RESEARCH PROGRAM

ON

OIL BURNING

STEAM LOCOMOTIVES

*

EXHAUST NOZZLE

AND

STACK HEIGHT TESTS

*

ENGINE SP-4401

*

LOCOMOTIVE STANDING TEST PLANT

SACRAMENTO, CALIFORNIA

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

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* Index of Tests, Data Sheets, and Graphical Results are bound separately on back of front cover for convenience of reference.

FOREWORD

This report covers a series of standing tests on various front end arrangements in locomotive SP-4401, Class GS-1, made at Sacramento Locomotive Test Plant in connection with research program on oil burning steam locomotives as authorized by GMO-35006. This series of tests was conducted to determine what improvements can be made in present front end arrangement without major modification or alteration of design. These tests also developed fundamental information on front end performance necessary for the ultimate improvements to be obtained from the entire research program.

For identification, tests in this series are designated by prefix "SN", indicating changes to stack and nozzle. Present Southern Pacific standard firepan arrangement and design were maintained constant during this series of tests, the changes being confined to front end only. Each test arrangement, also, was assigned an identifying letter following the prefix as indicated in detail on Index of Tests appearing in opposite section.

RECOMMENDATIONS

The following recommendations are made, based on results of these tests and on conclusions shown on pages 36 to 40:

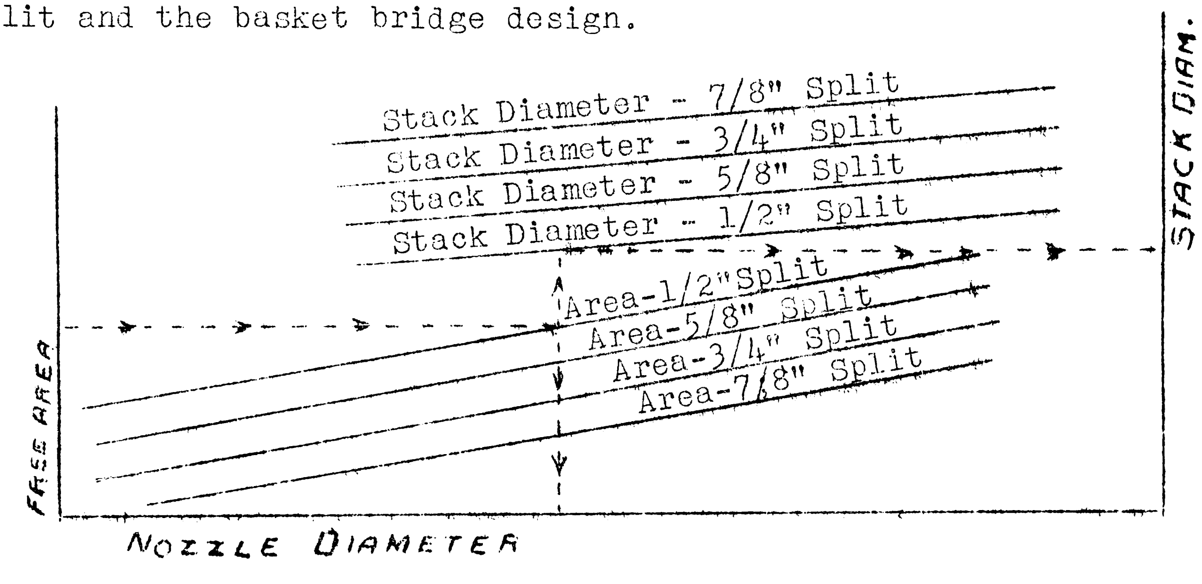
1) In order to obtain immediate operating economies and to insure fuel savings made possible by application of basket type spark arresters as developed by Report ST-1, it is recommended that 1/2" square cross split be applied to all GS class locomotives in place of the 3/4" square cross split now used.

2) When indicated modifications in firepan drafting arrangement are developed as result of current investigation, designated as ST-3, "Recommendations for Interim Improvements", further improvements in stack, nozzle, and cross split arrangement should be made, based on information developed by this ST-2 study.

3) Spray valve sleeves in feedwater heater should be adjusted in length, if necessary, to compensate for the decreased back pressure resulting from the use of improved front end arrangement.

4) Reduced back pressure operation made possible by improving front end arrangement necessitates elimination of all possibilities of steam and air leaks in smokebox. It is, therefore, recommended that a suitable smokebox door gasket or front end cement be used to seal the joint between door and smokebox front.

5) Development by model study of proper exhaust nozzle diameter-cross split relationship for given stack height required for optimum performance with any desired free area of nozzle and a given size stack throughout desired range. This information should be in graphic form, preferably nomographic, similar to arrangement shown below, and should include both the present S.P. style square split and the basket bridge design.



This model study will provide information necessary for the extension of front end improvements to locomotives other than GS class.

6) Model study should also include detailed investigation of design and characteristics of basket bridge cross split, including data on proper width of split and height of split above nozzle as related to nozzle and stack diameter. This investigation should also include development of information necessary to determine free area of nozzles with basket bridge splits. For practical application, results should be in graphic or nomographic form as outlined in Recommendation No. 3.

7) Investigation should be made in road service of combustion air conditions, in classes of locomotives other than the GS class, to permit correlation of data and application of the standing test developments to those classes.

INTRODUCTION

Adoption of a cylindrical basket type spark arrester (as developed by Standing Test Series ST-1) to supplant the Master Mechanic's style arrester, merited an immediate investigation of the exhaust nozzle, cross split and stack relationships to determine changes necessary to reduce cylinder back pressure consistent with the improved spark arrester as well as to develop any other savings and operating economies that could be readily obtained by relatively minor modifications to the locomotive front end during the interim period required for completion of the entire Research Program and application to the locomotives of a final and complete recommended arrangement.

The actual savings to be made through the reduction of back pressure cannot of course be fully determined by means of the combustion test facilities alone which do not include the necessary dynamometers and related equipment required to permit operation of the locomotive pistons to develop power. The potential savings have been, however, illustrated in the original survey for this Research Program as prepared by Battelle Memorial Institute, which indicated possibilities of achieving fuel savings of the order of 10%, at locomotive outputs commonly used, through reduction of the cylinder exhaust pressure.

The purpose of the ST-2 series of tests is to develop the necessary front end information to assist in the eventual full realization of fuel savings resulting from reduced back pressure operation.

A further purpose for this series of tests is to establish some fundamental precepts for guidance in the overall program, for, considering the many years of general use and the importance of the usual design of locomotive exhaust nozzles, cross splits and stacks, there has been a definite lack of basic and fundamental information available in the literature. This is true despite the rather extensive front end model tests conducted by Mr. E. G. Young of the University of Illinois (Bulletin 256 and Supplementary Bulletin No. 274), and is particularly true of information applicable to oil burning locomotives, on which the conditions are at considerable variance with those existing on coal burning locomotives. Even as late as 1933 Mr. Young stated, "It is to be doubted whether data derived from the most carefully conducted road tests could add much to the information thus available (from empirical knowledge concerning front end design and action) and it is certain that no addition has been made by many otherwise well conducted laboratory tests, where incomplete or obviously erratic data have made impossible any conclusions with regard to draft action and gas flow."

The changes made during the ST-2 series were intentionally confined to those of a minor nature, such as might easily be made without the necessity of shopping of locomotive. Major modifications, such as increase in diameter of smoke stack were not considered as such work can best be initially performed by model tests to determine which size stacks warrant standing tests. Diameter of stack used during ST-2 series is currently the largest used on Southern Pacific locomotives.

Some of the arrangements tested may well have been improved by appropriate changes to the stack diameter, and at such time as a desirable firepan has been developed and front end model tests completed, the arrangement of the locomotive front end will of necessity have to be more thoroughly explored to assure a coordinated and optimum overall combustion arrangement, for which work the present series will have provided suitable and essential background information.

In these standing tests of various front end arrangements, the steam produced is exhausted at the nozzle, inducing the draft to burn the oil, and it is of primary importance that the steam conditions at the nozzle be typical if the results are to be truly indicative of those in service. Considerable preliminary work, not covered in this report, had to be done during dynamometer tests and at standing test plant towards development of a suitable temperature-pressure relationship, which will be discussed later in detail.

As a major aid in assuring reproducibility of test results in road service by simulating service conditions of exhaust steam at the nozzle, the patented steam desuperheating system developed by Mr. W. F. Collins, Engineer of Tests, New York Central System, was incorporated in the test installation in an improved, automatically controlled arrangement.

This feature, together with complete description of the test plant and apparatus, is to be fully covered in Report ST at a later date. However, the method of obtaining suitable exhaust steam conditions is essentially as follows:

The main pistons of the locomotive are removed and the main valve rings and bushings are replaced with those of suitable design for controlling the flow of high pressure superheated steam to the cylinders by a micrometric valve positioning gear arrangement on valve stems. Multiple water spray nozzles are placed in the locomotive cylinders together with appropriate baffles to mix the superheated steam and water thoroughly.

In operation, the main valves are positioned approximately, the throttle fully opened and the superheated steam allowed to pass into the cylinders through the rear valve ports which control the flow. As the throttle is opened, the desuperheating system is also placed in operation and as the highly superheated steam passes through the main cylinders the cold water from the multiple sprays is converted into steam, reducing the final temperature of the mixture to that for the exhaust steam condition desired.

The conversion of the spray water into steam results in an excess of steam over that actually generated in the boiler and hence this excess or "surplus" must be removed by bleeding off, so that the amount to the exhaust stand is only that produced in the boiler. Otherwise, the simulation of road service conditions would not exist and the results would be misleading.

In this test plant, the bleed off of the surplus steam is controlled automatically to a unity ratio with the amount of water sprayed into the steam; the quantity of spray water being controlled automatically to maintain the selected exhaust steam temperature.

This surplus steam is bled off at the front steam chest heads into a "Y" shaped pipe and on out through a metering orifice and control valve into a muffling tank.

The remaining steam from the cylinders passes through the exhaust passages to the exhaust stand, where, with the feedwater pump in operation a portion is diverted into the feedwater heater chamber and the balance issues from the exhaust nozzle to create the draft in the smokebox that would be obtainable in actual road service.

CONDITIONS OF TEST

In these tests, no changes were made to the firepan, which was the existing standard on Pacific Lines and is as shown by sketch in Dynamometer Test No. 11. This firepan has a large radius round bottom, with small air opening at burner and main air inlets consisting of two radially directed air ports located adjacent to the flash wall, one on each side of the engine, with a smaller auxiliary port also located adjacent to flash wall but at transverse center of pan, midway between the two side air ports. This auxiliary air port is normally not used except in firing up and is closed off by a manually operated damper door on the hopper.

It was noted during the course of these tests that a considerable amount of carbon formation occurred in the firepan, indicating the necessity of the firepan drafting changes now being developed.

The test plant is equipped for automatic control of water level, boiler pressure, exhaust steam temperature and surplus steam bleed off and, consequently, many of the usual uncertainties of testing are thereby eliminated by the excellent steady test conditions normally attained.

Many refinements in apparatus and procedure were necessary and, particularly, improvements in the spray nozzles and baffle arrangement in the cylinders that accomplished the desuperheating of the steam.

Another of the refinements made in the interests of stability of tests was the relocation of the exhaust steam line from the Worthington type S-2 hot water pump which ordinarily vents into the feedwater heater chamber. This line was removed from the heater chamber and vented up into the smoke jack at roof of building as the discharge of this high pressure steam into the heater caused an undesirable reaction and disturbance to the exhaust steam pressure at the nozzle. No accompanying change in feedwater temperatures could be found and presumably the loss of this comparatively minor amount of steam from the hot water pump exhaust was compensated for by a slight increase in condensation of the exhaust steam drawn from the main exhaust. Since this slightly lowers the exhaust steam available for producing draft, it is on the safe side from a standpoint of determining road service adaptability of any of the arrangements tested and there appears no reason for the change causing other than improved results.

In this connection, the feedwater pump system was the only auxiliary operated during this series of tests and the only additional steam taken from the boiler was for the fuel oil atomizer. Both feedwater pumps and the atomizer use superheated steam. The fuel oil supply was heated by house steam, whereas in service this steam and that required to operate the generator, air pumps and to supply train heating in some instances, would create an extra demand on the boiler.

During these tests the primary control in setting the various test rates was the pressure of the exhaust steam in the Wye pipe for bleeding off the surplus steam. The nature of the test facilities is such that it is preferable that this pressure and the approximate corresponding temperature of the exhaust steam be predetermined to permit reasonably close pre-adjustment of the bleed off metering orifice. A subsequent slight readjustment in the orifice setting must be made when exact exhaust steam temperature desired has been determined from exhaust nozzle pressure. The feedwater and fuel controls are temporarily hand set during opening of the throttle but when once turned over to the automatic operation they will find themselves with each subsequent change in rate with but slight further adjustment, if any, required.

The firing rate during these tests was limited only by the ability of the feedwater pump system, which was rated at 9,000 gallons of water per hour, to supply water to the boiler. Since this limit was quite readily reached with all but a few of the front end arrangements tested, it was not possible to develop anything pertinent as to what extent the changes favorably affected the evaporative capacity of the boiler. With those arrangements affecting the evaporative capacity unfavorably, the results were usually quite apparent and one arrangement (Series SNH) would not even fire well enought to test.

Length of test period was varied to suit particular conditions but normally covered periods of one hour, or at least 45 minutes, at rates at or below approximately half capacity and either 30 or 45 minutes at the upper rates. Some tests were run for several hours.

No data were taken until test conditions were satisfactorily stabilized and test period was extended as necessary in those few instances where undue differences were found between 15 minute segments of the test. It was not uncommon for the fuel meter readings for consecutive 15 minute periods to agree within a few hundredths of a gallon indicating the uniformity produced by the automatic controls. At times, the water used was also very consistent, varying but one or two gallons.

The importance of proper sanding of tubes and flues was demonstrated during certain tests where excess air was low. The flues were always thoroughly sanded before each test period but with some of the nozzles and cross splits there was considerable tendency for soot to form. This could be detected readily by observance of the temperature rise of the flue gas at various locations in the smokebox and the higher degree of superheat in the steam to cylinders. When testing such arrangements, small amounts of sand were used frequently during the test to avoid changes in conditions.

Illustrative of the effect of soot was one instance, not included in this data, where sanding the flues reduced the flue gas temperatures about 50 °F. while at the same time the temperature of the superheated steam dropped approximately 30 °F. With the close control provided by the automatic equipment, the removal of some accumulations of soot produced practically simultaneous increases of the order of 1% oxygen in the flue gas.

TEST PROCEDURE AND METHODS

The test procedure and methods were those generally recognized, and recommendations of the ASME test codes were followed where practicable.

All tests were run with a so-called "flying" start and stop with fuel and water meter readings being taken at 15 minute intervals. Such other data as were not automatically recorded were taken at 5 minute intervals; all data readings being coordinated by a system of signal lights.

The fuel oil, of the high viscosity, residual blended type with gravity of about 8.7 to 10.0 °API, was heated to a readily flowing consistency and fired through a 3-1/2" size Von Boden-Ingalls burner by automatic controls. The quantity used was measured through a 2" size nutating type meter, the smallest division on the register being 0.02 gallons. The meter was calibrated on oil, by weighing, at service temperatures and rates of flow.

Fuel atomizing steam was superheated and was manually controlled, being adjusted as necessary to provide a clear fire with a minimum of drumming.

The water level in the boiler was automatically controlled and recorded, the normal variation in level being of the order of ± 1/4", making corrections for boiler level at start and finish negligible.

Water to the feedwater heater and from the feedwater heater to the boiler was metered by nutating type meters, each carefully calibrated under simulated service conditions at operating temperatures and rates of flow. The cold water meter presented no difficulties to calibration; however, the hot water meter in service is subjected to pulsations in flow from the reciprocating hot water pump, handles water of varying degrees of temperature and the discharge is against a cushion type boiler check.

While the nutating type meter is inherently non-coasting, or non-over-running, there is normally a heavy water shock effect in the hot water pipe line as the check valve closes, and to cushion this pressure an air pressure chamber about 16 feet long by 8 inches in diameter was connected into the line by a length of smaller diameter, air cooled pipe which prevents heating of the water in the chamber with consequent loss of the air space.

The calibrations of the hot water meter were made with the meter in its normal service position, including use of the pressure chamber, and the flow from the meter was diverted from the boiler to a large calibrating tank, the discharge end of the pipe being fitted with a locomotive type safety valve set to open at 250 PSIG to simulate the action of the boiler check.

Temperature measurements were made by individually designed thermocouples of iron-constantan, or chromel-alumel, as necessary, connected to electronic potentiometers of the continuous balance type.

Calorimeters were installed to sample the saturated steam just entering the dry pipe, and in the dry pipe, primarily to provide a ready indication of excessive carry-over since all steam used in these tests was superheated.

In this connection, it was found desirable to use a foam suppresant in the feedwater and variations in the quality of the saturated steam were subsequently negligible.

Firebox and smokebox drafts were observed on water manometers of the single tube type connected into a reservoir of sufficient area to insure inconsequential variation of the zero point with maximum draft. To make all draft readings of a simultaneous nature, interlocked cut off cocks were incorporated in the manometer assembly in such manner that while observing the exhaust nozzle pressure all draft manometer levels could be trapped at their instantaneous related positions and the readings made accordingly.

In connection with the AAR recommendations as to the location of the steam "seal" or impingement point in the locomotive stack as covered on page F-221-1937 of the Manual of Standard and Recommended Practice, stack explorations were made by means of the probing apparatus shown in Figure 2-1, to establish the location of the lower edge of the exhaust steam jet where it impinged on the stack, forming a seal against down drafts.

This pipe probing device is provided with handles for convenience in use and has a small rubber balloon at the outer end which fills when the steam jet impinges on the probe opening and collapses when probe end is in an area of "draft" or sub-atmospheric pressure.

In operation, the probe end is held closely to the inside of the stack and moved up and down sufficiently to establish the lowest point the balloon is filled. There is considerable latitude in the determinations thus made, especially with some combinations of nozzle, cross split and stack but for all practical purposes the method serves very well. Because of inadequate clear area over the stack, the probing had to be confined to one side and the rear of the stack.

The results were reported as the distance from the top of the stack down to the determined impingement point, in inches.

Exhaust nozzle pressure - temperature curve shown on Figure 2-2 was used as a control in establishing test conditions. In developing this curve for control of exhaust temperature-pressure relations, many of the points obtained during dynamometer test were plotted and a tentative average curve was drawn. On this curve, the average temperature for 15 PSIG nozzle pressure was found to be 379 $^{\circ}$F. and this was selected as a starting point since a large percentage of locomotive operation is represented. In addition, lines showing the change in state of the steam from representative steam chest pressures to the related nozzle pressures during dynamometer tests were plotted on a steam chart, and an average slope of these lines for various arrangements and rates was determined, since it was obviously impossible to simulate them all. The point representing 15 PSIG and 379 $^{\circ}$F. was then plotted on the steam chart and through it a line was drawn having the average slope as determined above. From this line the temperatures for other pressures from 2 PSIG to 24 PSIG were found and the pressure-temperature curve, shown on Figure 2-2, was drawn.

The curve thus developed is advantageous and while not technically suitable and correct for all the combinations of nozzles tested, it is a necessary compromise to avoid undesirable and extensive pre-testing of a trial arrangement in road service.

It is realized that use of the curve will not produce results that can be exactly duplicated in road operation, inasmuch as a variation in steam pipe temperature,when operating at the same nozzle pressure, will result from changing nozzle areas. This variation will have some effect on nozzle temperature, which in turn affects the amount of steam required to produce any given nozzle pressure, making it difficult to obtain direct quantitative comparison of the amount of water that would be evaporated at similar nozzle pressures when using different size nozzles. However, it is presumed that within the range of nozzle sizes used during these tests a reasonably accurate indication is given of the effect on nozzle pressure of changes in nozzle size.

The further assumption is made that in those cases where the evaporation is more or less than would be actually obtained in road operation, the amount of oil fired and the air flow will also be proportionately higher or lower. The firing rate-air flow relation would therefore be correct. As this relation is one of the most important developed from these series, the exhaust nozzle pressure-temperature curve shown in Figure 2-2 appears to be sufficient for the purpose and the best that can be derived without making a separate road test with each arrangement before trying it out on the test locomotive.

DISCUSSION OF TEST SERIES

The ST-2 series of tests with the general prefix "SN" represents the combination of recommendations of representatives of the Southern Pacific Company, the T&NO, and the Battelle Memorial Institute in this phase of the program and was developed at conferences with all concerned to afford the information desired.

For ready reference, the various test arrangements and designations are shown in Index of Tests preceding the curves in opposite section.

Test series SNA covered the present Southern Pacific standard front end with the newly adopted design of basket type spark arrester. During these tests the Battelle Memorial Institute representatives made extensive firebox surveys. This series will be the basis for judging extent of improvements and effects of change.

Test series SNB was made to determine comparative effect of cross split as used by T&NO Lines.

Test arrangement SNC incorporated smaller cross split applied to present standard nozzle size and stack height. This reduced cross split size is presently standard on all classes of locomotives except the GS class.

Test series SND was made in a further attempt to reduce the cylinder back pressure, and a basket cross split similar in design to that illustrated in figure 3-263 of the 1947 edition of the Locomotive Cyclopedia was selected. The results with this cross split on the 8" diameter nozzle were so promising, and simple of application, despite not being wholly suited for service application with present firepan arrangement that the subsequent series SNE, SNF and SNG were made primarily on the basis of improvements noted from similar changes in stack height above nozzle during dynamometer tests on other classes of power. Changing position of the lower end of the stack extension, with fixed location of top of stack, not only affects the stack length and stack-nozzle relationship, but also changes the position of the stack with regard to the tubes and flues and, therefore, can affect the proportion of the gas flowing through the various flues and tubes when there are no baffle plates, as with the present spark arrester. In series SNG, the spark arrester was removed only because of restricting the stack entrance at this low position.

Test series SNH with the 8" diameter nozzle and no cross split, was scheduled at the request of the Battelle Memorial Institute personnel for information purposes only, as it was realized that without cross split, the open nozzle would not maintain sufficient boiler pressure for any test. Plans for continued tests with this arrangement were abandoned following a trial in which it barely maintained 150 PSIG boiler pressure, even with the blower on and little of the surplus steam bled off. Had this series been feasible, it could have supplied information of value on the effect of the raised, basket style cross split on cylinder back pressure.

As shown in Index of Tests, the series SNI tests were with an open nozzle of an area equal to that of an 8" diameter nozzle with a Southern Pacific standard 1/2" square cross split. This was to establish how the air flow was affected and whether or not the steam flow-nozzle pressure relationship was the same as for the larger nozzle with the cross split. This was necessary because, as previously indicated, there is a dearth of the necessary fundamental principles of locomotive stacks and nozzles in published information and, in the few reports available, little is clearly evident on the action of the cross split and the relation of similar nozzle areas produced by various combinations of nozzle diameters and cross splits, and plain open nozzles.

Test series SNJ and SNK with 10" stack height were made for comparison with series SNC and SNB, respectively, to establish the benefits, if any, in lowering the stack extension when the SP standard and T&NO cross splits were used.

Test arrangements SNL and SNM with 8-1/4" nozzle diameter and 10" stack height were included to provide data on arrangements with performance between that of the 8" diameter nozzle combinations with T&NO and SP standard cross splits and the 8" diameter nozzle with basket bridge.

Test arrangement SNN was developed by the Battelle Memorial Institute representatives after studying the data from the various other arrangements. Their calculations indicated that this diameter nozzle with the 1/2" square basket split should produce an air flow equal to that obtained at high rates with the 8" diameter nozzle and 1/2" square SP standard cross split and yet have a lower back pressure for the same steam flow.

Some such combination appeared to be a logical extension of the operations with the basket cross split and possibly with some modification of the basket split in height or size, or both, with perhaps a different stack size, it would produce desirable results;

however, the combination as tested did not prove satisfactory. It is possible that the reason for the poor performance of the SNN series was that the steam jet did not completely fill the stack with steam, which further emphasizes the importance of the cross split and the need for fundamental information on nozzle area-cross split relations to make locomotive nozzle performance predictions of practical value.

DISCUSSION OF DATA AND RESULTS

In Figure 2-20 and subsequent figures where results of more than one test arrangement are plotted together, they have been grouped arbitrarily as follows, because of the large number involved.

Results from series SNB, SNK and SNM are plotted together to show comparative results obtained with arrangements using the 3/4" T&NO style cross split. Data from series SNC, SNI, SNJ, SNL and SNN are plotted together to show relative performance with the 1/2" square SP cross split and those other arrangements theoretically calculated to provide results comparable with those obtained with 8" diameter nozzle and 1/2" cross split. Results from series SND, SNE, SNF and SNG are plotted together to disclose the relative performance of the 8" diameter nozzle and 1/2" square basket bridge with the four stack lengths tested. Results from series SNL and SNM, representing optimum performance with 1/2" square SP cross split and 3/4" T&NO style cross split, respectively, are plotted together with the results from series SNA and SNF representing the two extremes of effective nozzle area, the SNA arrangement, of course, also being the present Pacific Lines standard for GS locomotives.

Figures 2-3 and 2-4

These tables summarize the essential calculated and averaged data for the individual series which are presented in various succeeding figures in graphic form.

The boiler efficiencies were calculated using the water meter readings as compared with previously reported efficiencies from Dynamometer Car tests which have been determined using an amount of water-to-boiler calculated from a heat balance on the feedwater heater conditions.

The figures on the smokebox gas composition represent the results of Orsat analyses and continuous sampling over the whole test period. The figures on air flow rates and excess air are therefore also average, having been calculated from the gas analyses by formula shown on Figure 2-4.

Smokebox drafts reported are those measured inside the spark arrester at position referred to as No. 1, at the axial centerline of the smokebox and as such are of the nature of an average of those found at various locations near the tube sheet. The draft drop through the spark arrester is insignificant, being of the order of but a few tenths of an inch of water. This confirms findings in ST-1 series of tests.

Smokebox gas temperatures tabulated are those obtained at position referred to as No. 1, which is on the axial centerline of the smokebox some distance from the tube sheet and just to the rear of the spark arrester.

Firebox draft was measured through a drilled staybolt in the side wall of the firebox in the general location recommended by the various test codes.

Figures 2-5 to 2-17, inclusive, show detailed graphical results from each individual series of tests (except Series SNH which failed to produce satisfactory steaming). Each figure contains sketch showing front end arrangement used, as well as detail of nozzle and cross split design. Discussion of these results follows:

Figure 2-5 (Series SNA)

This series covers the existing standard combination of nozzle size and cross split for this class of locomotive and it should be particularly noted that a nozzle pressure of approximately 18 PSIG, (corresponding approximately to 20 PSIG back pressure in service), was reached at relatively low firing rate.

With the generally accepted restriction of the operating back pressures to about 15 PSIG maximum, it is evident that much of the capacity of the engine is wasted, in addition to losing a very considerable amount of power in overcoming a high back pressure.

The boiler efficiency curves are also noteworthy on this present standard arrangement, primarily because in very few succeeding tests were they so low, probably in a great part because of reductions in excess air. The large 3/4" cross split is standard on the GS class locomotives only; the 1/2" splits being specified for other classes.

Figure 2-6 (Series SNB)

These curves serve to illustrate the performance with the existing T&NO standard arrangement, although conducted with the low resistance basket type Southern Pacific standard spark arrester. Appreciable improvement in the boiler efficiency is shown as well as greater boiler capacity without excessive nozzle pressure.

Figure 2-7 (Series SNC)

This series produced results quite similar to those with the 3/4" T&NO cross split (Series SNB) except for some increase in firing rate for similar exhaust nozzle pressures, as might be expected from the slightly greater clear area of the nozzle with this arrangement.

Figure 2-8 (Series SND)

This series produced the first definite change from the usual relations and offered much that is desired in performance of the front end.

To avoid possibility of going beyond the practicable size in boring nozzle tips and yet provide a means of producing a reduction in cylinder back pressure beyond that existing on the many engines using the 1/2" square SP standard cross split, the basket bridge cross split was tried, as offering a logical and simple means of accomplishing this end. While not considered practicable for road application with present firepan drafting arrangement, the basket bridge has definite possibilities and should be subjected to further study during course of research program.

Indicative of these possibilities with this basket type bridge is the favorable entrainment characteristics shown by the relative flatness of the CO_2 curve which means practically constant excess air and the high firing rates for low exhaust nozzle pressures. It can be noted by referring back to Figure 2-5 covering the present SP standard arrangement (Series SNA) that the same firing rate could be maintained with very nearly half the presently necessary exhaust nozzle pressure.

Figure 2-9 (Series SNE)

The series and the succeeding ones with the basket cross split and different heights of the stack extension above the nozzle were made to determine if the slight disadvantage of this combination of cross split and nozzle size could not be overcome in line with improvements effected in the SP Class locomotives as reported in Dynamometer Test No. 5.

This series with the stack 7" above the nozzle shows a somewhat greater change in CO_2 with firing rate and an especially high boiler efficiency at the lower rates; however, there was still insufficient latitude in firing for it to be desirable for service.

Figure 2-10 (Series SNF)

This series with the basket cross split and the stack 10" above the nozzle shows a return to the flat CO_2 curve but this combination is not considered suitable for service with present firepan arrangement but has definite possibilities as mentioned in discussion of Figure 2-8 (Series SND).

Figure 2-11 (Series SNG)

The series was made with stack only 3" above nozzle despite a knowledge that the small flare on the stack extension might tend to choke the flow of gases somewhat, the purpose being to emphasize the effects produced, by making the maximum possible change in stack position.

As indicated by the slight increase in firing rate for equal water rate, the boiler efficiency was slightly lowered as was the superheat.

This arrangement could not be considered suitable for road service.

Figure 2-12 (Series SNI)

The series with no cross split and a plain open nozzle of area equivalent to the clear area of an 8" nozzle with the 1/2" square cross split was not intended for possible road operation, but for basic information and future reference purposes.

Great difficulty was experienced in firing with this arrangement and large quantities of sand had to be used to counteract the excessive formation of soot in tubes and flues. Except for the automatically controlled conditions of operation in the test plant it is unlikely that sufficient fire could otherwise have been maintained to cover even the small range of test shown.

Figure 2-13 (Series SNJ)

This arrangement was the same as SNC but with the stack extension lowered to 10" above the nozzle, which had appeared from previous tests to be the best height. In this connection, the 10" height of stack above nozzle had also been found to produce the best results on SP Class locomotives in Dynamometer Test No. 5.

Some improvement in boiler efficiency resulted from lowering the stack and engine fired better at low rates, permitting test at 5 PSIG exhaust nozzle pressure, which was not possible with the SNC series.

Figure 2-14 (Series SNK)

This series shows no particular differences from the SNJ beyond the slight shifting of the curves consistent with the slight difference in clear area of the nozzle with the T&NO and the 1/2" square cross splits.

Figure 2-15 (Series SNL)

In this series, as with some others, the maximum firing rate was limited by the capacity of the feedwater supply equipment. It will be noted, for example, that at the maximum firing rate of about 6,000 pounds per hour, the exhaust nozzle pressure was several pounds less than with the SNJ and SNK arrangements. Although the entire CO_2 curve is up considerably from the SNJ and SNK tests with the 8" nozzle, there was no smoking even at the higher rates despite a sharply rising CO_2 curve which is indicative of a tendency to excessive smoking; the flatter CO_2 curve, as for arrangement SNF, being preferable as indicating more nearly constant excess air.

Figure 2-16 (Series SNM)

This series shows some improvement over the series SNK, the shape of the boiler efficiency curve being inverted and there being no drop off at the highest rates shown. For equivalent firing rates, an appreciable reduction in exhaust nozzle pressure was effected without producing any observed difficulties in firing.

Figure 2-17 (Series SNN)

Boiler efficiencies in this series were among the highest during any tests, presumably for the most part because of the very low excess air. The CO_2 curve here again shows the desirable flat shape characteristic of the experimental design of basket split. The exhaust nozzle pressure curve shows no improvement over the 8" nozzle and 1/2" cross split. Observations made during tests showed that stack was not filled completely and impingement points were high in stack. At times during test runs, down draft existed in stack at rear quarter about 8" on circumference of stack and up to 2-1/2" to 3" into stack. At low rate test run (6 PSIG wye pipe pressure) impingement pattern was very distorted, being 33" from top of stack at sides and only 8" at back.

Figure 2-18: Comparative Results of Firing Rate of 5000 lbs. Oil Per Hour.

In this figure some of the most informative data on the various arrangements are compared and presented in ascending order of exhaust nozzle pressure for a firing rate of 5,000 pounds of oil per hour. This rate was selected as being typical for all series of tests and in addition as being particularly representative of the major portion of our locomotive operation in service.

This figure is especially illustrative of the comparative results with the various combinations tested.

The basket bridge cross splits showed greatest reduction in exhaust nozzle pressure at this firing rate. However, observations during the test indicated that the air flow was insufficient as the stack showed too dark a color, although no particular trouble was experienced in firing. Modifications to firepan drafting arrangement or other changes will be necessary to correct air flow if this design split is to be made practicable for service requirements.

The next arrangement in order of ascending exhaust nozzle pressure is the SNL, with 8-1/4" nozzle and 1/2" square cross split. With this arrangement, air flow was increased appreciably with no serious change in boiler efficiency, and observations during the test proved that the boiler pressure could be raised readily. This was further checked by lowering the boiler pressure and hand-firing against the injector and feedwater pump. No difficulty was experienced when holding or raising the boiler pressure. This arrangement, therefore, provided the maximum practicable reduction in exhaust nozzle pressure because air flow was the minimum compatible with service requirements.

Figure 2-19: Boiler Efficiency -vs- Excess Air

This curve of boiler efficiency -vs- excess air is included for illustrative purposes only, to show the general trend of increase in boiler efficiency with decreasing excess air. The points shown are those from all tests and while the many factors other than excess air cause the dispersion of the points, the main variable affecting boiler efficiency in these tests was the air flow, since no changes were made in boiler, firebox or firepan design. In addition to obtaining increased power in the cylinder due to reduction in exhaust nozzle pressure, it is apparent that a saving can also be accomplished by the usually attendant decrease in excess air.

Figures 2-20, 2-21, 2-22, and 2-23: Firing Rate -vs- Exhaust Nozzle Pressure.

These curves show that with the SNL and SNM arrangements, an equal firing rate can be maintained with exhaust nozzle pressure lowered as much as 5 to 6 PSIG below that obtained with the present SP standard nozzle and cross split.

Figures 2-24, 2-25, 2-26 and 2-27: Water Rate -vs- Exhaust Nozzle Pressure.

As could be expected because of the relatively small variation in boiler efficiency with the various arrangements, these curves of water rate -vs- exhaust nozzle pressure show practically identical characteristics with those of firing rate -vs- exhaust nozzle pressure. These curves primarily illustrate the magnitude of the change in evaporation rate with change of effective nozzle area for equal exhaust nozzle pressure.

Figures 2-28 and 2-29: CO_2 and O_2 -vs- Lbs. Air per Lb. Oil

These curves of measured carbon dioxide and oxygen content of the flue gas -vs- calculated pounds of air per pound of oil and calculated excess air are included to illustrate the degree of accuracy of the data on air flow and excess air shown on subsequent curves.

Figures 2-30, 2-31, 2-32 and 2-33: Air Flow -vs- Firing Rate.

These curves show the expected reduction in air flow with increase in effective area of the nozzle. However, it does not necessarily follow that a decrease in nozzle size will always produce an increase in air flow. This is illustrated by comparing data obtained with arrangement SNN, 7.44" diameter nozzle, and arrangements SND, SNE, SNF and SNG, 8" diameter nozzle, all with the basket bridge cross split. In this instance, the smaller diameter nozzle induced practically the same or lower air flow.

The results of series SNI as shown on Figure 2-31 were interesting, since this arrangement was designed to have a free area of the nozzle identical with the 8" nozzle and 1/2" cross split which induced a high rate of air flow. As shown by Figure 2-31, the test with this open nozzle showed induced air flow to be far less than with its mathematical equivalent in free area but with cross split.

Figures 2-34, 2-35, 2-36, 2-37 and 2-38: CO_2 and Excess Air -vs- Exhaust Nozzle Pressure.

This group of curves shows that in general the carbon dioxide increases and excess air decreases with increasing exhaust nozzle pressure, regardless of the arrangement tested. However, some variations in the shape of the curve result from the different arrangements and in series SNN the general trend was reversed.

In considering curves in this group it should be understood that, as for example on Figure 2-38, the firing rates for series SNF with the 1/2" basket bridge covered practically the same range as those for series SNA with 3/4" square cross split. Hence, the basket bridge provides a very nearly constant percent of excess air over the whole range of possible firing rates.

Figures 2-39, 2-40, 2-41, 2-42, 2-43, 2-44, 2-45 and 2-46: Smokebox and Firebox Draft -vs- Exhaust Nozzle Pressure

These curves of smokebox draft -vs- exhaust nozzle pressure and firebox draft -vs- exhaust nozzle pressure both show essentially the same characteristics and in addition would correspond roughly with a curve of air flow -vs- exhaust nozzle pressure, since during these tests the resistance of the firepan to air flow was unchanged. The values of the draft in these tests will more nearly represent the trend in air flow than would be the case with coal fired locomotives where the resistance to air flow through the grate and firebed may vary considerably.

Figures 2-47, 2-48, 2-49 and 2-50: Stack Impingement -vs- Exhaust Nozzle Pressure.

These graphs show that the impingement points as measured are prone to be somewhat erratic and the main interest shown is that with the 8" nozzle and basket bridge the impingement point moved lower in the stack with increasing exhaust nozzle pressure, whereas for other styles of cross split the impingement points were either at a nearly constant location or moved upwards. This in some measure may serve to explain the better performance of the basket bridge in maintaining excess air at the high rates and would place some question on the AAR recommendations for having the steam "seal" or impingement point in the area about 12" from the top of the stack. The only instance in which this high impingement point was approached closely was in series SNN using the 7.44" diameter nozzle with 1/2" basket bridge which was not considered among the best arrangements.

In connection with the impingement of exhaust steam at the side of the stack, it was noted that from arrangement to arrangement this point did not always occur in the same location around the periphery of the stack, and for this reason Photograph 2-2 is interesting. The forward displacement of the steam jet would indicate a possibility of improvement by a shift of the stack forward with respect to the nozzle or perhaps the application of a deflecting baffle plate on the tube sheet side of the spark arrester.

<u>Figures 2-51, 2-52, 2-53, 2-54 and 2-55:</u> Firebox and Boiler Sheet Temperatures.

These data and graphs show the effect on firebox and boiler sheet temperatures of variations in the height of the stack above the nozzle, the location of the nozzle being fixed and the changes being made by adding lengths to the stack extension. These changes then have the effect of moving the entrance to the stack vertically with relation to the tubes and flues and as shown by the graphs a definite variation in firebox and boiler sheet temperatures does result. The 10" height of the stack above nozzle was selected on the basis of Figure 2-54 showing the greatest uniformity in temperatures over the range of firing rate. In these graphs, it is interesting to note that the maximum sheet temperatures do not necessarily occur at maximum firing rate.

<u>Figures 2-56, 2-57, 2-58, 2-59 and 2-60:</u> Draft Isobars on Front Tube Sheet.

These data and charts of probable location of draft isobars (points of equal pressure) on front tube sheet were also considered in selecting the 10" height of stack above nozzle. From these charts also, it is evident that vertical location of the entrance of the stack with respect to the tube sheet must be considered in a locomotive front end arrangement where no baffle plates are used.

<u>Figures 2-61, 2-62, 2-63, 2-64, and 2-65:</u> Gas Isotherms on Front Tube Sheet.

These data and charts of probable location of flue gas isotherms (lines of equal temperature) on front tube sheet were another means of indicating the effect of vertical variation in the location of the end of the stack extension. The differences shown are slight and the reason for the unsymmetrical distribution is as yet unknown.

<u>Figures 2-66 and 2-67:</u>

These curves serve as a further means of selecting an optimum height of stack above the nozzle and in these the 10" height again shows appreciable advantage in lower flue gas temperatures.

SUMMARY OF RESULTS AND CONCLUSIONS

1) For the GS class locomotives, the 8-1/4" diameter nozzle with 1/2" square SP cross split provides the lowest practicable cylinder back pressures and best resultant fuel saving obtainable with the present standard firepan and stack diameter, although results indicate that further improvement can be obtained when appropriate modifications in firepan drafting are made.

2) With the basket type spark arrester, a change in the height of stack above nozzle, accomplished by use of stack extension rings, does not cause any substantial differences in air flow rate for the height changes obtainable with present standard stack extension and exhaust stand.

3) With the Type E superheater and the basket type spark arrester, a change in the height of stack above nozzle, accomplished by use of stack extension rings, does cause substantial changes in boiler and firebox sheet temperatures and for the standard firepan, the 10" height reduces their variation with firing rate.

4) The basket cross split design, besides producing the greatest reduction in exhaust nozzle pressure, closely approaches an ideal which would provide a constant percentage of excess air over the full range of firing rates, thereby eliminating the usual need for compromise in the selection of nozzles and cross splits. The favorable performance characteristics of this design of cross split warrant further serious consideration and study.

5) There are no essential differences in the performance of the Southern Pacific and T&NO standard designs of cross split other

than that to be expected from the difference in nozzle restriction, and any further work with flat splits should be confined to the simpler SP design.

6) Higher equivalent evaporation rates for given fuel ratio are obtained by improving nozzle and split arrangement to operate at lower back pressures. Conversely, for a given evaporation rate, the improved arrangements reduce fuel consumption (as shown graphically on Page 2-68) and increase boiler efficiency.

In this connection, refer to discussion of Figures 2-18 and 2-19. On the basis of the excess air shown by the curves and from Figure 2-19, there would be a 2.9% improvement in boiler efficiency with Series SNF over Series SNA at a firing rate of 5000 lbs. oil per hour and a 2.0% improvement with Series SNL over Series SNA at the 5000 lbs. per hour rate. Boiler efficiencies as plotted for each series show an improvement of 3.7% with Series SNF over Series SNA, and a 2.4% improvement with Series SNL over SNA, both at 5000 lbs. oil per hour firing rate.

Figure 2-68 shows approximately 3.4% increase in equivalent evaporation with Series SNF over Series SNA and 2.3% with Series SNL over SNA, both at 5000 lbs. per hour firing rate.

7) Performance of a nozzle cannot be predicated on free area of the nozzle alone as clearly demonstrated by the actual tests with and without a cross split.

8) As a corollary, it follows from Conclusion 7, above, that a ratio of area of stack to area of nozzle based on the free area of the nozzle will not always be consistent with performance. The fallacy of the use of the free area of the nozzle for stack-nozzle ratios is exemplified by the comparative performance of the 7.087"

diameter nozzle without cross split (Series SNI) and the 8" diameter nozzle with 1/2" square cross split (Series SNC), both having exactly equal stack-nozzle ratios based on free areas, yet the performance of the open nozzle proved to be very poor, probably because of permitting down drafts in the stack.

9) For application of test results to other classes of locomotives, an empirical relation of optimum nozzle diameters and cross splits for various stack diameters will be necessary to permit selection of specified free area nozzle-cross split combinations that will fill certain diameter stacks, assuring proper performance.

10) With the unbaffled basket type spark arrester the exhaust steam jets tend to have a forward displacement in the stack, the correction of which could improve the stack filling properties.

11) Possibility of change to nozzles and cross splits on classes of locomotives other than the GS class, with basket type spark arrester or without spark arrester should be developed by road service trial on representative locomotives of the various classes. This is particularly true of AC class locomotives which were formerly equipped with restrictive spark arresters similar to the previous standard on GS class locomotives. The results of these ST-2 series of tests indicate that a slightly larger nozzle could satisfactorily be used when basket type spark arresters are installed, combined with application of gaskets to insure leak proof smokebox doors. Size of nozzle to be based on preliminary road test data as covered by Recommendation No. 7 (page 3).

12) Observations made during tests confirmed necessity for use of either gaskets or front end cement to seal air leaks. To insure successful operation with improved front end arrangements, and to obtain full economies resulting from reduced back pressure, all possibilities of steam and air leaks into smokebox must be eliminated.

13) The importance of proper sanding of tubes and flues was demonstrated by these tests as soot accumulations were found to interfere considerably with heat transfer causing increased flue gas temperatures with consequent loss of effective heating value from fuel.

14) Feedwater heater spray valve sleeves on Class GS-2, 3 and 6 locomotives are of proper length (1-1/4") to compensate for decreased back pressure. Other GS classes should have sleeve length checked and where found to be in excess of 1-1/4", should be shortened sufficiently to compensate for the loss in temperature of the lower pressure exhaust steam to heater.

15) During course of research program, consideration should be given to the application to test locomotive of a larger size feedwater pump and higher capacity, controllable delivery injector in order to extend the range of evaporative capacities studied with various test arrangements as well as to permit study of the relative effect on combustion of feedwater heating by injector and feedwater heating from exhaust steam.

16) Consideration should also be given to relocating feedwater pump delivery on test locomotive to opposite boiler check to determine effect on the present unequal steam temperatures in left and

right main steam pipes and to disclose if any connection exists between location of feedwater injection and expansion and contraction damage to one side of flue sheet.

17) During course of program, test locomotive should be equipped with steam space spray type boiler check to determine effect of this method of feedwater injection on relative boiler sheet temperatures in the interest of reducing boiler maintenance.