RESEARCH PROGRAM

ON

OIL BURNING

STEAM LOCOMOTIVES

**

MAXIMUM

EXHAUST NOZZLE PRESSURE

DETERMINATIONS

**

LOCOMOTIVE STANDING TEST PLANT

SACRAMENTO, CALIFORNIA

OFFICE GENL. SUPT. MOTIVE POWER
SOUTHERN PACIFIC COMPANY
SAN FRANCISCO, CALIFORNIA

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* Calculation Sheet, Tables, and Graphs are bound separately on back of front cover for convenience of reference, as follows:

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MAXIMUM EXHAUST NOZZLE PRESSURE DETERMINATION

Introduction

The data and results obtained from comprehensive investigation of front end arrangements, including exhaust nozzle and cross split dimensions at Locomotive Standing Test Plant, as covered by Report No. ST-2, dated April 28, and subsequent test work, have furnished the necessary information to develop a system for determining maximum exhaust nozzle pressure for classes of locomotives, other than the GS-1 class, actually under test. The details of this method of calculation are set forth herein and typical applications to certain specific classes of locomotives are shown in Tables A and B, under Appendix "A", page 10. On certain classes of locomotives, the probable decrease in back pressure due to changes in nozzle and cross split sizes, as determined by this method of calculation, can result in ultimate fuel saving due to increased cylinder horsepower without increase in fuel consumption.

Maximum exhaust nozzle pressure is determined by the nozzle area and the amount of steam flowing to and discharged from the nozzle at the maximum hot water rate. The maximum hot water rate is fixed by either the rated evaporative capacity of the boiler or the required boiler evaporation at maximum horsepower output; i.e., cylinder steam consumption plus auxiliary steam requirements, whichever is smaller. The ratio of rated evaporation to required evaporation is a measure of boiler capacity.

The attached form, together with necessary tables and curves, shows method used to calculate boiler evaporative capacity, required boiler evaporation, steam flowing to the nozzle and maximum exhaust nozzle pressure.

Boiler Evaporation

Heating surface of tubes and flues, in square feet, is determined from their outside diameter and length. Evaporation, in pounds per hour per square foot of heating surface, depends upon the length of the tube or flue and the spacing between tubes or flues. The values, Tables, I, II and III, used for heating surface per tube or flue and evaporation per square foot of heating surface are based on generally accepted information. Total heating surface of tubes and flues is found by multiplying the number by the heating surface per tube or flue, and total evaporation is then found by multiplying total heating surface by the evaporation per square foot.

Heating surface of the firebox is determined from the dimensions of the firebox, and is shown for all classes of Southern Pacific locomotives in the Locomotive Diagram Book. In calculating firebox evaporation, a figure of 80 pounds per hour per square foot of heating surface, based on most recent information, is used.

Addition of the evaporation from firebox, tubes and flues results in a figure which is called "calculated evaporation." When engine is equipped with feedwater heater, it is possible for the boiler to evaporate an additional amount of water because the water is heated to a high temperature by exhaust steam before being delivered to the boiler. A figure of 8 percent for types "B" and "BL" equipment, and 13 percent for types "S" and "SA" equipment, is used for the feedwater heater adjustment. The figure used for types "B" and "BL" equipment is based on authoritative information, and the higher figure for types "S" and "SA" equipment is used, estimated on the basis of tests showing that hotter water is delivered by these two types. The feedwater heater adjustment is taken as a percentage of the feedwater heater capacity or of the calculated evaporation, whichever is smaller. In addition, an adjustment in evaporation is made for oil-burning locomotives, inasmuch as all published figures for evaporation from firebox, tubes and flues are based on tests made on coal-burning locomotives. It is a well known fact that a hotter and more uniform fire is obtained when oil is used as fuel, and a figure of 5 percent increased evaporation is assumed as a reasonable oil burning adjustment. This is taken as a percentage of the calculated evaporation. The sum of the calculated evaporation, feedwater heater adjustment and oil burning adjustment is the adjusted calculated evaporation, or rated boiler evaporation.

Required Boiler Evaporation

The required boiler evaporation is the steam used by the cylinders at maximum horsepower output plus auxiliary steam consumption.

Cylinder steam consumption is determined by multiplying pounds of steam per cylinder horsepower hour by maximum potential cylinder horsepower. Steam used per cylinder horsepower hour depends upon boiler pressure and degree of superheat, the latter being determined by type of superheater, tube and flue sizes and ratio of tubes to flues. Table IV, based on authoritative information, is used to find steam required per cylinder horsepower hour.

Maximum potential cylinder horsepower is calculated from the formula shown on sheet entitled "Cylinder Horsepower." Curves shown are piston speed -vs- speed in miles per hour for various combinations of piston stroke and driver diameter, and piston speed -vs- mean effective pressure as a percentage of boiler pressure for various boiler pressures. The diagonal lines at the left are plotted as a guide in determining the approximate speed at which maximum cylinder horsepower will be reached for a given driver diameter. In using the curves, a speed in miles per hour, "V", is selected and the piston speed is found from the intersection of this speed line with the proper stroke-driver curve. The intersection of the piston speed line with the proper boiler pressure curve determines the percent mean effective pressure, "C". The corresponding values of "V" and "C" are used in the formula to calculate the cylinder horsepower for the speed selected. This is first done for at least three speeds and a curve of speed -vs- cylinder horsepower is plotted in the lower right-hand corner. This curve should reach a maximum at some particular speed and drop off at higher speeds. If the maximum is not found from the speeds originally selected, it will be necessary to select additional ones, either higher or lower, as indicated by the shape of the plotted speed-horsepower curve.

Auxiliary steam consumption includes that required to heat and atomize the oil, requirements for air pumps, generator, etc., feedwater heater if equipped and, in passenger service, steam required to heat the train. In plotting curve "C", it was estimated that steam required for auxiliaries such as air pumps and generator is 1200 pounds per hour, steam to heat and atomize the oil is 2 percent of the hot water rate and heating an average train requires 3800 pounds per hour. Feedwater heater steam consumption varies with hot water rate and values used are based on tests made on Engine 4401 at Standing Test Plant, Sacramento. Curve "C" shows auxiliary steam requirements for engines in freight and passenger service, with and without feedwater heater, -vs- hot water rate. Curve "A", Boiler Evaporation (Hot Water Rate) -vs- Cylinder Steam Consumption, was developed from curve "C" in order that the required boiler evaporation for a given cylinder steam consumption can be found.

Steam to Nozzle

Steam flowing to the nozzle is equal to the cold water rate less steam used by auxiliaries. After the maximum hot water rate has been determined by the method described above, it is possible to find the cold water rate required to supply this amount of hot water. On engines equipped with feedwater heater, the maximum hot water rate may be supplied entirely by the feedwater heater or by a combination of feedwater heater and injector operation, depending on the feedwater heater capacity. In the former case, the cold water rate is equal to the hot water rate less steam condensed in the feedwater heater and, in the latter, it is necessary to find the amount of cold water which will supply the feedwater heater when it is being operated at maximum capacity and then add the water supplied by the injector. Water supplied by the injector is equal to hot water rate less water supplied by the feedwater heater. Curve "B" is used to find the cold water which must be supplied to the feedwater heater for any given rate of hot water being delivered to the boiler by the feedwater heater. The cold water supplied to the feedwater heater depends upon the amount of steam being condensed in the heater, or the condensate factor, which in turn is dependent upon exhaust nozzle pressure. Curve "B", which shows cold water required for any hot water rate at various exhaust nozzle pressures, was developed from data obtained during tests on Engine 4401. For engines not equipped with feedwater heater, the cold water rate is equal to the hot water rate.

Auxiliary steam consumption at the selected hot water rate is found from curve "C", and this value subtracted from the cold water rate is the amount of steam flowing to the nozzle,

Maximum Exhaust Nozzle Pressure

Exhaust nozzle pressure is found from free nozzle area and steam flowing to the nozzle. Curve "D" shows free nozzle area for various combinations of nozzle diameter and cross split. Curve "E" shows calculated steam flow -vs- nozzle area for various exhaust nozzle pressures for engines equipped with Type "A" superheaters. Curve "E" was calculated from the formulae $V_2 = 223.7 \sqrt{h_1 - h_2}$ and $W = A_2 \times V_2 / v_2$; h_1 and h_2 are heat contents at inlet and discharge sides of nozzle, A_2 is nozzle area, v_2 is specific volume of the steam at the discharge side of the nozzle, and W is steam flow in pounds per second. In applying these formulae, it was necessary to know the exhaust nozzle pressure-temperature relation for engines with Type "A" superheaters, and this information was obtained from Dynamometer Test Report No. 6 on a Class SP Locomotive. Steam flow was also calculated for the exhaust nozzle pressure-temperature relation used in standing test of Engine 4401, and the calculated values checked very closely with those actually measured during tests. Curve "F", plotted from data obtained during test of Engine 4401, shows steam flow -vs- nozzle area for various exhaust nozzle pressures for engines equipped with Type "E" superheaters.

Conclusions

In applying this method of determining maximum exhaust nozzle pressure, it should be understood that some of the figures used are only approximate, and it is not expected that it will be possible to exactly duplicate the results in road service. However, in all cases, a reasonable figure for exhaust nozzle pressure is obtained and indications are that some classes of locomotives are equipped with nozzles which will produce excessively high nozzle pressures at the maximum hot water rate. By following the procedure described above for different nozzle sizes, it is possible to predict accurately the change in exhaust nozzle pressure which will result from a change in nozzle area.

APPENDIX A

TYPICAL CALCULATIONS OF MAXIMUM EXHAUST NOZZLE PRESSURE

Attached Table A shows boiler evaporation, required evaporation, steam to nozzle and maximum exhaust nozzle pressure, calculated in accordance with paper entitled, "MAXIMUM EXHAUST NOZZLE PRESSURE DETERMINATION," for several classes of locomotives.

Maximum exhaust nozzle pressures shown in Table A indicate that F and Mt type locomotives are now equipped with the largest nozzles which can be used with the existing fire pan and drafting arrangements. This is also true of Classes Mk-7, 8, 9 locomotives. However, in comparison, maximum exhaust nozzle pressures for Classes Mk-2, 4, 5, 6 and P-8, 10 appear to be higher than that necessary to produce sufficient air flow for proper combustion.

Table B shows reduction in maximum exhaust nozzle pressure which would be obtained by enlarging nozzle diameter 1/4" on these classes. Nozzle pressures would be reduced 14 to 19.5 percent, and would then be approximately the same as on the other classes mentioned above.

It is recommended that road trials be made on several engines of the Mk-2, 4, 5, 6 and P-8, 10 Class locomotives with nozzles enlarged 1/4" in diameter. It is also recommended, when the trials are made, that the side draft chutes on Class P-8 be cut down at least 5" and on Class P-10 at least 3" to provide additional clearance between chutes and firepan and easier entry of air into the firepan. The engines should also be inspected for possible interference by piping to air flow and any necessary changes made.

TABLE A

Class	FWH Type	Boiler Evaporation	Maximum Potential Cylinder HP	Cylinder Steam Consumption	Required Boiler Evaporation	Boiler Capacity	Steam to Nozzle	Nozzle Dia.	Nozzle Cross Split	Nozzle Area	Maximum Exhaust Nozzle Pressure
F-1	-	65450	3250	64030	66500	98.4	62950	7-3/4"	1/2"	36.8	18.0
F-1a	4-S	72850	3250	64030	67900	107.3	57250	7-3/4"	1/2"	36.8	14.8
F-3	-	76602	3735	73580	76100	100.7	73390	8-1/4"	1/2"	42.3	18.7
F-4,5	4-B	81210	3735	73580	77700	104.5	66590	8-1/4"	1/2"	42.3	15.1
Mk-2	-	55740	2545	52940	55100	101.2	52810	6-3/4"	1/2"	26.7	23.5
Mk-2a,4a	-	55740	2486	51710	53700	103.8	51430	6-3/4"	1/2"	26.7	22.5
Mk-2b,4,4c	3-BL	59190	2486	51710	55100	107.4	46010	6-3/4"	1/2"	26.7	18.5
Mk-4b	3-BL	59190	2545	52940	56400	105.0	47170	6-3/4"	1/2"	26.7	19.6
Mk-5,5c,6,6c	-	55740	3052	63480	65900	84.6	53430	7"	1/2"	29.2	20.6
Mk-5a,b,6a,b	3-B,BL	59190	3052	63480	67300	88.0	49990	7"	1/2"	29.2	18.2
Mk-7,8,9	-	56930	3213	62980	65300	85.6	54590	7-5/8"	1/2"	35.4	14.6
Mk-7a,9a	4-BL	61260	3213	62980	66800	91.7	50600	7-5/8"	1/2"	35.4	12.5
Mt-1,3	4-B,BL	73760	3535	68930	76700	96.2	58840	8"	1/2"	39.5	13.6
Mt-4	4-BL	73730	3535	68930	76700	96.1	58810	8"	1/2"	39.5	13.6
Mt-4	4½-BL	74390	3535	68930	76700	97.0	58160	8"	1/2"	39.5	13.3
Mt-5	4½-BL	74050	3535	68930	76700	96.6	57830	8"	1/2"	39.5	13.1
P-8,10	3-B	58680	2815	54890	62300	94.2	45780	6-3/4"	1/2"	26.7	18.3

TABLE B

Class	FWH Type	Present Nozzle: Dia.	Present Nozzle: Cross Split	Present Nozzle: Area Sq.In.	Present Nozzle: Stm to Noz at Maximum Steam Rate	Present Nozzle: Exh Noz Pr at Maximum Steam Rate	Proposed Nozzle: Dia.	Proposed Nozzle: Cross Split	Proposed Nozzle: Area Sq.In.	Proposed Nozzle: Stm to Noz at Maximum Steam Rate	Proposed Nozzle: Exh Noz Pr at Maximum Steam Rate	Reduction in Exh. Noz. Pr. Percent
Mk-2	-	6-3/4"	1/2"	26.7	52810	23.5	7"	1/2"	29.2	52810	20.2	14.0
Mk-2a,4a	-	6-3/4"	1/2"	26.7	51430	22.5	7"	1/2"	29.2	51430	19.2	14.7
Mk-2b,4,4c	3-BL	6-3/4"	1/2"	26.7	46010	18.5	7"	1/2"	29.2	46410	14.9	19.5
Mk-4b	3-BL	6-3/4"	1/2"	26.7	47170	19.6	7"	1/2"	29.2	47570	16.0	18.4
Mk-5,5c,6,6c	-	7"	1/2"	29.2	53430	20.6	7-1/4"	1/2"	31.6	53430	17.6	14.6
Mk-5a,b,6a,b	3-B,BL	7"	1/2"	29.2	49990	18.2	7-1/4"	1/2"	31.6	50390	15.5	14.8
P-8,10	3-B	6-3/4"	1/2"	26.7	45780	18.3	7"	1/2"	29.2	46180	15.3	16.4