COAL/OIL SLURRY COMBUSTION AND TRIBOLOGY - A CANADIAN EXPERIENCE

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Abstract

The Ontario Research Foundation has undertaken various coal slurry combustion R D & D projects during the past several years. The majority of this work was performed under the sponsorship of the Federal Department of Energy, Mines and Resources. The Ontario Research Foundation has recently completed a comprehensive project directed towards practical retrofitting of existing oil fired industrial systems to coal slurry firing.

This paper discusses the technical aspects relating to the wear characteristics of present generation burner fuel management systems while operating with a typical coal/oil slurry consisting of high ash coal from Eastern Canada. Two 300-hour firing tests were carried out using two industrial burners; one employed external atomization while the other utilized internal atomization. The tests were successfully carried out in a water tube test boiler originally designed to operate on oil. The major objective of the project was to evaluate the wear characteristics of a fuel delivery system and burner fuel tips employed during the 300-hour long duration combustion tests.

The test procedures used to evaluate wear in the fuel nozzles and assess the overall performance of the boiler are presented. Instrumentation used in the tests is discussed. Analyses and evaluations relating to boiler efficiency, carbon conversion, flyash characteristics, ash deposition, particulate and gaseous emissions and wear are also addressed.

Introduction

The continuous emphasis on reducing Canada's dependence on foreign oil has reflected in the priorities established by the Department of Energy, Mines and Resources (EMR) in implementing the coal conversion technology program. As part of this program, during 1978, the Ontario Research Foundation successfully demonstrated that present generation industrial burners can be used with coal/oil slurries without major modifications.

Earlier programs, carried out by ORF and others, have identified the significant contribution coal can make in reducing our consumption of fuel oil. However, in numerous programs wear problems have been experienced. This has been particularly evident with coal/oil slurries utilizing coals with high ash content.

Under the present economic environment there is an added incentive for utilizing coal/oil slurry technology in Eastern Canada where fuel oil consumers do not have viable alternative energy substitutes. Potential users of this technology are generally willing to implement conversion programs only if "trouble-free" and efficient operation can be achieved with existing hardware, and if conversion costs are low.

The factors affecting the design and wear characteristics of existing generation burner systems for conversion to coal/oil slurry are not well documented and continue to be areas of concern.

Recognizing this technology gap, the Canada Centre for Mineral and Energy Technology, Energy, Mines and Resources, Canada, commissioned the Ontario Research Foundation to undertake a comprehensive test program to provide technical and scientific information relating to the wear characteristics of fuel delivery components during extended coal/oil slurry combustion tests.

The long-term firing tests reported herein were carried out using coal/oil slurry with 40% w.w. coal in No. 6 oil. Prince Mine coal from Eastern Canada was used as the candidate coal because of its inherently high ash content.

Program Objectives

The objective of this research program was to develop a data base on wear characteristics of fuel delivery and atomizing systems of existing generation industrial burners during the extended combustion tests, using coal/oil slurries containing up to 40% w.w. beneficiated Prince Mine coal. In addition, the following important parameters associated with the combustion process were evaluated:

- Assessment of suitable wear resistant materials for critical burner components such as fuel tips, atomizers, etc.
- Assessment of the long-term operability of industrial boilers when firing with coal/oil slurry
- Evaluation of boiler efficiency in conjunction with slagging/fouling of the heat transfer surfaces.
- Quantification of gaseous and particulate emissions after long-duration firing tests.
- Qualitative assessment of flyash deposits on the heat transfer surfaces.
- Quantification of combustibles in the flyash.

The ORF test facilities used to carry out this research program are shown schematically in Figure 1. The facilities include the following major areas:

- Coal Processing
- Coal/oil Slurry Preparation and Delivery
- Combustion Facilities

Coal Processing

The first step in the process was to grind the pre-washed Prince Mine coal in ORF's pilot plant facilities. Two grinding processes were employed:

- Dry Grinding
- Wet Grinding

Dry Grinding: Part of the 60 tons of coal received was ground in a 4½' diameter Denver air swept ball mill. Process conditions were maintained to provide a final pulverized coal size of 90% through 200 mesh. The ground coal was dried, weighed and stored in 100-pound plastic bags.

Wet Grinding: A portion of the coal was prepared using wet grinding followed by a froth flotation beneficiation process. The wet grinding was carried out in a 3' diameter Denver ball mill where the coal was ground to nominally 90% through 200 mesh. The wet product was then beneficiated in a series of flotation cells. Varsol and MBIC frother were used as the flotation reagents. The froth product solids were separated in a Bird Solid Bowl Centrifuge and dried. The drying stage included both floor and electrical drying using 60 kW quartz heaters. Finally, the pulverized coal containing nominally 5% water was weighed and stored in 100-pound plastic bags. The analysis of the coal and oil used in the slurry is given in Table 1.

Coal/Oil Slurry Preparation and Delivery

ORF's previous research in coal/oil slurry demonstrated that a stable slurry could be produced utilizing low shear blending equipment, (i.e. propeller mixers).

Accordingly, the coal/oil slurry was prepared in a steam heated 100-gallon mixing tank which incorporated a 5" diameter propeller mixer driven by a 3 H.P. motor at 1750 r.p.m.

The slurry was prepared in batches by mixing a metered amount of No. 6 oil with measured amounts of "wet" and "dry" ground coal to provide a consistent ash concentration. Mixing continued for nominally forty-five minutes at a temperature of 175°F. The slurry was then transferred to a 500-gallon steam heated storage tank equipped with a propeller agitator to maintain proper solids suspensions and slurry uniformity.

Slurry fuel delivery to the test burner was achieved using a progressing cavity Moyno pump, Model 6M2CDQ, driven by a variable speed

D.C. motor. Fuel delivery rate was regulated by the variable speed pump. The fuel delivery system was designed so that the piping network used could be easily cleaned with oil after firing with coal/oil slurry. The fuel train was equipped with an in-line fuel preheater, control valves and strainer systems. A schematic of the coal/oil slurry preparation facility and fuel delivery system is shown in Figure 2.

Combustion Equipment

Boiler: The combustion equipment consisted of a packaged hot water test boiler with a single burner. This boiler was originally designed to operate with natural gas or oil and is shown in Figure 3. The boiler (Model L80), manufactured by Brian Steam Corporation, consists of a heavy steel boiler frame with downcomers on each side to enhance internal circulation and temperature equalization. The 4 ft W x 4 ft H x 10 ft L firing chamber is lined with high temperature insulating firebrick. The heat transfer section utilizes 2½" rigid board high temperature insulation to reduce jacket losses. The boiler utilizes "Bent Tubes" arranged in an "S" formation as the heat transfer tubes. The boiler system can be maintained at any desired steady state load since the hot water generated is not used in any other process. The only modifications made to the boiler were those required on the boiler front face to allow accommodation of the two test burners and to incorporate appropriate instrumentation sensors.

Test Burner: Two generic types of burner systems were employed in the program:

- External Fuel Atomization
- Internal Fuel Atomization

Externally Atomized Burner: A 10MM BTU/hr Vortometric[R] burner, shown in Figure 4, was chosen to represent the externally atomized category. The burner is designed to operate with liquid industrial fuels such as No. 6 fuel oil with clean combustion at low excess air levels. The burner exhibits good turn-down capabilities at low excess air and low pressure operation. Since fuel atomization occurs external to the atomizer assembly, pressures of fuel and atomizing medium are essentially independent of each other.

The atomizing medium (steam or air) is supplied through a separate passage and enters the atomizer gallery surrounding a vortex chamber. The fluid enters the vortex chamber through precision made tangential venturi inlets. In the vortex chamber, the velocity of the atomizing fluid increases as the fluid moves inward. At the discharge the fluid velocity is essentially sonic and velocity components are designed to produce a wide spray-angle and generate acoustical energy.

The fuel is delivered to the burner fuel tip through a centrally located fuel pipe. Six .047" diameter fuel orifices are machined at precise angles and locations. The low velocity fuel is directed into the high vortex atomizing zone surrounding the fuel tip. By the combined action of shear and absorption of acoustical energy the fuel is evenly atomized.

Internally Atomized Burner: A Peabody burner, Model F14.1-0-75-F9 HZ designed for oil firing at nominally 10 MM BTU/hr, was employed. The burner is of the internally atomized design and utilizes steam as the atomizing medium. Essentially the atomizer nozzle, shown in Figure 5, consists of a diverter, a mixer and a fuel tip. These intricate components direct the fuel and atomizing fluid through various premixing stages which provide a homogeneous slurry feed. The fuel is ejected through ten, 0.081" diameter fuel orifices to provide an even spray.

Prototype wear resistant burner fuel tips were manufactured to the original design specifications from M2 general purpose tool steel. Two fuel tips for each burner were manufactured from the M2 material in an annealed state. The fuel tips were then heat treated to develop a surface hardness of ∿60 Rc. One fuel tip for each burner was "nitrided" following heat treatment which resulted in a final surface hardness of 70 Rc (nominal).

Each of the test burners equipped with the prototype wear resistant fuel tip was operated at 1200 kW (4 MM BTU/hr) with 20% excess air. The firing tests were conducted in ORF's dedicated test boiler for a period of 300 hours with each test burner.

Instrumentation

To effectively address the program objectives operational data was collected throughout the long-term firing tests. Monitoring instrumentation consisted of various on-line analysers. Combustion variables, including oxygen, carbon monoxide and carbon dioxide, were monitored continuously using paramagnetic and infra-red analyses respectively.

Combustion airflow was monitored using a multipoint sampling grid in the blower inlet duct. Pertinent process temperatures were obtained using appropriate thermocouple instrumentation. Nitrogen oxides and sulphur dioxide emissions were measured in the exhaust gas using recognized test procedures. Particulate emission concentrations in the exhaust gas were evaluated using EPA Method 5.

Additional test data was obtained through analyses using specific procedures developed for this project.

The majority of on-line parameters monitored were transmitted and recorded on a 64-channel Esterline Angus data acquisition system. The data was stored on magnetic tape which, when interfaced with a Hewlett Packard 9826 mini-computer, allowed further data analyses.

Wear Evaluation

Three wear evaluation procedures were used during the program. These are:

- Weight Loss Analyses
- Microphotographic Analyses
- Massflow Resistance Analyses

These three procedures were used to compare the progressive wear characteristics of the burner fuel tips used. The procedures are briefly described below.

Weight Loss Analyses: The initial weights of the fuel tip under consideration were determined prior to the long-term combustion tests. The incremental weight loss was determined at each 50-hour test interval. This was accomplished by removing the fuel tip from the burner nozzle assembly, followed by a thorough cleaning process and weighing of the fuel tip using a precision Mettler scale having 0.1 milligram resolution.

Microphotographic Analyses: Initially microphotographs of each fuel tip orifice were taken and the total baseline fuel tip area was determined. Fuel tip holder assemblies were designed to ensure that the photographs taken were always at right angles to the fuel orifice. For the Vortometric burner, microphotographs of the fuel tip orifices were taken at a magnification of 50X, whereas the Peabody orifices were magnified by a factor of 30.

This test procedure was repeated at 50-hour test intervals following the weight loss analyses and the new total fuel orifice area was determined. Comparisons were then made with the baseline fuel tip area and the rate of increase was determined.

Massflow Resistance Analyses: The facility shown schematically in Figure 6 was used to evaluate the mass throughput of city water through the burner fuel tip at a constant pressure following the microphotographic analysis tests. Initial tests were carried out to determine the procedural error band ($\pm$ 0.5%) and to quantify the "baseline" massflow throughput with each burner fuel tip.

The fuel tip was placed in a specially designed adaptor and connected to the piping network. The line pressure was maintained at 20 psig and 5 psig for the Vortometric and Peabody fuel tips respectively. The mass throughput of water over a ten minute period was collected and weighed. This procedure was repeated for each burner tip at 50-hour test intervals and the increased mass throughput at the pre-selected constant pressures was established. The increase in massflow was compared to the "baseline" and the difference recorded.

Test Program

Long duration combustion tests were initiated on June 1, 1981 with the Vortometric[R] burner. Coal/oil slurry fuel was prepared in batches concurrently with the combustion tests as described earlier. During wear analyses, the boiler facility was maintained at thermal equilibrium by firing with natural gas.

During the 300-hour test period the following were evaluated:

- Combustion variables: including CO, CO_2 and O_2 on a continuous basis

- Boiler parameters: including temperatures, pressures and water flowrate on an hourly basis

- Flame characteristics: including stability, colour and concentricity at half-hour intervals

- Boiler efficiency at 12-hour intervals using the input output methods in accordance with ASME, PTC 4.1

- Wear evaluation of burner fuel tips at 50-hour intervals as described earlier

- Fuel delivery variables: including pressure and temperature at one-hour intervals. Coal/oil slurry fuel flowrate was determined on a weight basis at nominally 50-hour intervals

- Flyash collection and analyses for combustibles at each one hundred-hour test intervals

- Exhaust stack variables: including particulates, NO_x and SO_2 at the end of the 300-hour test

- Deposits: at the end of each 300-hour test the boiler was inspected and fouling was assessed.

The Vortometric burner tests were conducted on a 24-hour, five-day week basis with weekend shut-down. During the weekend shut-down a minimum amount of slurry was kept in the storage tank which was allowed to settle. At the beginning of the following week's testing the slurry in the storage tank was preheated and the slurry was reagitated prior to start-up. This mode of operation presented plugging problems during start-up. To overcome this problem, subsequent tests with the Peabody burner were carried out on a 24-hour continuous basis with no planned shut-downs. These tests were undertaken during the period of August 14th to the 31st, 1981.

After completion of each 300-hour test, the boiler combustion chamber and heat transfer tubes were inspected to determine ash accumulations. Following these inspections the boiler was thoroughly cleaned and the other test burner was installed.

Test Results

The test results are summarized in the following four major categories:

- Combustion
- Wear
- Emissiom
- General

Combustion

In general, satisfactory combustion characteristics were observed with both burners throughout the 300-hour continuous firing tests with coal/oil slurry fuel.

The flame characteristics of both test burners with coal/oil slurry fuel were similar to those observed when firing with oil. However, sparks were noticeable in the flame during firing with coal/oil slurry fuel.

Noise and vibration levels did not appear to have any significant change during COM operation with either test burners.

The change in thermal efficiency of the boiler tests as evaluated throughout the 300-hour continuous firing tests with coal/oil slurry is shown in Table 2 and Figure 7.

Carbon burnout efficiency based on analysis of the flyash was calculated to be above 99%. The test results for combustibles in the flyash are given in Figure 8. Flyash deposits were found on the surface of the heat transfer tubes and on downcomer support ledges.

Wear

The wear resistance performance of the Vortometric burner fuel tip is illustrated in Table 3 and Figures 9 and 10.

The wear resistance performance of the Peabody burner fuel tip is shown in Table 4 and Figures 9 and 10.

The surface hardness of both burner fuel tips did not show apppreciable change at the end of the test program.

The area of fuel tip orifices progressively increased throughout the test period. Figures 11 and 12 show microphotographs of the orifices before and after the 300-hour test period for the Vortometric and Peabody burners respectively.

The fuel delivery rate of the "Moyno" fuel pump decreased during the 300-hour test period. Figure 13 shows the pump performance over the test duration. The drop in delivery rate is attributed to wear of the pump stator/rotor assembly.

Emissions

The isokinetic particulate test results for both the Vortometric and Peabody burner tests are given in Table 5.

Gaseous emission data for NO_x and SO_2 for both the Vortometric and Peabody burners are given in Table 6.

Carbon monoxide concentration in the exhaust gas ranged between 20-300 ppm with the Peabody burner and 50-80 ppm with the Vortometric burner.

General

Plugging problems in the fuel tips and strainers were experienced during the program, however, in most instances these were readily corrected. On a few occasions the burner nozzle assemblies had to be dismantled to remove foreign material or oversize coal particles.

Problems were experienced during start-up after the slurry fuel had been left in the storage tank over the weekend. On two occasions the "Moyno" pump seized and had to be freed by dismantling.

Inspection of the boiler facility following the 300-hour test with the Vortometric burner revealed that extensive damage to the refractory had occurred. The cause for the refractory breakdown is attributed to the thermal shock that it was subjected to as a result of weekend shut-downs. New refractory was installed and the tests with the Peabody burner were carried out on a continuous basis with no shut-down. Final inspection following the 300-hour test with the Peabody burner did not reveal any refractory damage.

Discussion of Test Results

The flame pattern and stability of both the Vortometric and Peabody burners during coal/oil slurry firing was similar to that of oil. During the extended combustion tests, qualitative flame observations were made by technical personnel. The flame was viewed from an observation port located at the rear of the test boiler directly opposite to the burners.

It was generally found that the flame envelope was well defined and stable. The flame colour of the coal/oil slurry fuel appeared to be slightly more orange than an oil flame and some sparks were noticeable.

There was an apparent drop in boiler efficiency (less than 5%) when operating with coal/oil slurry fuel. The boiler efficiency appears to deteriorate with test duration. Efficiency was calculated using the ASME Input-Output method and is related to slurry feedrate. Since slurry feedrate was determined from pump calibration which was carried out at 50-hour intervals, deviations in feedrate were possible which could have resulted in slight errors in the energy input values used in the efficiency computations.

In addition, the efficiency reduction observed is the result of fouling of the heat transfer tubes and subsequent increase of stack temperature. Carbon monoxide levels in the flue gases were low throughout the coal/oil slurry combustion tests. This supports the theory that the drop in boiler efficiency was a result of poor heat transfer rather than due to incomplete combustion.

It is not surprising to find that substantially greater wear was observed with the internally atomized Peabody burner than the externally atomized Vortometric burner. The diameters of the orifices exhibited concentric wear. A significant portion of the total wear occurred during the initial 50-hour test period. An increase in the discharge coefficient of both test burners was found during the initial 50-hour firing period. The increase in the discharge coefficients is attributed to the smoothing of the sharp inlet edge of the orifices. It is hypothesized that once rounding of these sharp edges takes place the discharge coefficients remain essentially constant for the remainder of the test period. Table 7 shows the theoretical massflow and the measured massflow with both fuel tips used and their respective discharge coefficients.

Nitriding of the M2 tool steel improves its wear resistance. A preliminary test of 50 hours duration was carried out to compare the wear characteristics of a Vortometric fuel tip hardened and nitrided to nominally 70 Rc with one that was only hardened to nominally 64 Rc.

Results obtained show that the nitrided fuel tip exhibits improved wear resistance to coal/oil slurry fuel. During the 50-hour test period the nitrided fuel tip experienced nominally 25% of the wear experienced with the hardened fuel tip. Based on these results it was decided that the tests with the Peabody burner would be carried out using the "nitrided" fuel tip.

The particulate emission tests conducted show that a large portion of the ash generated during the tests remained in the boiler. Inspection of the boiler following each 300-hour test period substantiated this. A considerable amount of flyash was found on the trailing edge of the boiler heat transfer tubes and on the horizontal header support in the convective section. The deposits, reddish-brown in colour, were easily removed using an industrial vacuum cleaner. No evidence of slagging was observed. This is supported by the fact that the flue gas temperatures recorded in this region ranged between 1200°F and 1500°F. This temperature range is well below the ash fusion temperature for the Prince Mine coal.

Slight slagging occurred on the boiler sidewalls when operating with the Vortometric burner. This, however, is attributed to the relatively close proximity of the walls with the flame envelope.

Conclusion

Coal/oil fuels offer a near-term solution to extending the availability of fuel oil. Present generation boiler and burner systems can be operated with coal/oil slurry fuels without appreciable loss in performance and reliability. Nozzle wear in critical burner components can be minimized by using appropriate wear resistant materials such as hardened M2 tool steel. Wear in externally atomized burner systems is significantly lower than in internally atomized burner systems when operating with coal/oil slurry.

Modifications required to retrofit industrial oil-fired boilers to coal/oil slurry can be made at relatively low cost. Soot blowing and flyash collection systems are recommended when converting to coal/oil firing.

Acknowledgements

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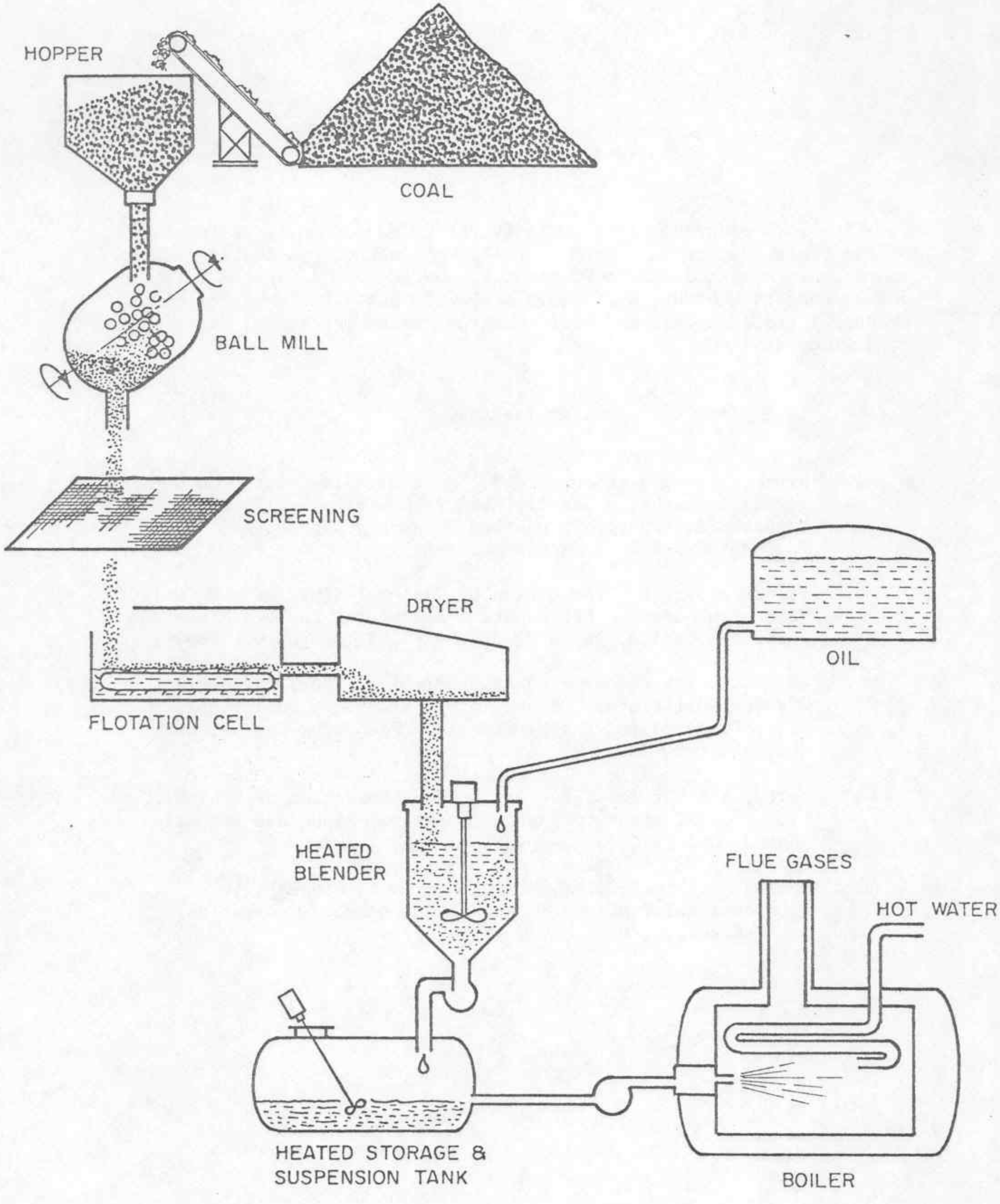


FIGURE 1. SCHEMATIC OF COAL OIL FACILITIES

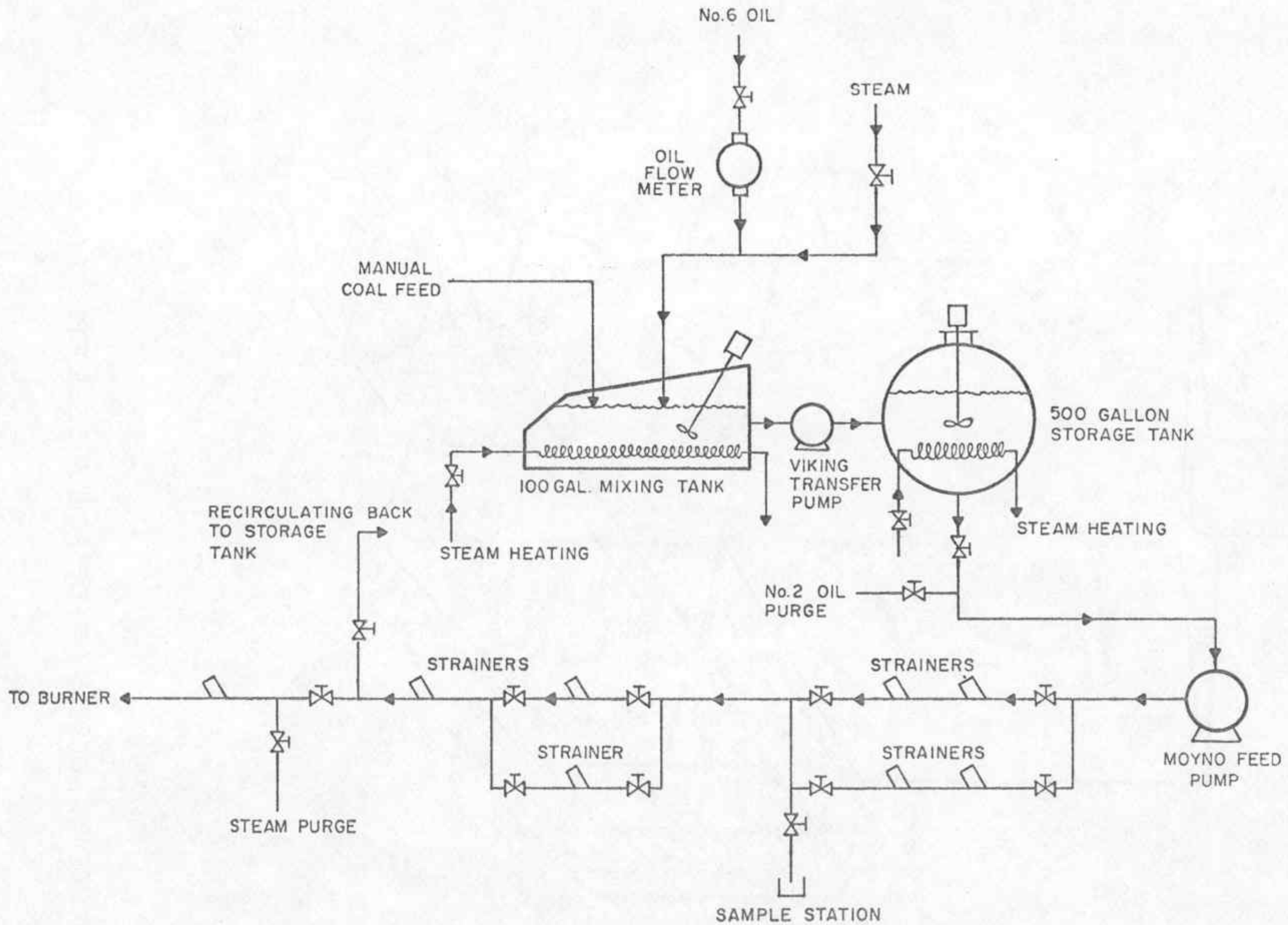


FIGURE 2. COAL OIL SLURRY FUEL DELIVERY SYSTEM SCHEMATIC

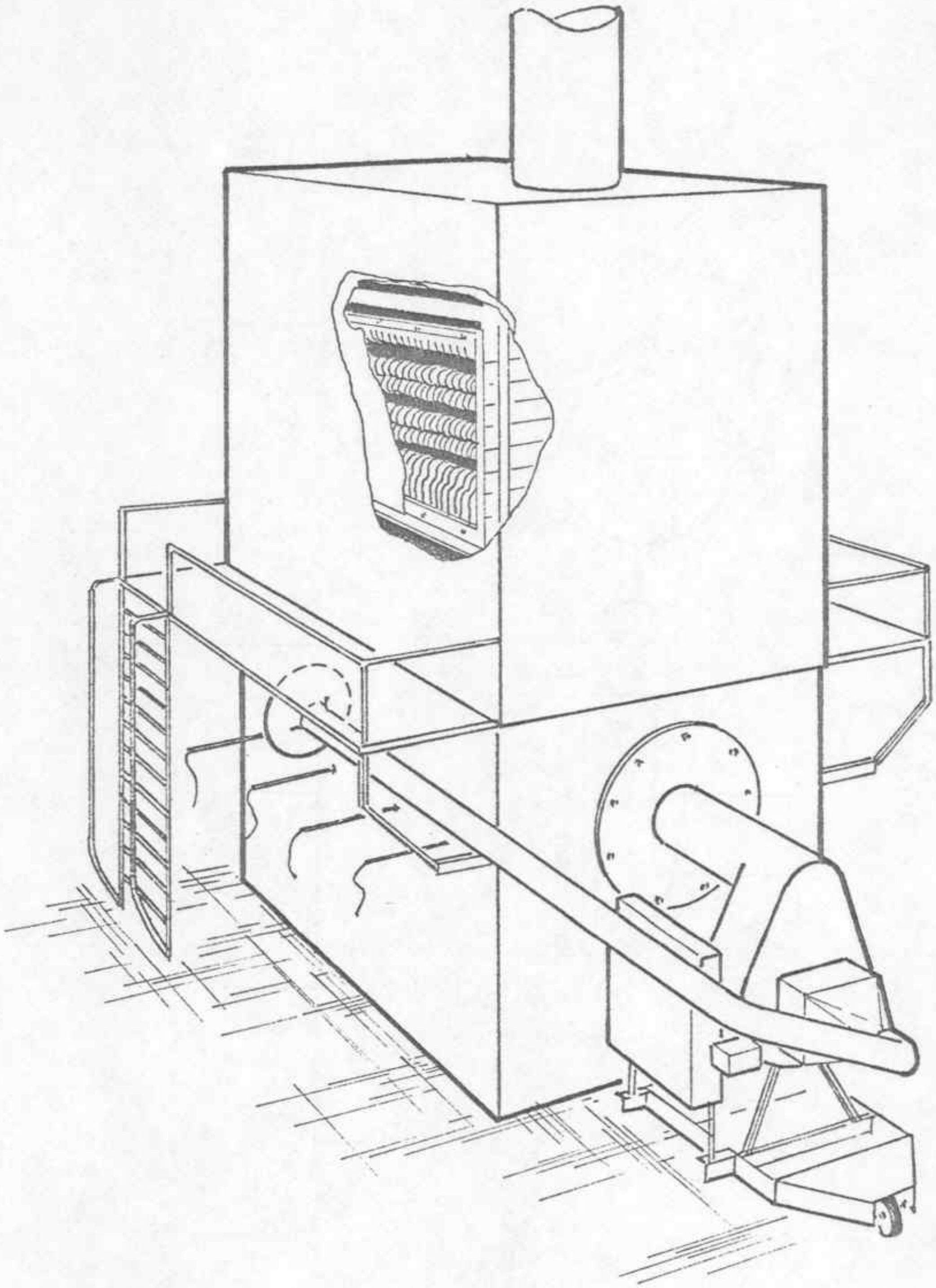


FIGURE 3. SCHEMATIC OF BOILER TEST FACILITY

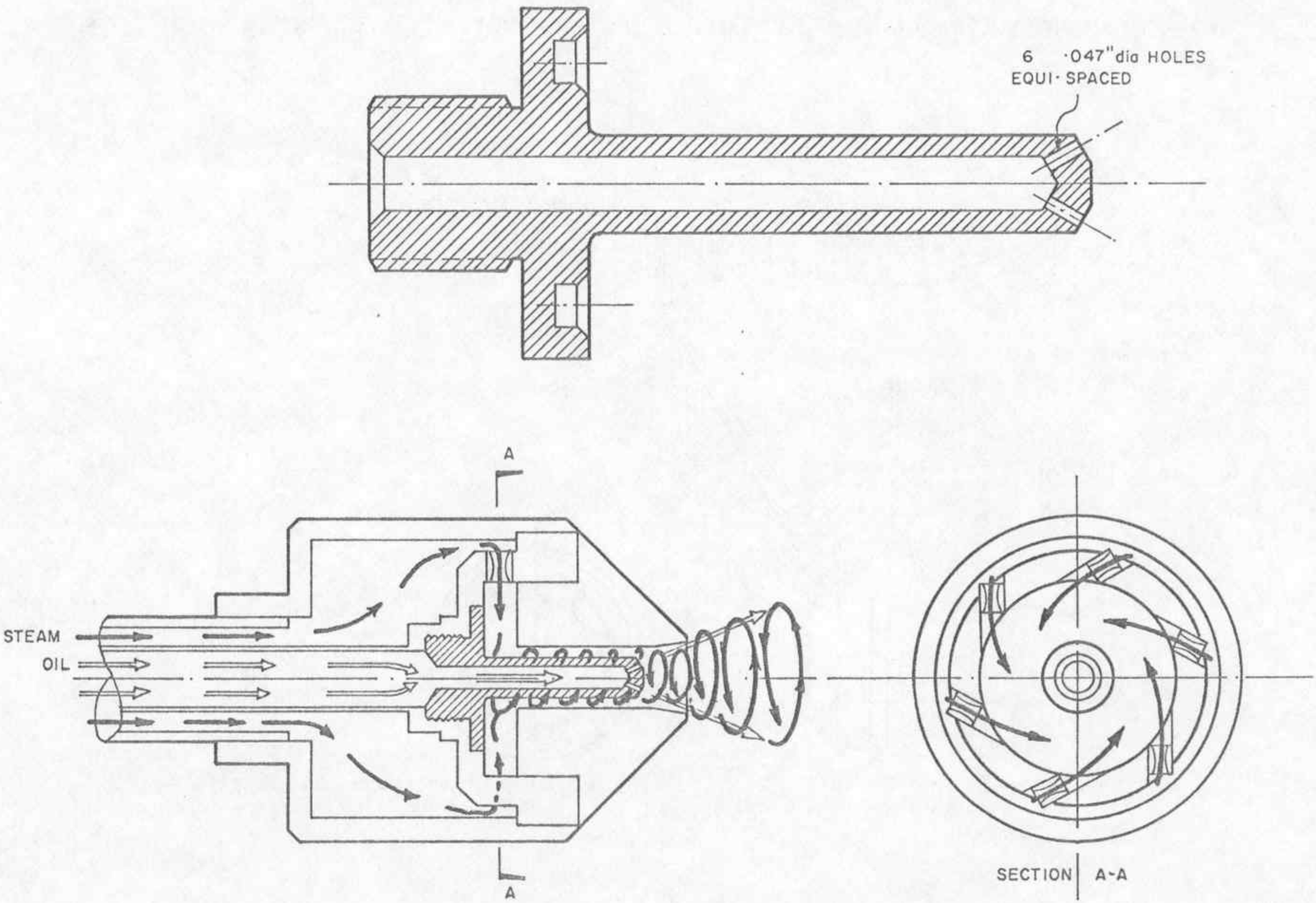


FIGURE 4. VORTOMETRIC BURNER FUEL TIP (EXTERNAL ATOMIZATION)

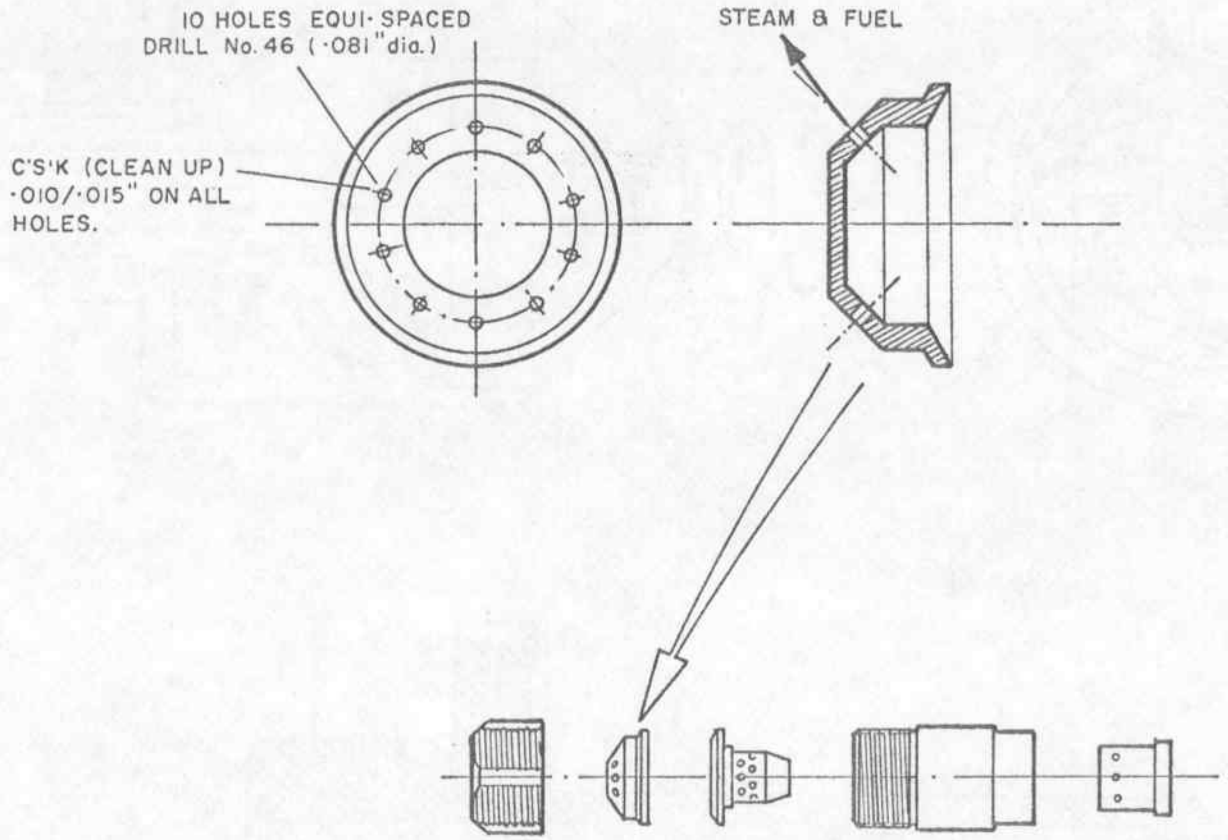


FIGURE 5. PEABODY BURNER FUEL TIP. (INTERNAL ATOMIZATION)

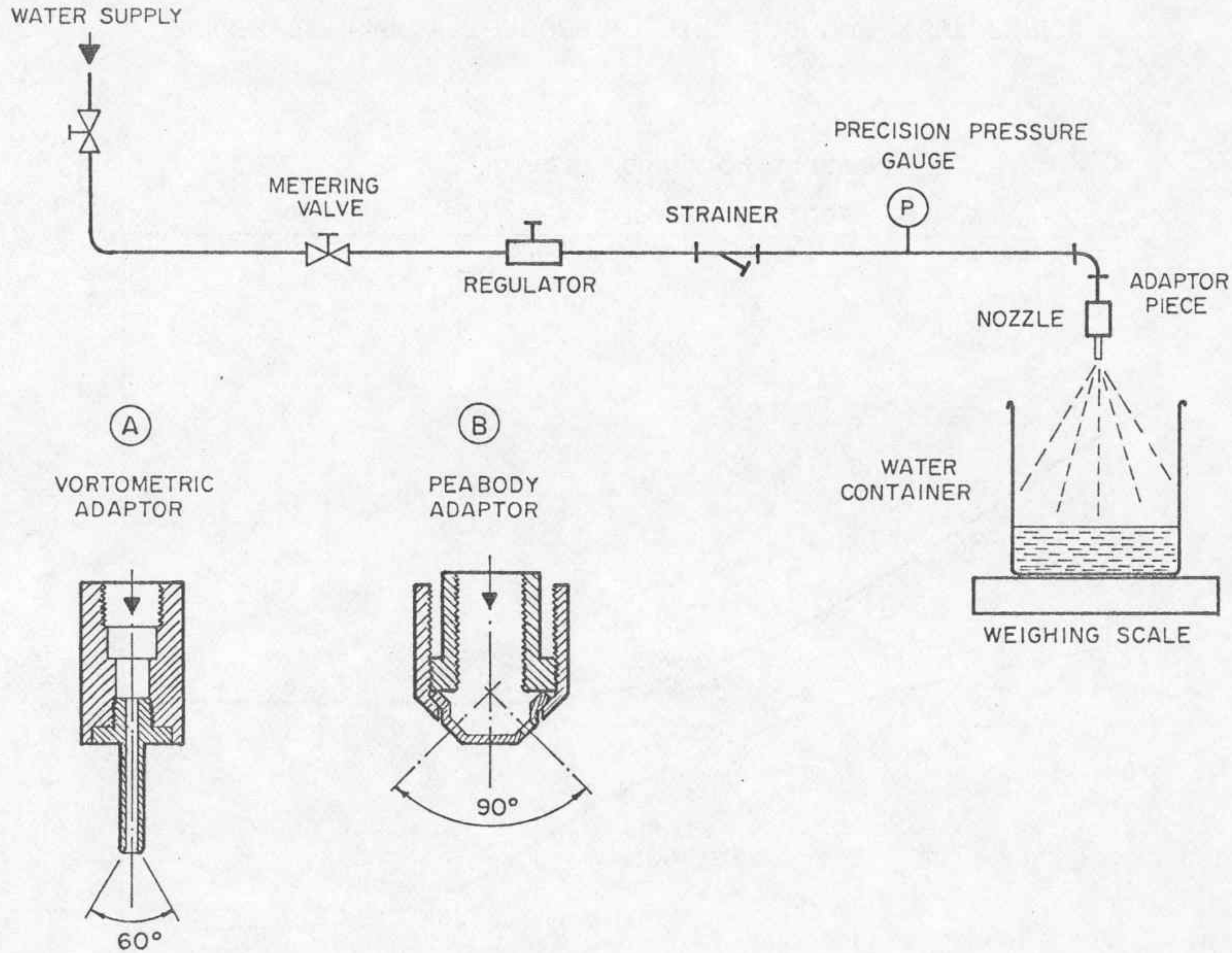


FIGURE 6. MASSFLOW RESISTANCE ANALYSIS TEST FACILITY.

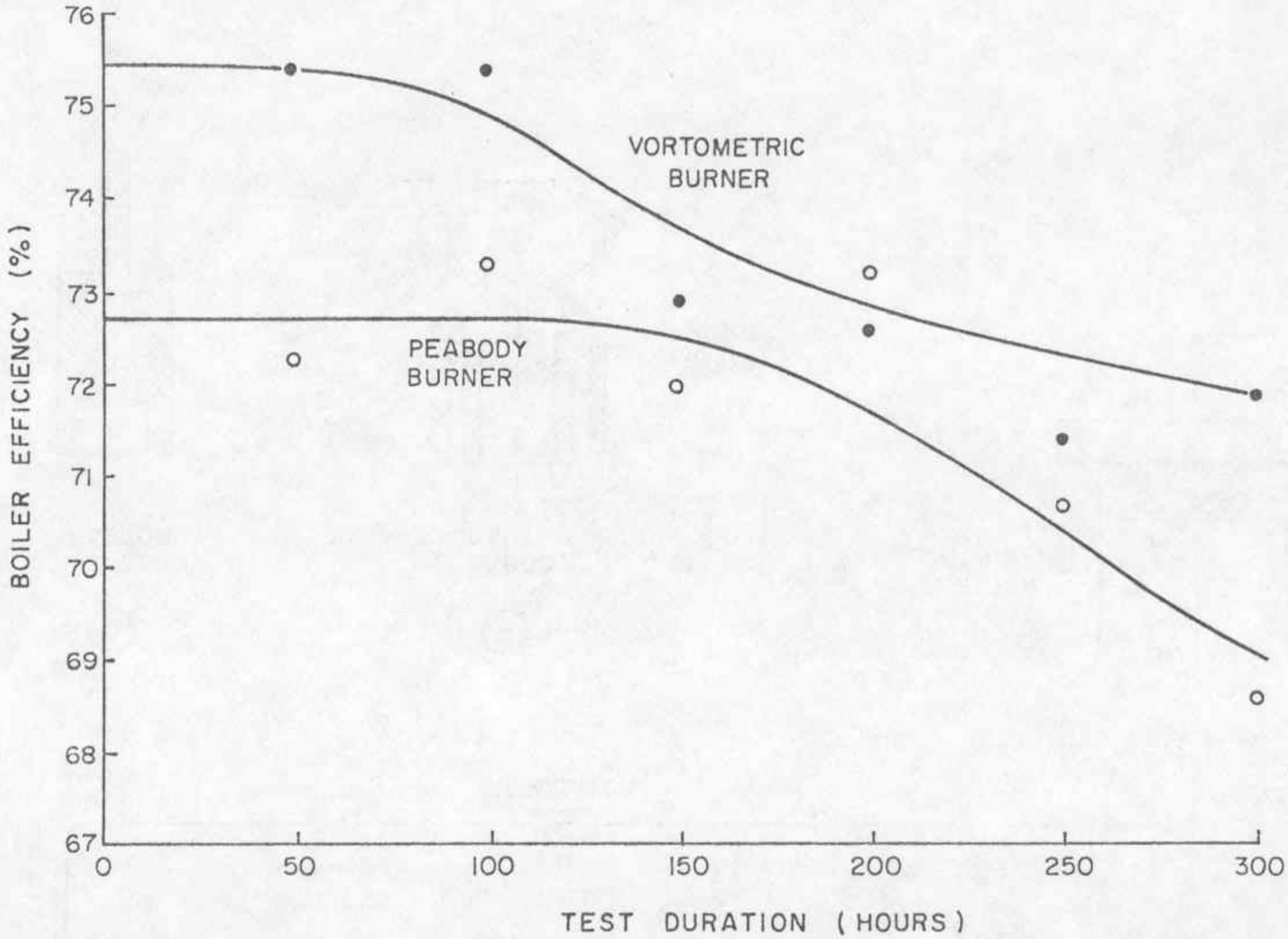


FIGURE 7. BOILER EFFICIENCY THROUGHOUT THE 300HOUR TEST PERIOD

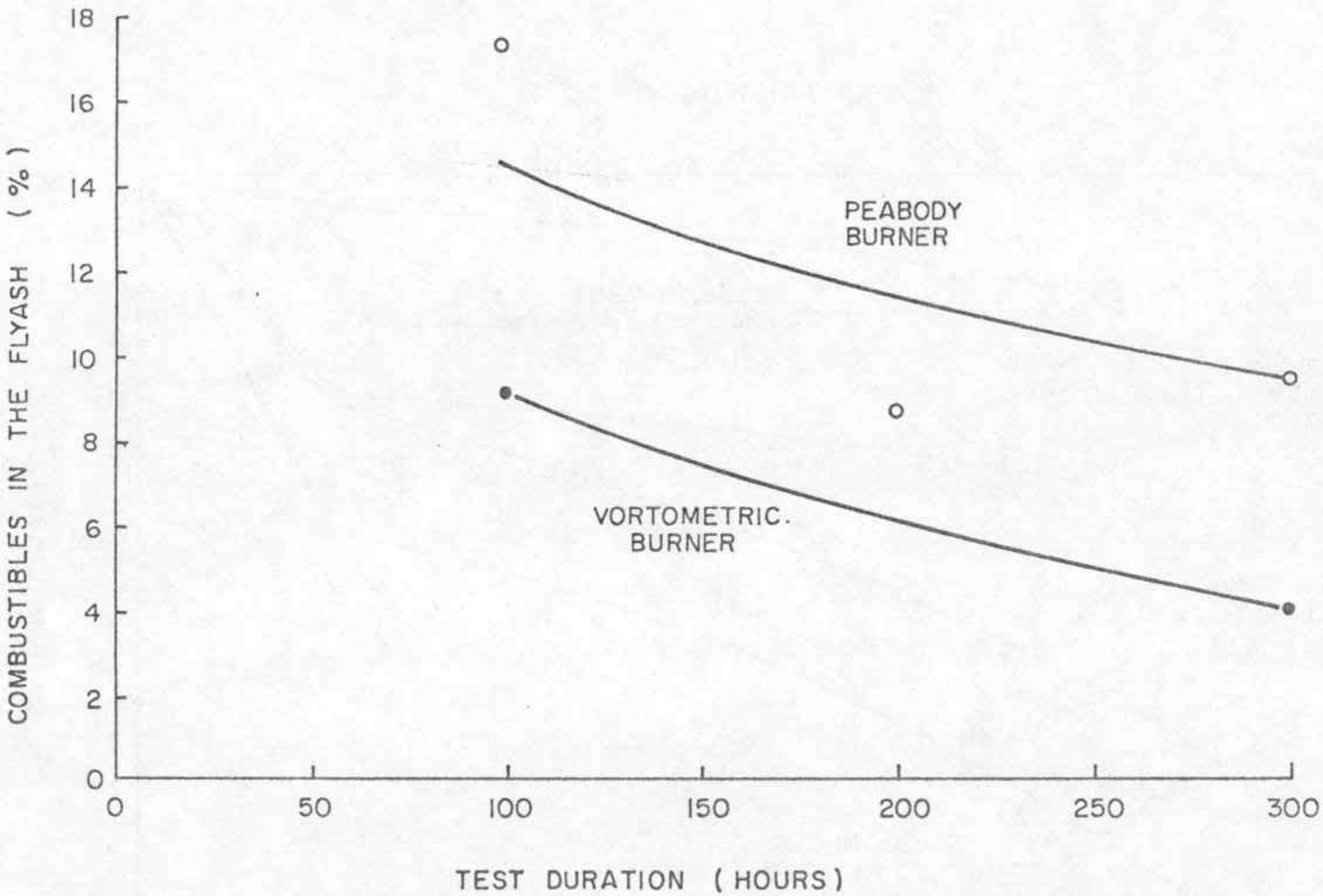


FIGURE 8. PERCENT COMBUSTIBLES IN FLYASH

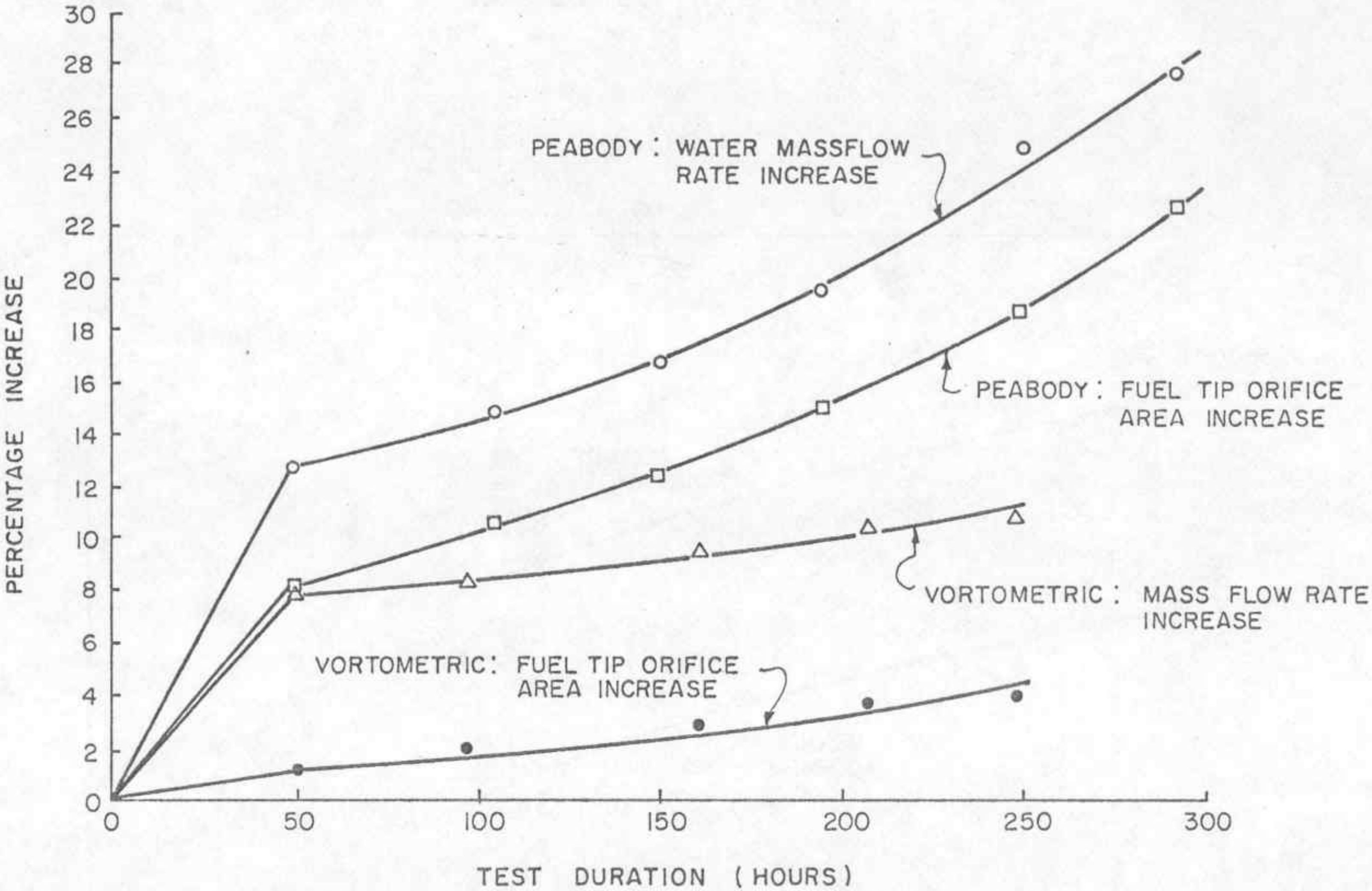


FIGURE 9. FUEL TIP WATER MASSFLOW RATE & ORIFICE AREA INCREASE OVER THE 300 HOUR TEST PERIOD

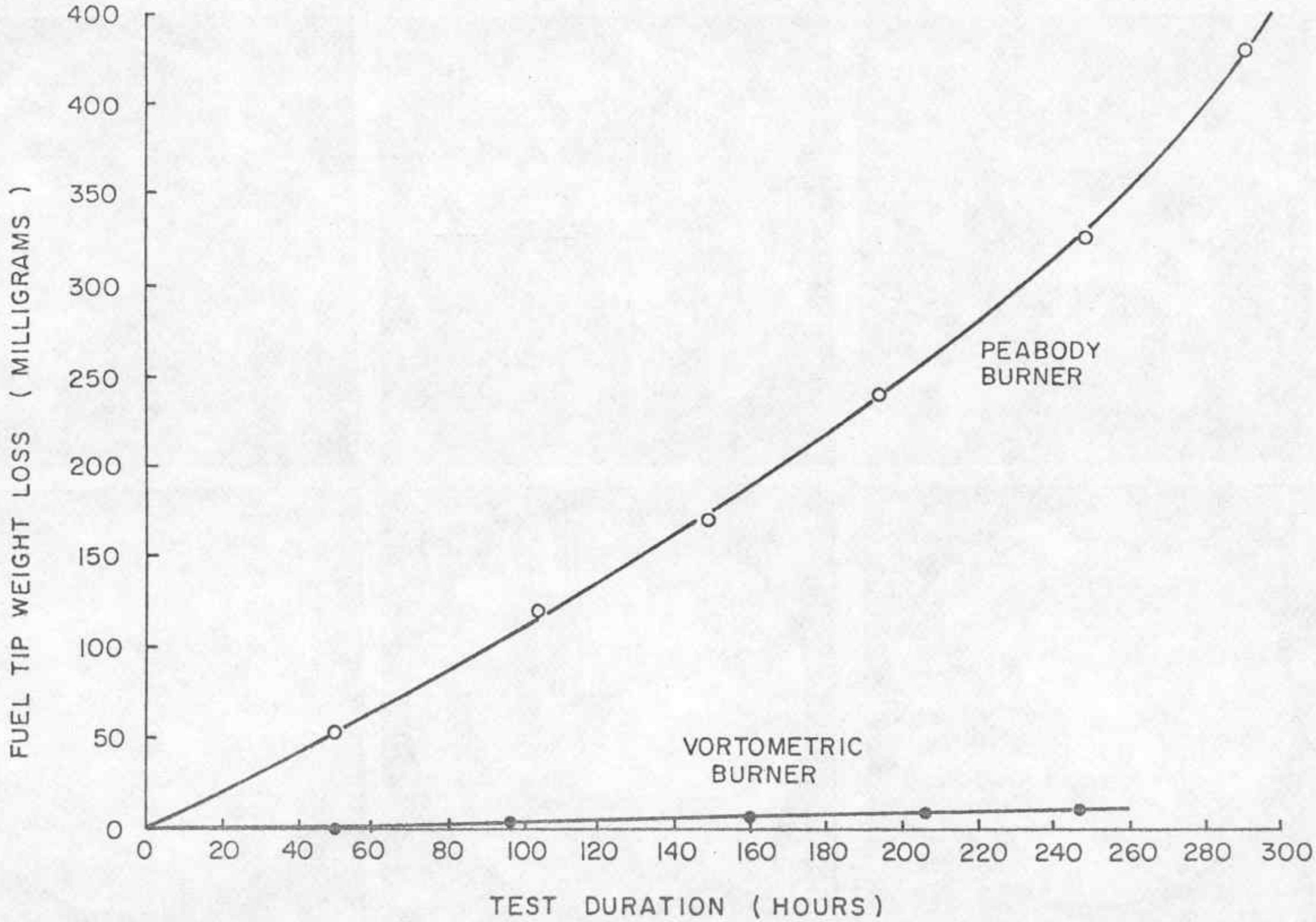


FIGURE 10. FUEL TIP WEIGHT LOSS OVER THE 300 HOUR TEST PERIOD.

Figure 11: Photographs of the Vortometric Burner Fuel Tip Orifices Before and After the 300-hour Test (50X Mag.) (M-2 Tool Steel Hardened to 64 Rc)

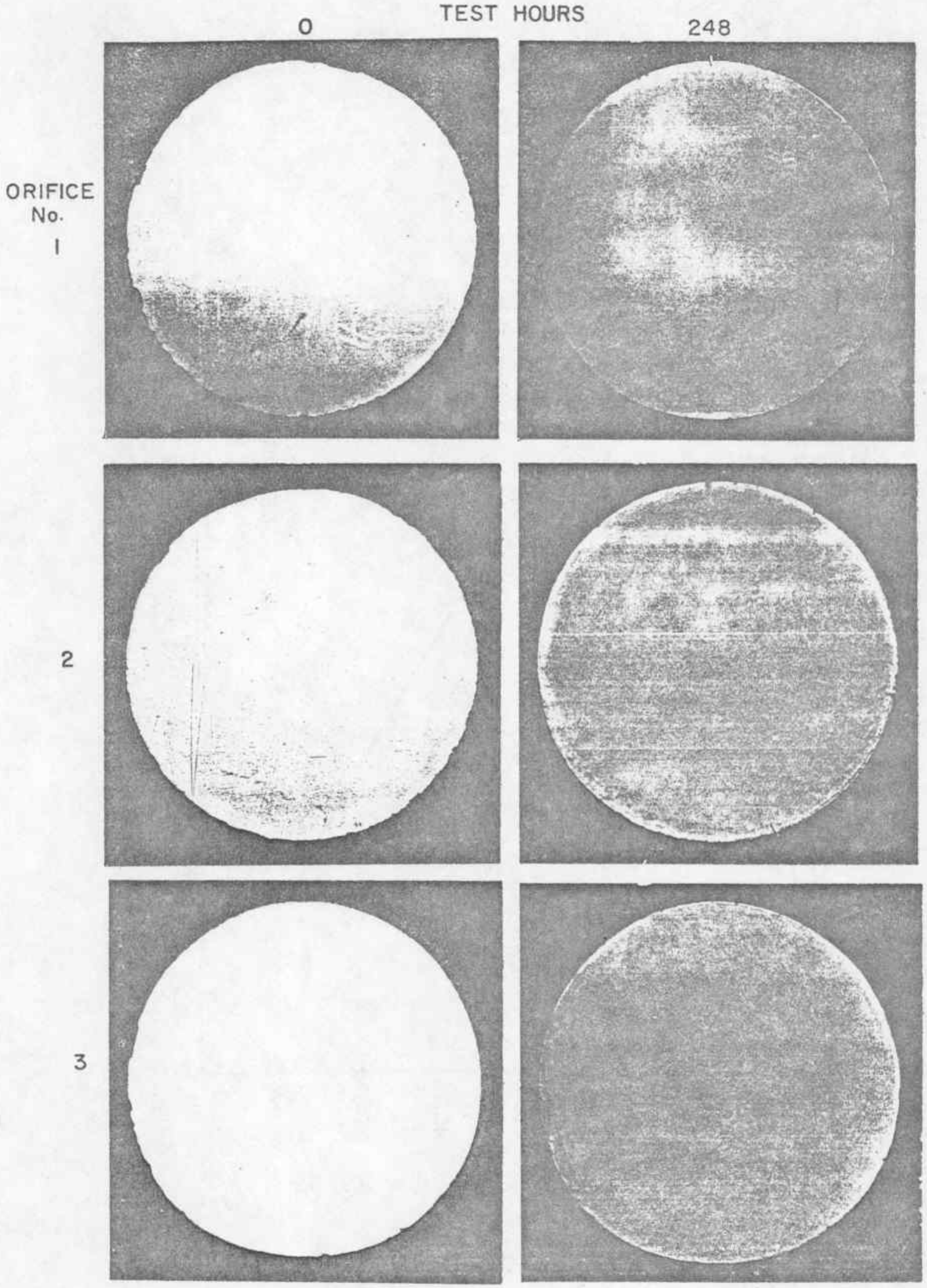


Figure 11/Continued... Photographs of the Vortometric Burner Fuel Tip Orifices Before and After the 300-hour Test (50X Mag.) (M-2 Tool Steel Hardened to 64 Rc)

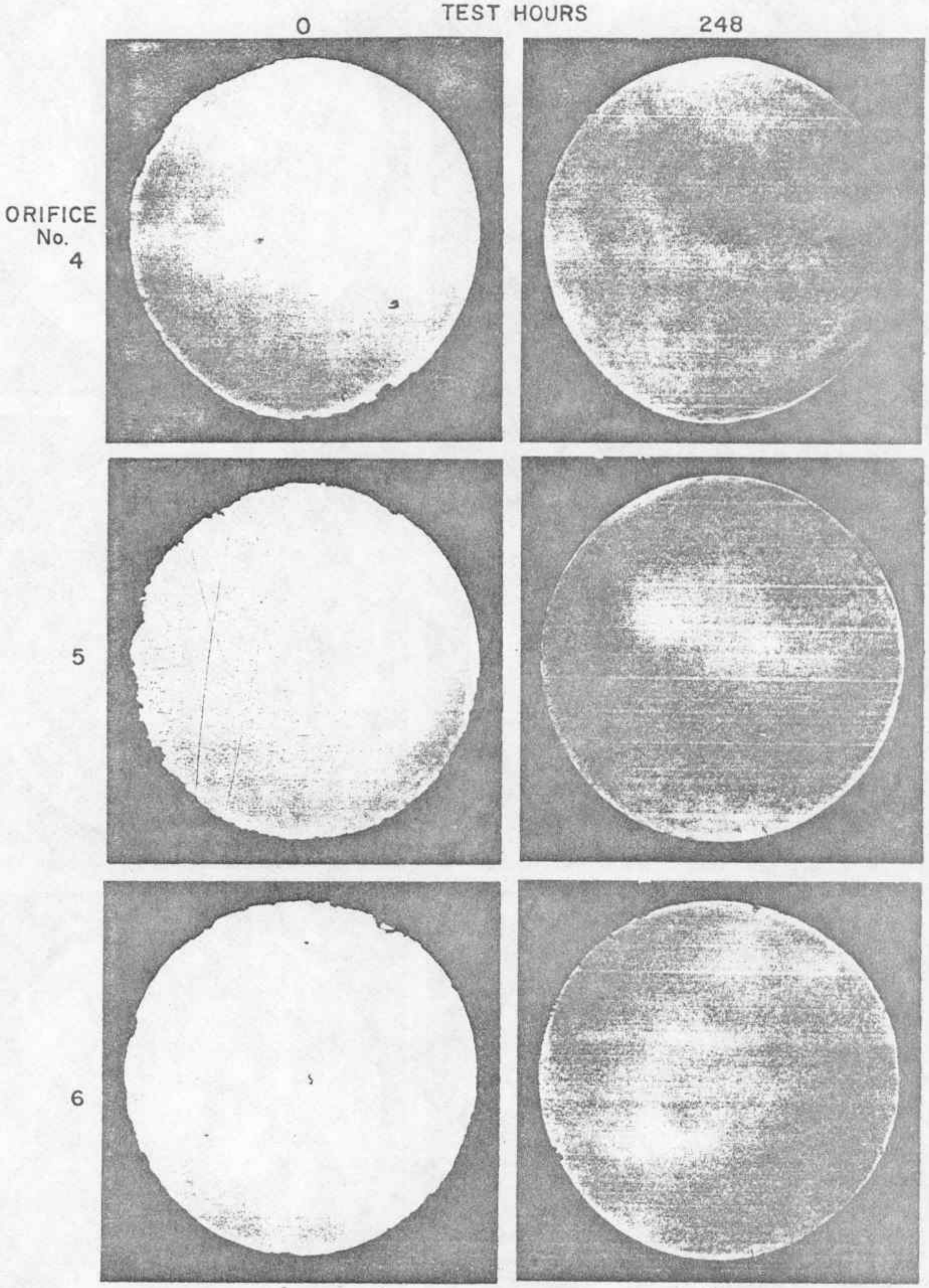


Figure 12: Photographs of the Peabody Burner Fuel Tip Orifice Before and After the 300-hour Test (30X Mag.) (M-2 Tool Steel Hardened and Nitrided to 70 Rc).

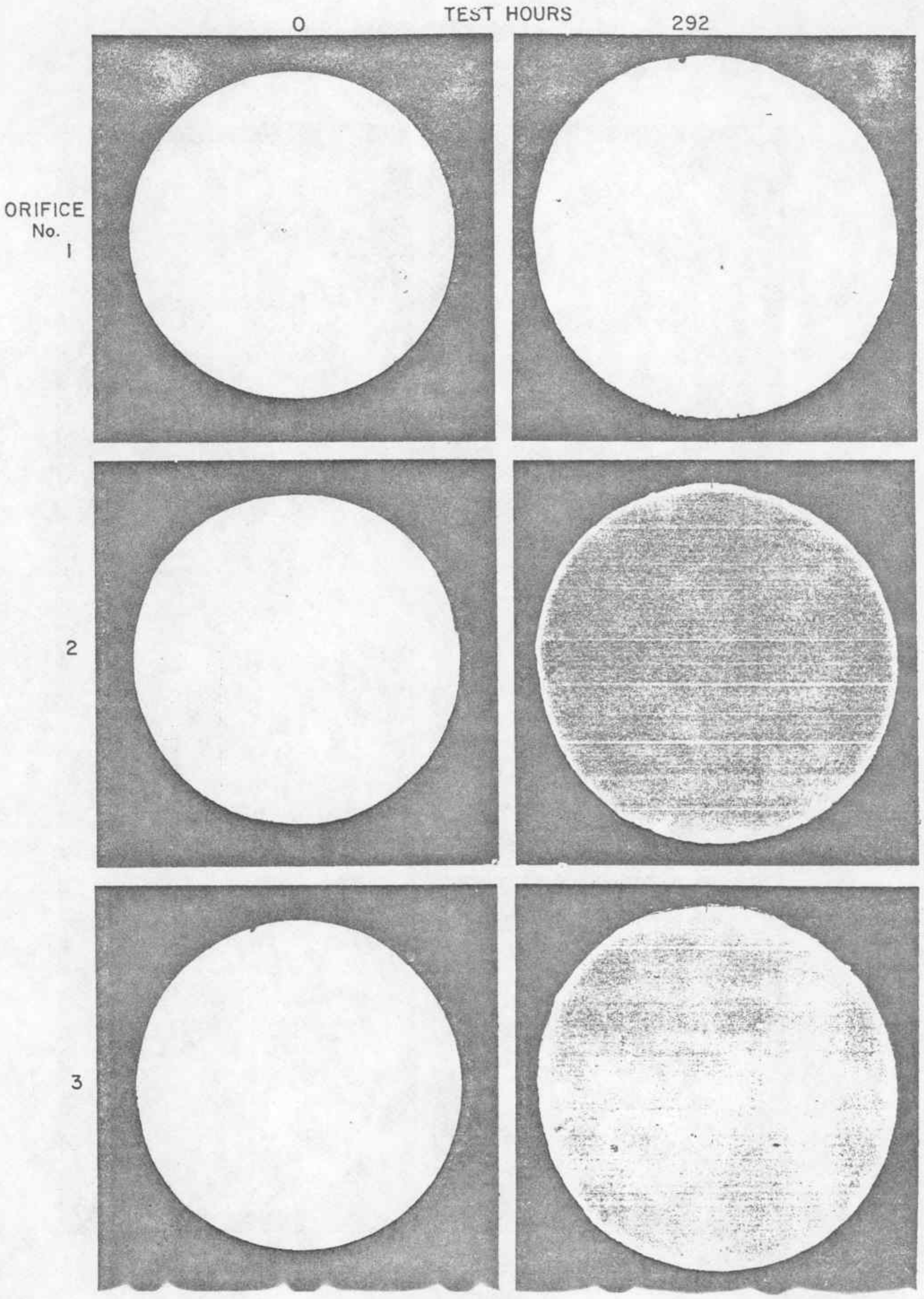


Figure 12/Continued... Photographs of the Peabody Burner Fuel Tip Orifice Before and After the 300-hour Test (30X Mag.)

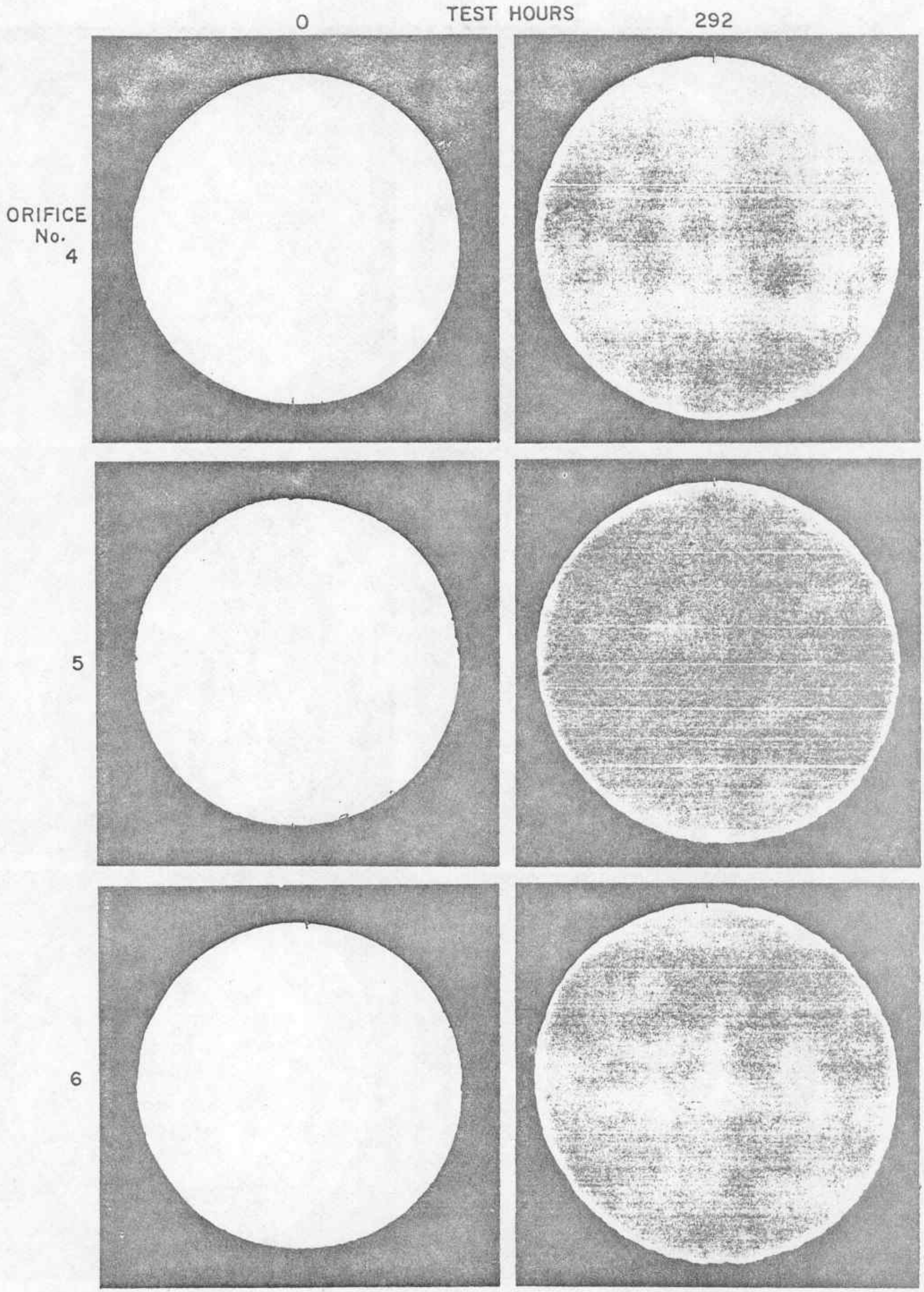
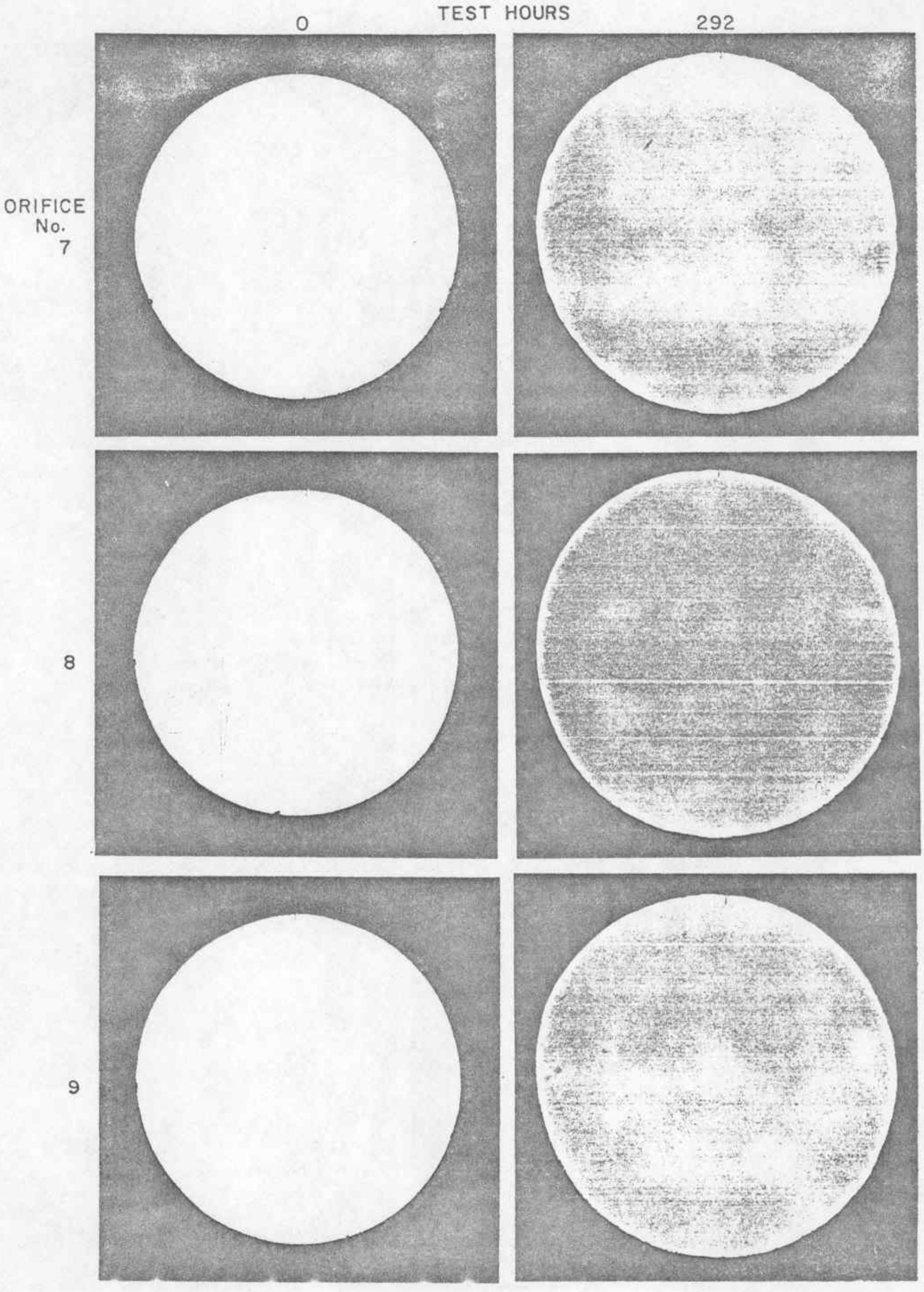


Figure 12/Continued... Photographs of the Peabody Burner Fuel Tip Orifices Before and After the 300-hour Test (30X Mag.)



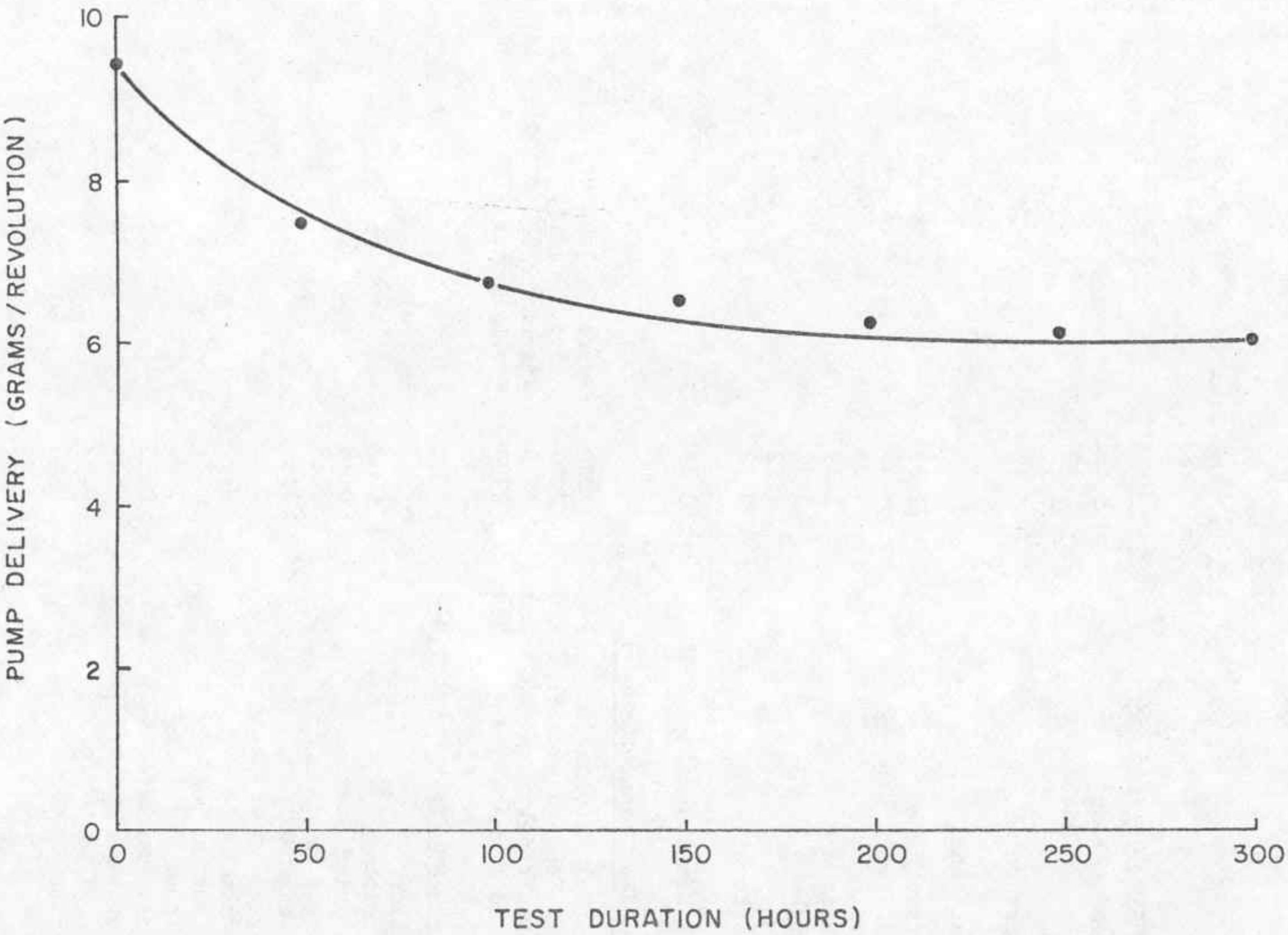


FIGURE 13. MOYNO PUMP FUEL DELIVERY OVER 300 HOUR TEST PERIOD
(FUEL : NOMINALLY 40 % COAL IN No. 6 OIL)

Bruno

Table 1. Fuel Analyses

	Prince Mine Coal (As Fired)	No. 6 Fuel Oil (As Fired)
Proximate Analysis	% by Weight	% by Weight
Fixed Carbon	55.48	
Volatile Matter	33.58	
Ash	7.22	
Moisture	3.72	
Ultimate Analysis		
Carbon	71.03	86.45
Hydrogen	4.40	11.32
Oxygen	9.06	0.60
Nitrogen	1.19	0.19
Sulphur	3.38	1.41
Ash	7.22	0.04
Moisture	3.72	<0.03
Higher Heating Value - BTU/lb	13,298	18,900

Ash Fusion Temperatures ^{o}F

Initial Deformation	Red.	2030	Specific Gravity - .9615
Soft Temperature SPH	Red.	2090	A.P.I. Gravity - 15.7
Soft Temperature HEMI	Red.	2225	Viscosity SFD @ 122^{o}F- 147 sec
Fluid Temperature	Red.	2390	Flash Point(ASTM D56)- 285^{o}F

Coal Ash Analysis % by Weight

Silica	25.24
Alumina	15.02
Titanium Dioxide	0.78
Ferric Oxide	50.89
Calcium Oxide	1.69
Magnesium Oxide	0.91
Sodium Oxide	0.68
Potassium Oxide	1.37
Sulphur Trioxide	1.44
Phos. Pentoxide	0.15
Manganese Dioxide	-
Strontium Oxide	0.02
Barium Oxide	0.05

Table 2. Boiler Efficiency Test Data

Boiler Efficiency \ Test Duration (hours)	50	100	150	200	250	300
Vortometric Burner:						
Input (kW)	1301	1181	1277	1195	1178	1175
Output (kW)	979	891	932	867	841	844
Efficiency (%)	75	75	73	73	71	72
Peabody Burner:						
Input (kW)	1255	1208	1144	1117	1177	1153
Output (kW)	885	885	823	817	832	791
Efficiency (%)	72	73	72	73	71	69

Table 3. Fuel Tip Wear Data - Vortometric Burner (External Atomization)

Test Data	1st	3rd	5th	12th	17th	19th
Test Identification	Baseline	51h	97h	161h	270h	248h
Fuel Tip Weight Loss (mg/h)	N/A	0.03	0.06	0.06	0.06	0.05
Total Fuel Tip Orifice Area (mm^2)	6.70	6.77	6.83	6.88	6.94	6.94
Total Fuel Tip Orifice Area Increase (%)	N/A	1.10	1.93	2.70	3.58	3.66
Water Massflow Rate (20 psig Supply Pressure) kg/h	324.5	349.7	351.0	355.2	358.6	359.2
Water Massflow Rate Increase (%)	N/A	7.8	8.2	9.4	10.5	10.7

Test Conditions:

Firing Rate: ∿1200 kW
Excess Air : ∿20%
Fuel: ∿40% Coal in No. 6 Oil (Weight Basis)
Fuel Tip Material: M2 Tool Steel Hardened to ∿60 Rc

Table 4. Fuel Tip Wear Data - Peabody Burner (Internal Atomization)

Test Date: August, 1981	14th	20th	23rd	25th	27th	29th	31st
Test Identification	Baseline	50h	105h	150h	195h	250h	292h
Fuel Tip Weight Loss (mg/h)	N/A	1.09	1.16	1.15	1.24	1.31	1.47
Total Fuel Tip Orifice Area (mm^2)	33.08	35.72	36.55	37.15	37.97	39.21	40.52
Total Fuel Tip Orifice Area Increase (%)	N/A	8.0	10.5	12.3	14.8	18.5	22.5
Water Massflow Rate (kg/h) (5 psig Supply Pressure)	595.6	671.4	684.0	694.7	710.7	742.7	759.6
Water Massflow Rate Increase (%)	N/A	12.7	14.8	16.6	19.3	24.7	27.5

Test Conditions:

Firing Rate: ∿1200 kW
Excess Air: ∿ 20 %
Fuel: 40 % Coal in No. 6 Oil (Weight Basis)
Fuel Tip Material: M2 Tool Steel Hardened and Nitrided to 70 Rc

Table 6. Sulphur Dioxide and Nitrogen Oxide Concentrations and Emission Rates

Test No	Date	Burner	Sulphur Dioxide Concentrations			Average SO_2 Emission Rate kg/h	Oxides of Nitrogen Concentrations			Average NO_x Emission Rate kg/h as NO_2
			Maximum ppm	Minimum ppm	Average ppm		Maximum ppm	Minimum ppm	Average ppm	
1	June 24/81	Vortometric	1400	1250	1300	5.05	610	420	530	1.48
2	June 24/81	Vortometric	1400	1250	1300	4.70	610	420	530	1.38
3	June 25/81	Vortometric	1300	1150	1200	4.66	680	550	620	1.17
1	Aug. 31/81	Peabody	700	400	675	3.48	465	200	280	1.04
2	Aug. 31/81	Peabody	950	575	800	4.12	460	100	380	1.41

Table 7. Theoretical Massflow From The Fuel Tip Orifices

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Test Duration (Hours)	0	50	100	150	200	250	300
Vortometric Fuel Tip							
Actual Measured Massflow (kg/h)	324	350	351	355	358	359	
Theoretical Massflow (kg/h)	402	406	410	413	416	417	
Discharge Coefficient	0.80	0.86	0.86	0.86	0.86	0.86	
Peabody Fuel Tip							
Actual Measured Massflow (kg/h)	596	671	684	695	711	743	760
Theoretical Massflow (kg/h)	995	1075	1100	1118	1143	1180	1220
Discharge Coefficient	0.60	0.62	0.62	0.62	0.62	0.62	0.62

Theoretical Massflow Q

$Q = t\rho A \sqrt{2gH}$

where

t = time

A = Area

ρ = Density

H = Total Head

g = Gravitational Constant

$$\text{Discharge Coefficient} = \frac{\text{Actual Measured Massflow}}{\text{Theortical Massflow}}$$

Table 5. Particulate Concentrations and Emission Rates

Test #	Date	Burner	Total Particulate Collected	Volume Sampled		Particulate Concentration		Volumetric Flowrate		Particulate Emission Rate	
			mg	m^3	ft^3	g/m^3	gr/ft^3	m^3/S	ft^3/min	kg/h	lb/h
1	June 24/81	Vortometric	1124.3	1.759	62.12	0.639	0.279	0.405	858	0.93	2.05
2	June 24/81	Vortometric	1276.8	1.693	59.78	0.754	0.330	0.377	798	1.02	2.26
3	June 25/81	Vortometric	1177.8	1.809	63.88	0.651	0.285	0.404	856	0.95	2.09
Average								0.395	837	0.97	2.13
1	Aug. 31/81	Peabody	1676.3	1.598	56.45	1.05	0.458	0.537	1140	2.03	4.47
2	Aug. 31/81	Peabody	1436.8	1.576	55.66	0.912	0.398	0.537	1140	1.76	3.88
Average								0.537	1140	1.90	3.93