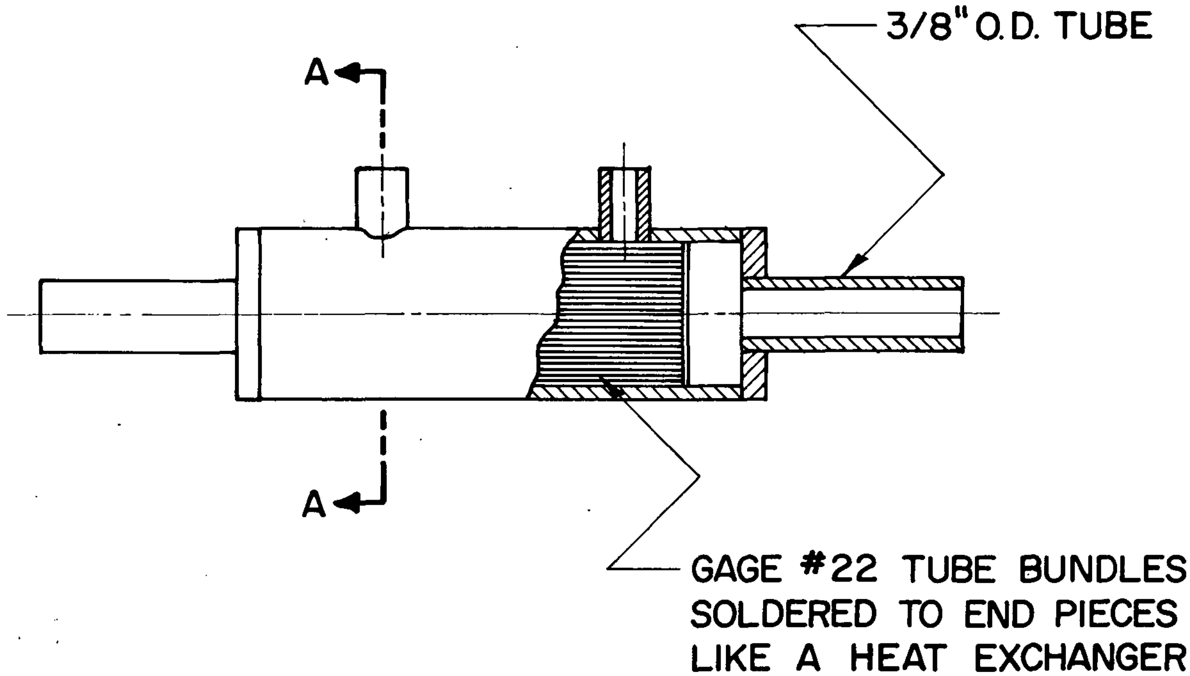
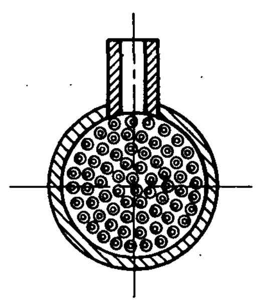


FIGURE 22. WATER-COOLED FLAME ARRESTOR—017





SECTION A-A

FIGURE 23. FLAME ARRESTOR—018

3.0 Conclusions

1. The literature search indicated that flame arrestors for GH_2-GO_2 mixtures would be especially difficult for the nickel-iron battery because the watering manifold is essentially a long pipe. In a pipe, a GH_2-GO_2 flame accelerates to detonation. There is no time to quench the flame. In the performance of this work Ref. No. 24 "Performance of Metallic Foams as Flame Arrestors" by J. P. Davis, K. N. Palmer and Z. W. Rogowski presented the most directly applicable examples.

2. The gas evolved by a Ni-Fe cell is a hydrogen/oxygen mixture. While it is not always stoichiometric, it is always flammable whether the mixture is hydrogen rich or hydrogen lean.

3. The gassing rate for a Ni-Fe cell is the greatest during the later part of the battery recharge and overcharge. This is also the most critical time from a flame safety view point due to the likely close proximity of people and equipment during battery charging operation.

4. There are arrestors devices and materials capable of preventing flash-back flame propagation or detonations. However, continued research and experimentation are needed to develop their design for use in a battery watering/vent system.

5. A combination of foam metal and one-way valve flame arrestors, shown in Figure 24, is likely to give some protection at the module level in a battery and it is adapable to the Ni-Fe battery watering/venting system.

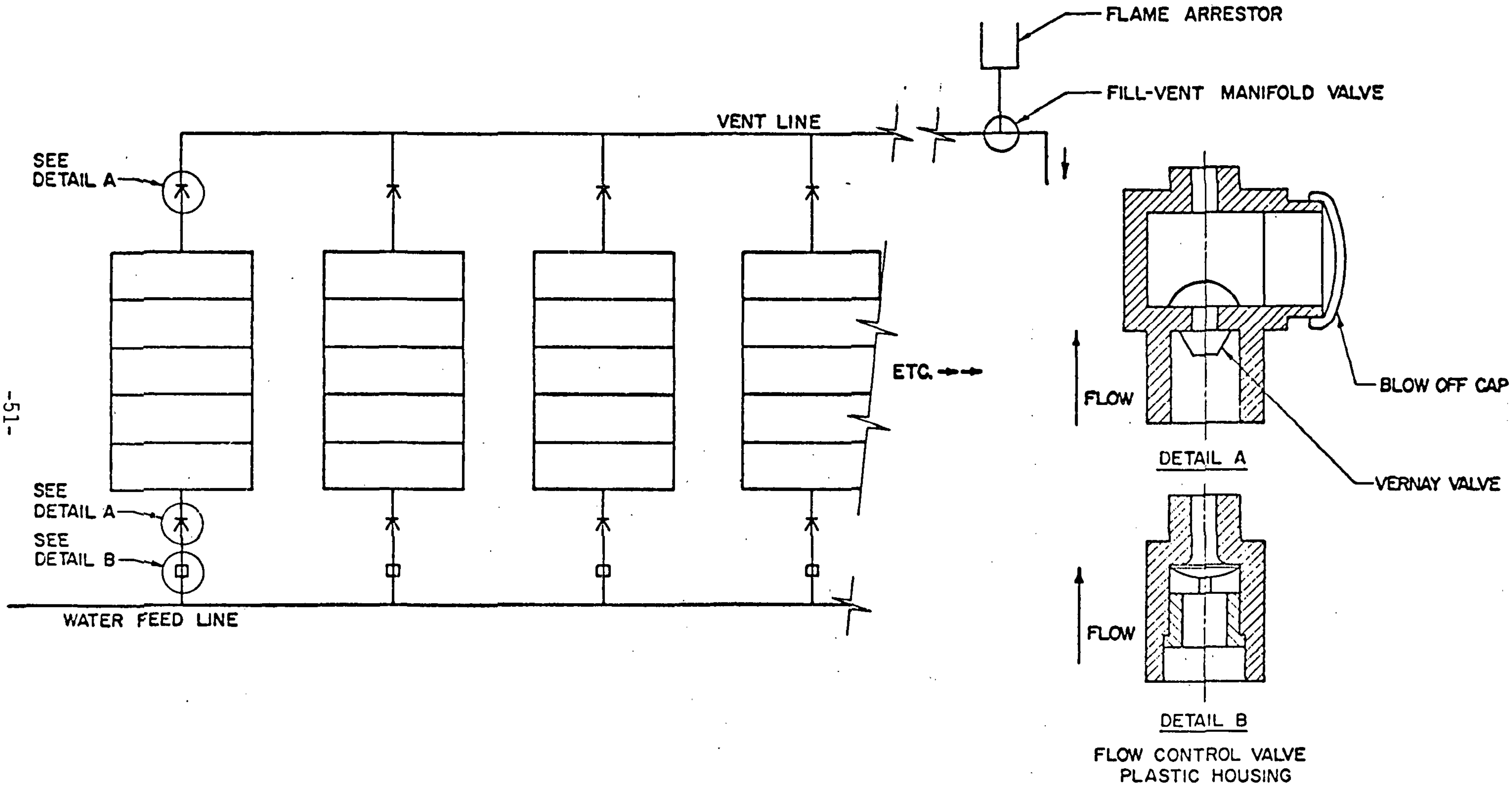


FIGURE 24. PROPOSED INSTALLATION OF FLAME ARRESTOR INTO BATTERY SYSTEM

4.0 Recommendations

The following are recommended for the prevention of flame propagation or detonation in a Ni-Fe battery system.

1. The elimination of possible ignition sources in the battery system is a mandatory prevention measure for safety reasons. An example of an ignition source is a loose intercell connector due to an improperly torqued terminal nut.

2. During the battery charging cycle the current should be tapered to a reasonable low level, 15 hour rate, to reduce the rate of gas evolution.

3. The manifold for watering and venting a battery system should be arranged so that a minimum size and length of tubing will be used. The manifold length between arrestors has a great influence on the resulting flame propagation speed and the possible transition to a detonation which could rupture the system.

4. Rearrangement of the battery water/vent system to adapt the one-way valves for module protection is recommended for further testing and anlysis. See Figure 24.

5. While useful results have been obtained from the funded battery flame arrestor study, continued research and extensive experimentation are required before selected arrestors could be

put to use in a watering/venting system with the assurance they will cover all possible battery operating conditions in an electric vehicle.

6. The air dilution system using a blower is still a good expedient; an effective explosion deterrent device for use in a nickel-iron battery system at this time.

5.0 List of Battery Technical Terms and Symbols

1. Charging - A portion of the battery cycle wherein energy is being stored in the battery.

2. Discharging - A portion of the battery cycle wherein energy is being delivered to an electrical load.

3. Over-Charging - A portion of the battery cycle wherein energy is being applied to a battery which is already charged.

4. Stand - The state of a battery while it's not in use electrically.

5. C/6 - The battery capacity in amp-hours, divided by a time in hours indicates the magnitude of a current in amperes, charge or discharge. C/6 amperes would be a current which would charge or discharge a battery in six hours.

6. Head Space - The space above the plates and below the cover of a battery.

7. Stoichiometric - The point at which the quantity relationship of chemical reactants is the same as in the products they will form.

8. Detonation - Is combustions at a speed well above the speed of sound in the unburned gas mixture, usually 1 mile per second or higher.

9. Deflagration - Is combustion at speeds below the speed of sound in the unburned gas mixture.

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