Test of a Prototype Dual Fluid Cycle 501-KB Engine

Prepared for
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Supplemental Data Package

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INTRODUCTION

This supplement to the Test of a Prototype Dual Fluid Cycle 501-KB Engine presents performance analysis results which were the basis for the performance results presented in the primary report. The performance results in this supplement are based primarily on fuel-air burner outlet temperature (F/A BOT) calculated from test measurements and the properties of air, steam and the products of combustion. An adjustment was made in the primary report to the calculated BOT to present performance in terms of parameters consistent with operator measured and specification presentation parameters. The main contribution of this report is to show the performance as a function of burner outlet temperature and to show the correlation with the computer performance synthesis.

DISCUSSION

AREAS REQUIRING MORE DEFINITION

The test program identified several areas which should be better defined prior to production of a DFC 501-KB engine. These were as follows.

Indicated Turbine Temperature

Analyses during the performance testing had shown that the engine instrumentation of turbine inlet temperature was not giving an accurate indication that could be used for performance assessment. A burner outlet temperature has been calculated from test data accounting for the properties of the air, steam and products of combustion. Table S-I summarizes the performance of the test engine for one test condition (maximum continuous rating temperature and the maximum test steam rate, 1800°F and 5.0 lb/sec) for the three steam injection locations. Injection of steam into both manifolds gave the best thermal efficiency. Table S-II gives the same information using indicated temperature as the parameter. Using this cross-section of data, front injection gives the highest power (actual BOT is the highest) whereas the dual injection gives the best thermal efficiency.

Table S-I

Performance at 1800°F F/A BOT

Performance Parameter	Baseline $W_S = 0$	Steam Flow, W_S = 5.0 lb/sec Front Injection	Rear Injection	Front & Rear Injection
SHP	3970	6440	6440	6440
η_{th}	.275	.344	.344	.348
TIT T/C	1830*	1860	1920	1880

*Not typical for 501K/T56 engines

Table S-II

Performance at 1800°F Indicated T.I.T.

Performance Parameter	Baseline $W_S = 0$	Steam Flow, W_S = 5.0 lb/sec Front Injection	Rear Injection	Front & Rear Injection
SHP	3820	6150	5850	6060
η_{th}	.272	.345	.3454	.348
BOT F/A	1770*	1740	1680	1720

*Not typical for 501K/T56 engines

The variation of indicated thermocouple temperature is shown in Table S-III. The table shows that the ΔT was a function both of steam rate and method of steam injection for the test engine. There was yet another, but smaller, variation with temperature level.

Table S-III

ΔT as a Function of Steam Rate and Injection Location

Injection Location	ΔT* at various steam rates, W_s 0 lb/sec	2.2 lb/sec	3.6 lb/sec	5.0 lb/sec
Front	30	60	60	60
Rear	30	70	100	120
Front & Rear	30	45	70	80

* ΔT = (T/C indicated temp - F/A computed BOT), °F

As shown in Table S-III, the ΔT with no steam flow was +30°F for the test engine. This compares to -50°F typical for the 501-K/T56 family of engines. Thus the demonstrator engine was not typical of production engines in direction or magnitude of ΔT. This aspect of performance evaluation is to be defined with an engine typical of production engines during forthcoming planned testing. This would include the establishment of ΔT value(s) with steam rate and, if the effect still exists with a production typical engine, a means of compensating indicated TIT to maintain a near constant BOT with varying steam flow.

Turbine Outlet Temperature

There was considerable variation of turbine outlet temperature (TOT) between the two thermocouple readings indicating a large, variable pattern. The measured temperature was 40-100° less than anticipated which probably was due to the variable pattern. More recent testing as part of using TOT for engine control showed an outlet pattern not inconsistent with the differences obtained with the two thermocouples. These other tests have confirmed that two thermocouples are insufficient to obtain a representative average turbine outlet temperature measurement.

Emissions

Because of the extra fuel required to offset the lack of superheated steam, any emission measurements would have been meaningless towards confirming an expected improvement from the steam introduction. An engine with typical production engine characteristics operating with superheated steam will be needed to define the emission characteristics of a DFC 501-KB engine.

SIMULATION MODEL

Adjustments were made to the computer simulation model to match the baseline demonstrator engine performance with no steam injection. This same model accounting for the effects of steam injection and assuming no adverse effects on combustion efficiency, combustion pressure loss or loss in turbine efficiency due to local disturbances, gives results that form a locus of the best test performance achieved with steam injection.

With this further examination of the data, it can still be stated that this demonstrator engine confirms the benefits expected from the dual fluid cycle.

DETAIL TEST RESULTS

Most of the detail test results are presented using a calculated BOT value based on the properties of air fuel and steam as discussed earlier in place at the thermocouple (T/C) indicated turbine inlet temperature.

Overall Performance

The first series of plots has grouped the data such that the Z parameter is rate of steam injection with symbols denoting the point of injection. The variations of steam rate about each nominal value are shown in Table S-IV.

Table S-IV

Variations of Steam Rates During Test

Steam Injection Location	Steam flow variation during test, lb/sec for the various nominal values			
	1.0 lb/sec	2.2 lb/sec	3.6 lb/sec	5.0 lb/sec
Front	.951-.955	2.26-2.29	3.55-3.59	4.85-5.10
Rear	---	2.17-2.19	3.50-3.63	5.05-5.08
Front and Rear	---	2.11-2.17	3.56-3.69	5.03-5.08
Simulation Program	1.0	2.23	3.57	5.0

Figure 1, SHP vs. η thermal - The lines drawn are the results from the computer simulation for this particular engine. Note that this forms an upper boundary for the test results. Also note that at the highest rate of steam injection, the dual injection method is superior.

Figure 2, SHP vs. BOT - BOT is a calculated value from the test results assuming constant combustion efficiency. No pattern of data has been observed due to the steam injection method. Again, the lines are the computer simulation. A second temperature scale is shown for Figure 2 (and various other figures); that of Indicated TIT (T/C). The corresponding TIT values were based on the BOT values and the -50^{o}F ΔT typical of 501-K/T56 engines. These TIT values were used as the basis for presenting the results in the general report as the best estimate at this time of what an operator would observe when operating a DFC version of a typical production 501-KB. As stated previously in this supplement and in the general report, more testing is required to more accurately define the effect of steam injection on ΔT.

Figure 3, η Thermal vs. BOT - Note here again that the computer simulation forms the upper boundary and that at the highest steam rate the dual injection method is the best.

Figure 4, W_f vs. BOT - The variation of fuel flow with injection point suggests an effect upon combustion efficiency. BOT is based upon the assumption of constant efficiency.

Figure 5, R_c vs. BOT - Note that these values are less than that of a typical engine with higher airflow.

Indicated Temperature

The next series of plots, Figures 6, 7 and 8, are arranged to determine the variation of ΔT; the difference between engine thermocouple indicated temperature and computed burner outlet temperature. In this instance, the "Z" parameter is point of steam injection and each figure is for a different steam rate. The T_c vs. BOT values are shown in Figure 6 for 2.2 lb/sec steam flow, W_s; Figure 7 for 3.6 W_s; and Figure 8 for 5.0 W_s. The baseline calibration with no steam injection is shown on each curve. A summary of these results has previously been shown in Table III.

Note that the +30^{o} ΔT for the baseline calibration (T_c - BOT) is <u>not</u> typical of 501 or T56 engines.

The lines were drawn with no ΔT variation with level of BOT in order to determine the pattern of ΔT variation with steam rate and point of injection. It appears that in addition, there is some slight variation of ΔT with level of BOT.

Turbine Out Temperature

Figure 9, Calculated TOT vs. Calculated BOT - Little variation is noted here with steam rate or point of injection. There is agreement within 10° between the simulation and the values based upon test.

Figure 10, Measured TOT vs. Calculated TOT - The measured TOT is 40-100° less than the calculated TOT, varying with both rate and method of steam injection. The TOT was measured with two thermocouples. The difference between these two values was as much as 150°. The hot and cold spot shifted between thermocouples. With this great variation and the shifting about, it is suggested that an average value of turbine outlet temperature was not established by measurement on this test.

Overall Performance - Indicated Temperature

This series of plots gives the overall engine performance for each injection method with lines of steam rate as a function of thermocouple indicated turbine inlet temperature. The faired lines are as a result of combining the ΔT established earlier with the smoothed lines of performance versus BOT. SHP vs. T_c for each of the three steam injection locations are shown in Figures 11, 12 and 13. Corresponding thermal efficiency plots are shown in Figures 14, 15 and 16.

It is to be pointed out again that the ΔT has increased with steam injection. In order to achieve the full potential of the dual fluid cycle, a method of "biasing" temperature will be needed if this observed shift should continue with a DFC version of a typical production engine. This could be done electronically or by operator instructions.

Other

Plots of turbine K factor were made to help in the determination of the variation in performance with point of injection. The change in K factor with steam rate was in the direction anticipated with a variation of + 1/2% - 1 1/2% due to point of injection. This variation did not allow a rationalization of the performance differences to be made.

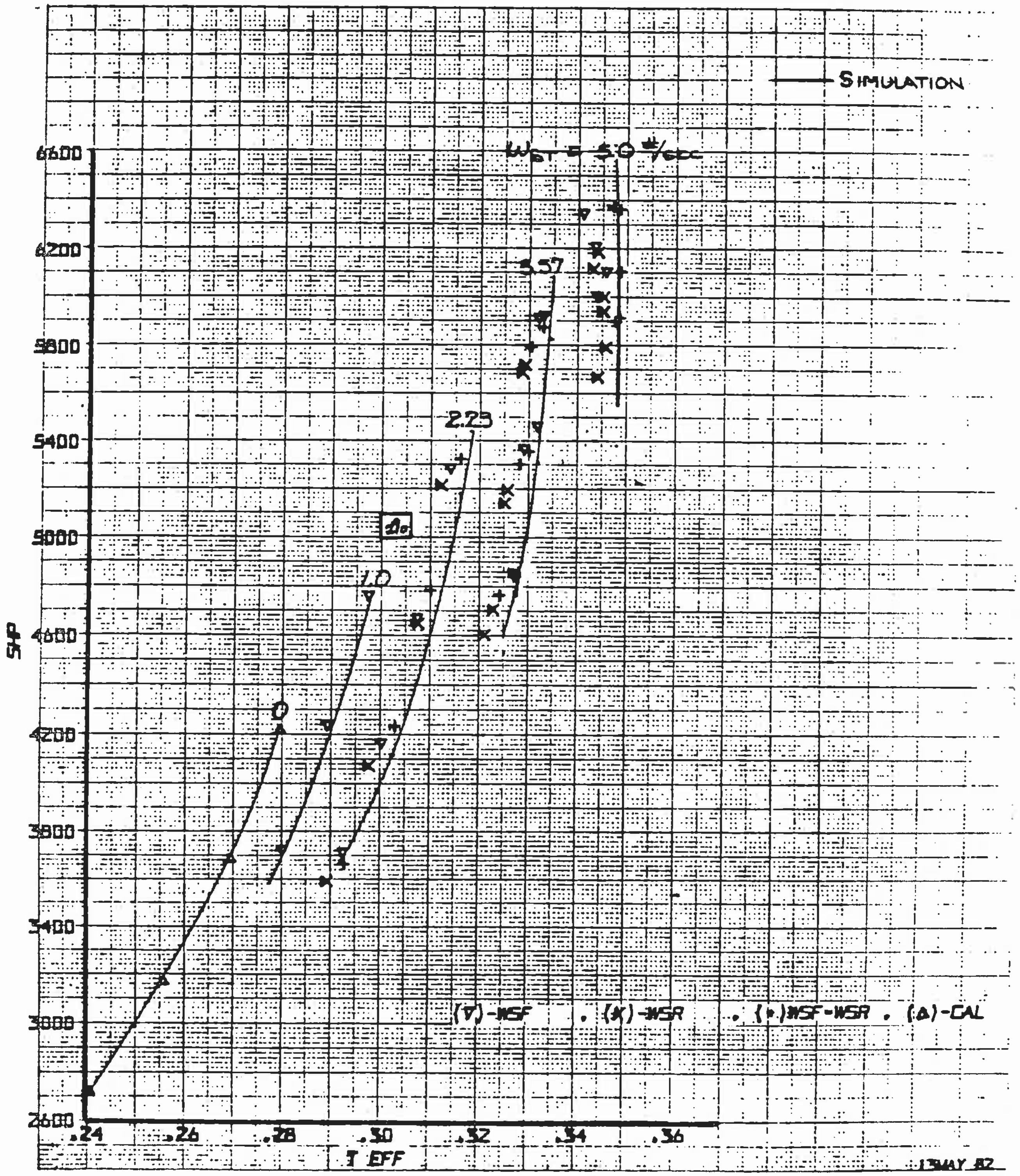

Figure 1. 501 steam injection test data - SHP vs Thermal Efficiency

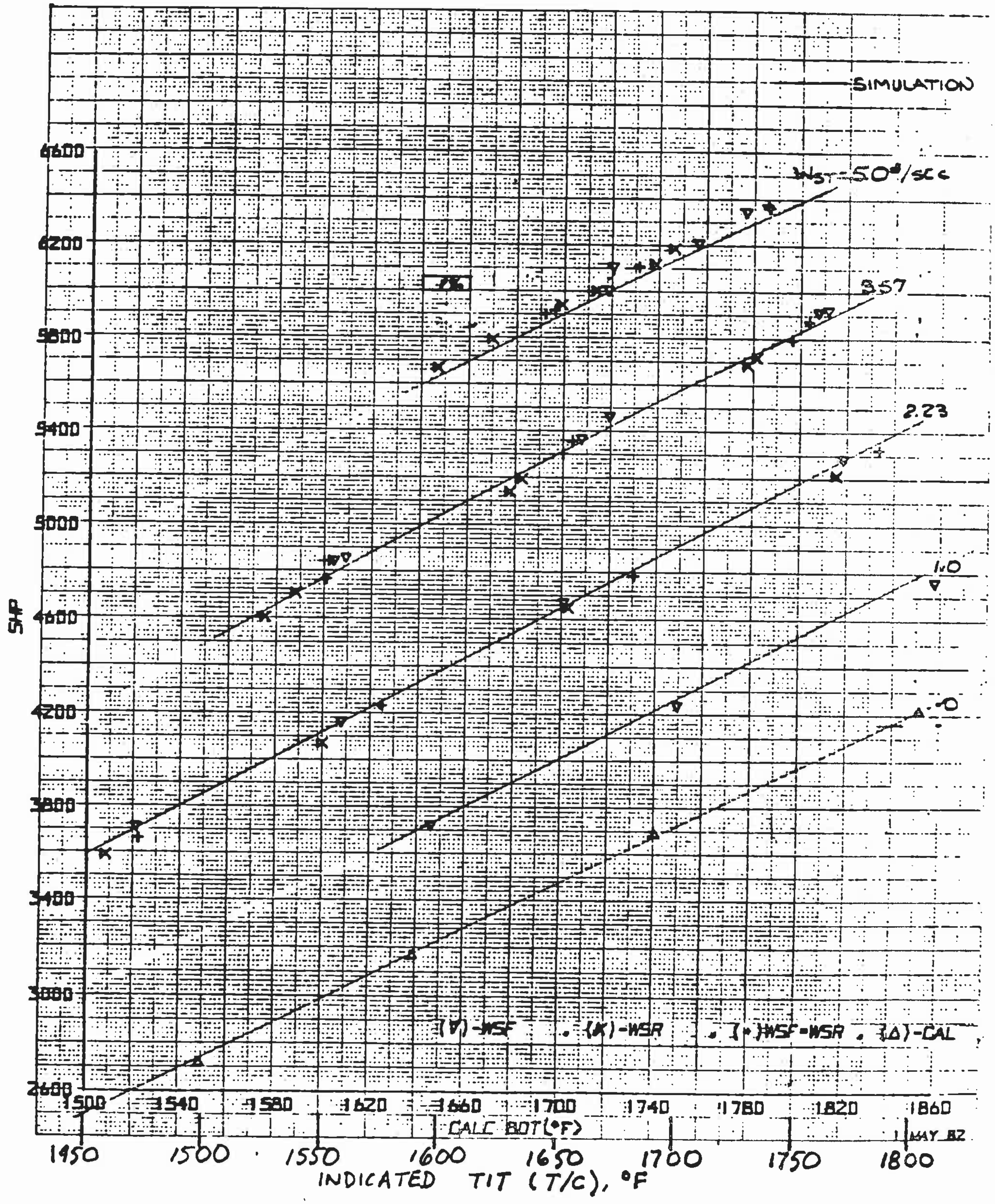

Figure 2 501 steam injection test data - SHP vs calc BOT

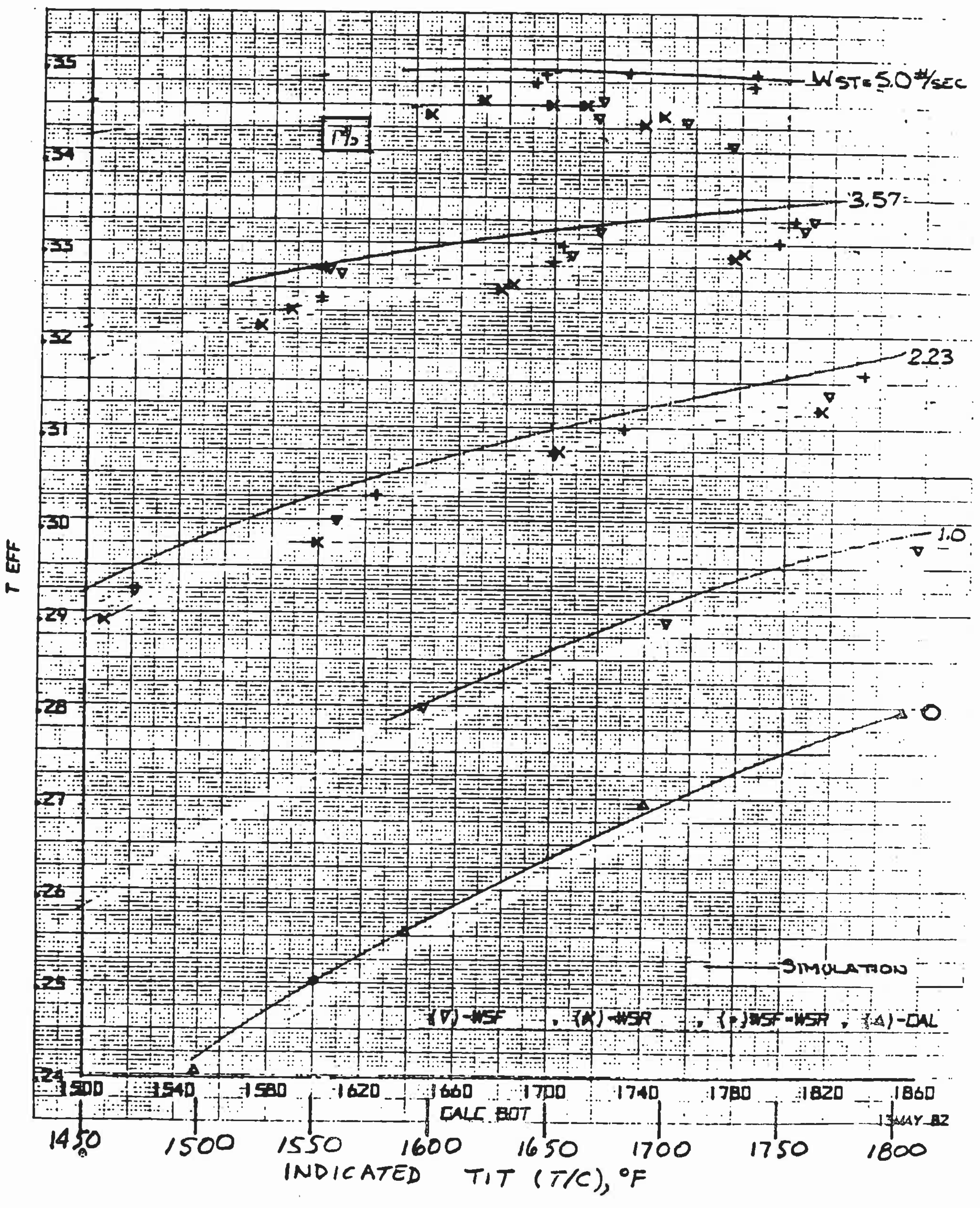

Figure 3 501 steam injection test data - Thermal Efficiency vs calc BOT

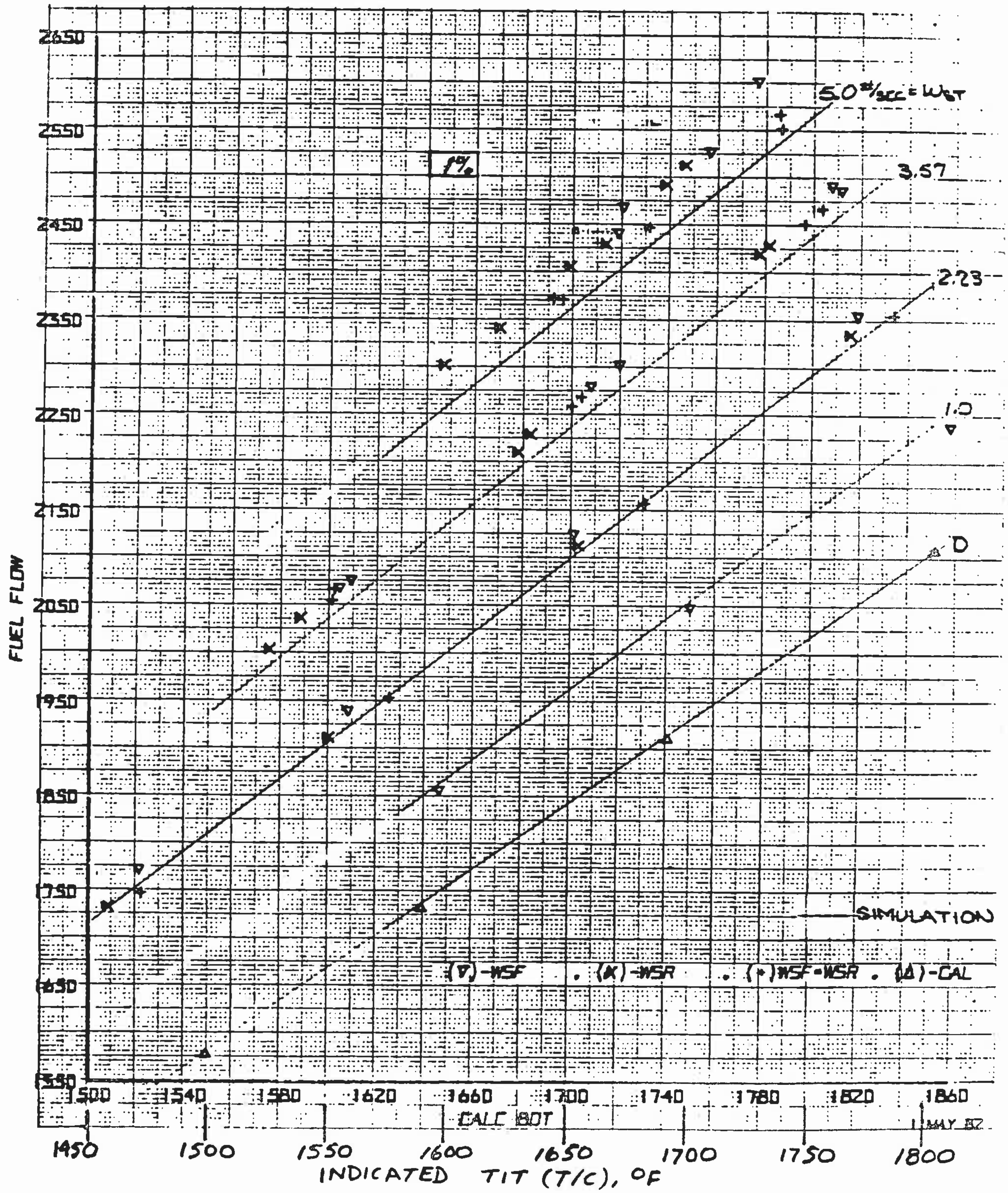

Figure 4 501 steam injection test data - W_f vs calc BOT

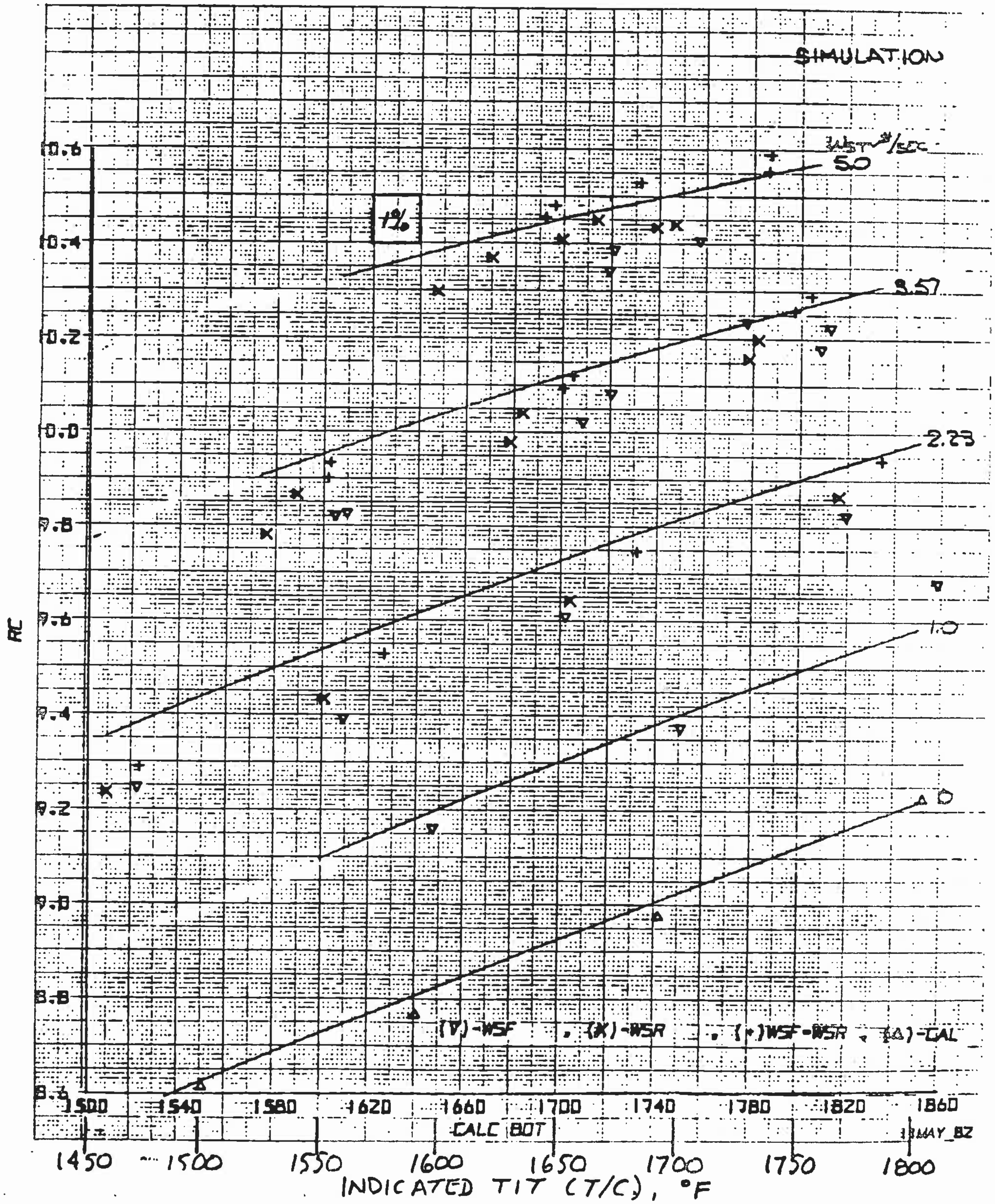

Figure 5   501 steam injection test data - R_C vs calc BOT

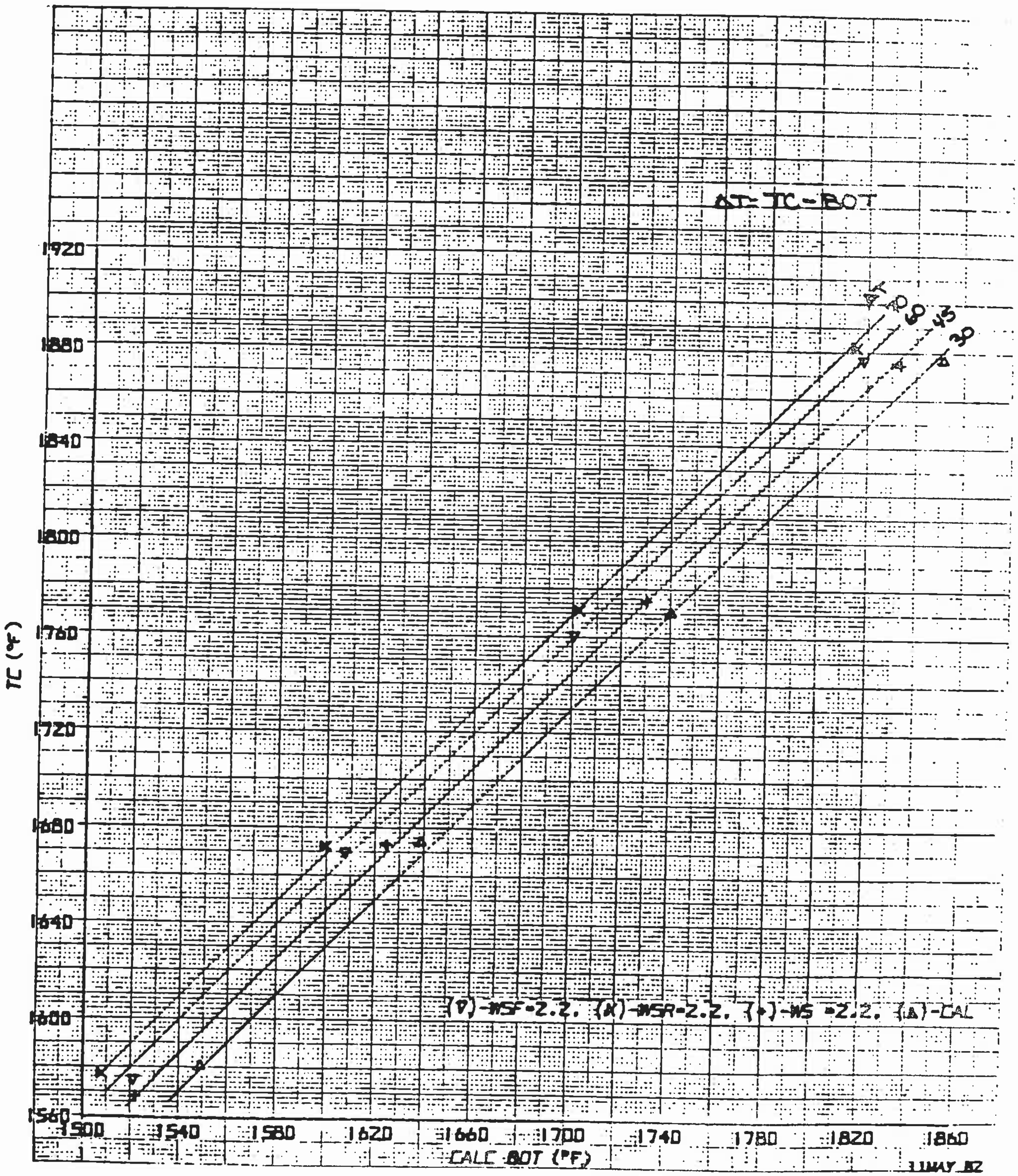

Figure 6   501 steam injection test data - T_c vs calc BOT for W_s-2.2

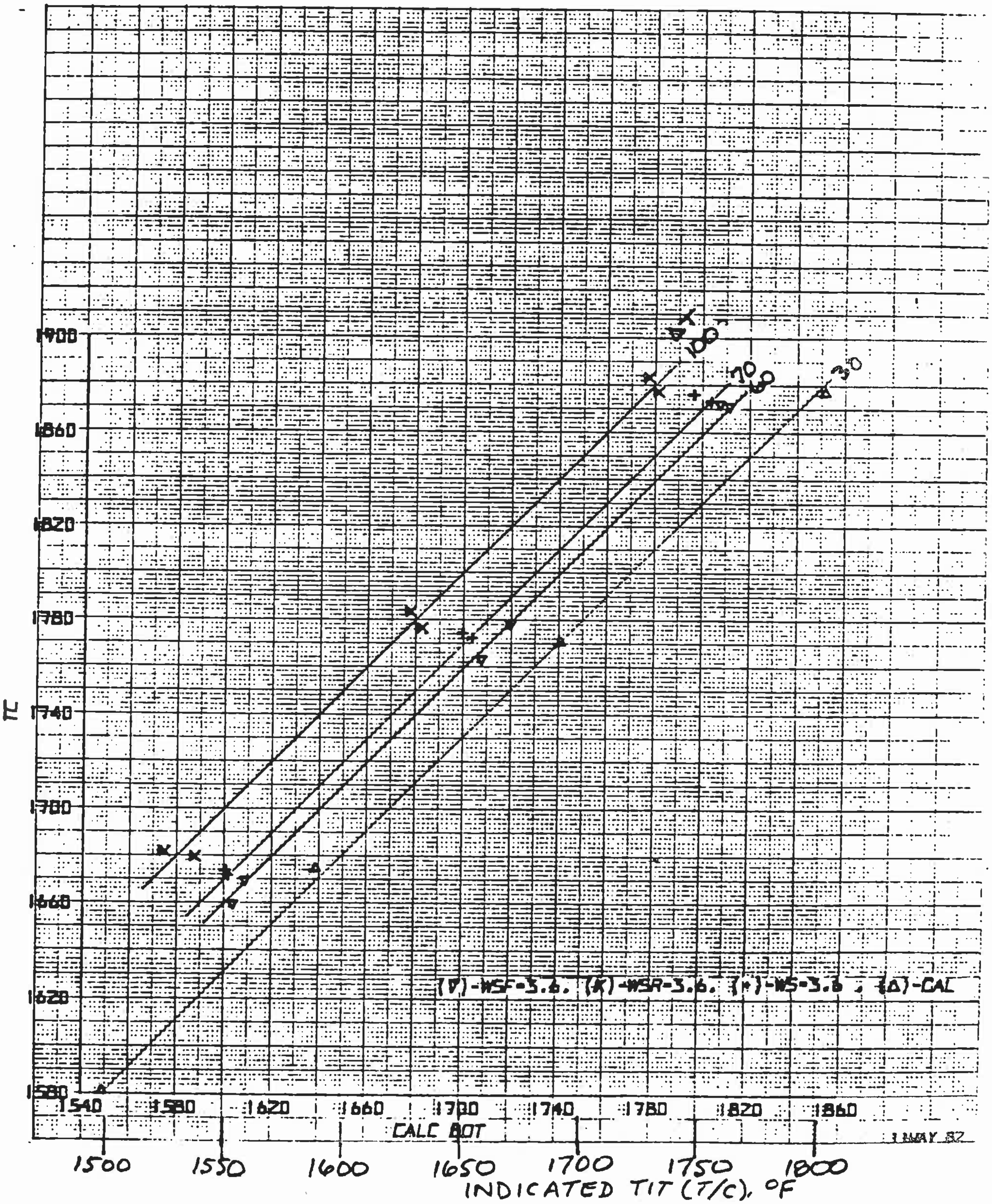

Figure 7 501 steam injection test data - T_C vs calc BOT for W_S=3.6

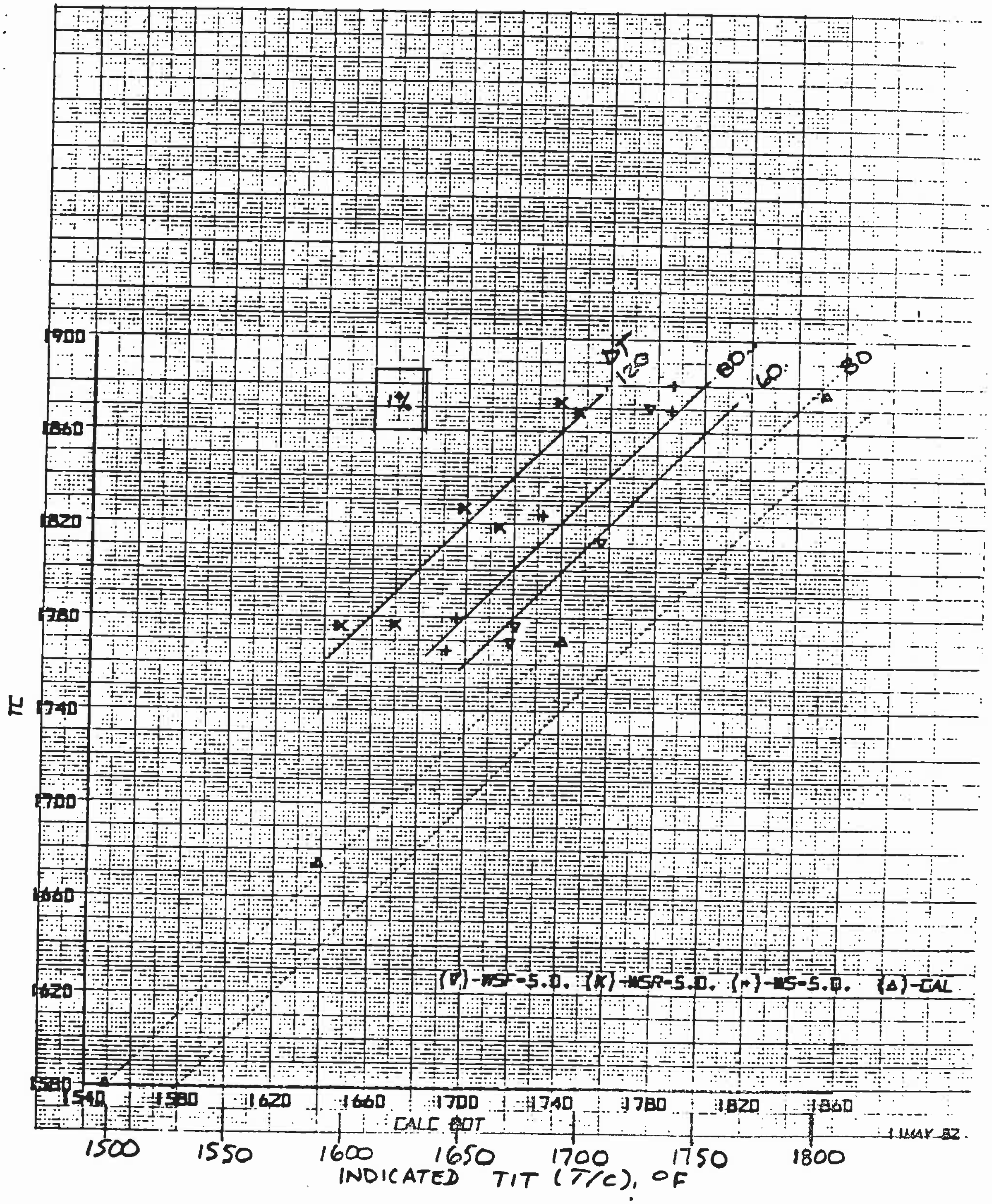

Figure 8 501 steam injection test data - T_C vs calc BOT for W_S=5.0

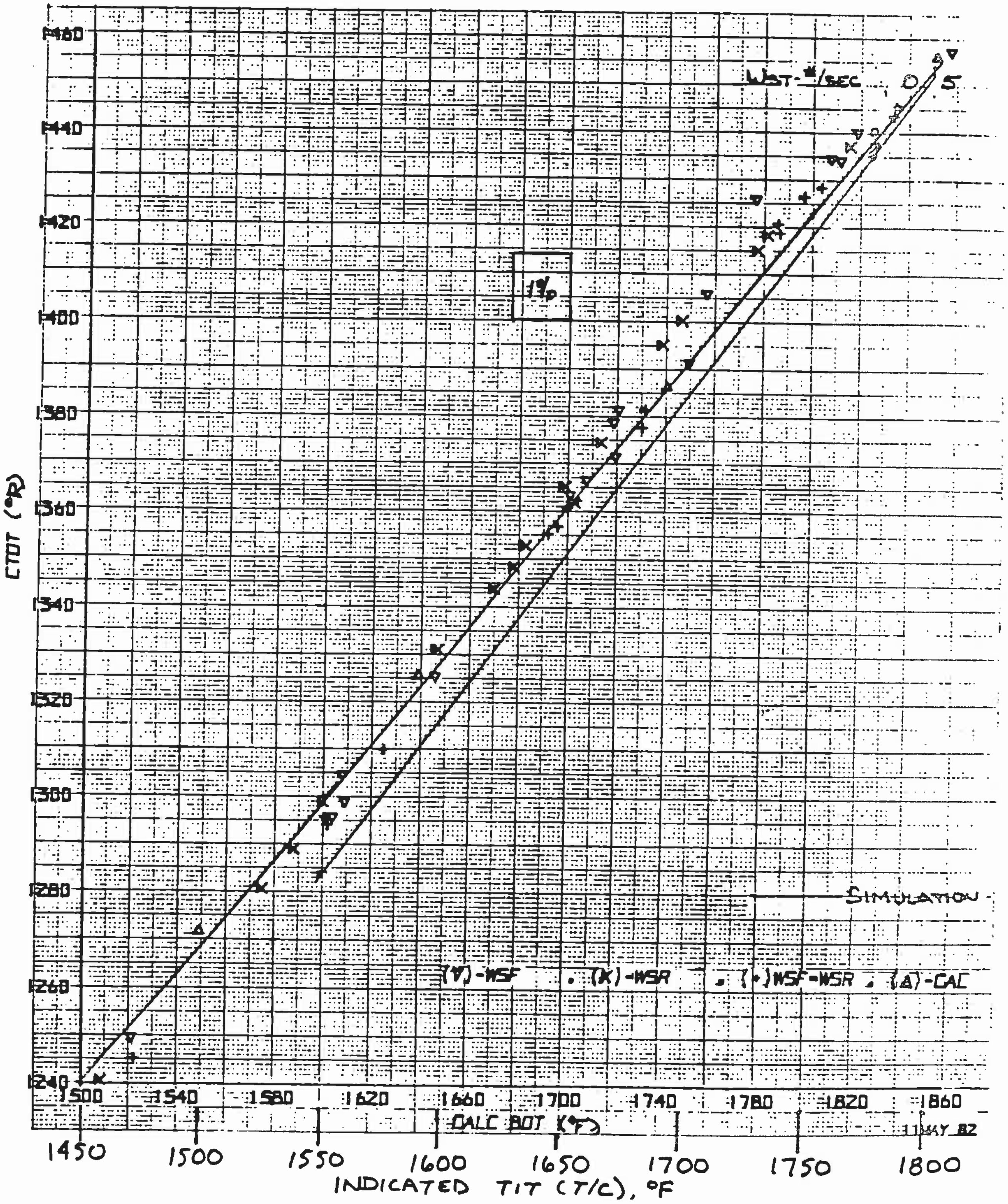

Figure 9 501 steam injection test data - Calc TOT vs calc BOT

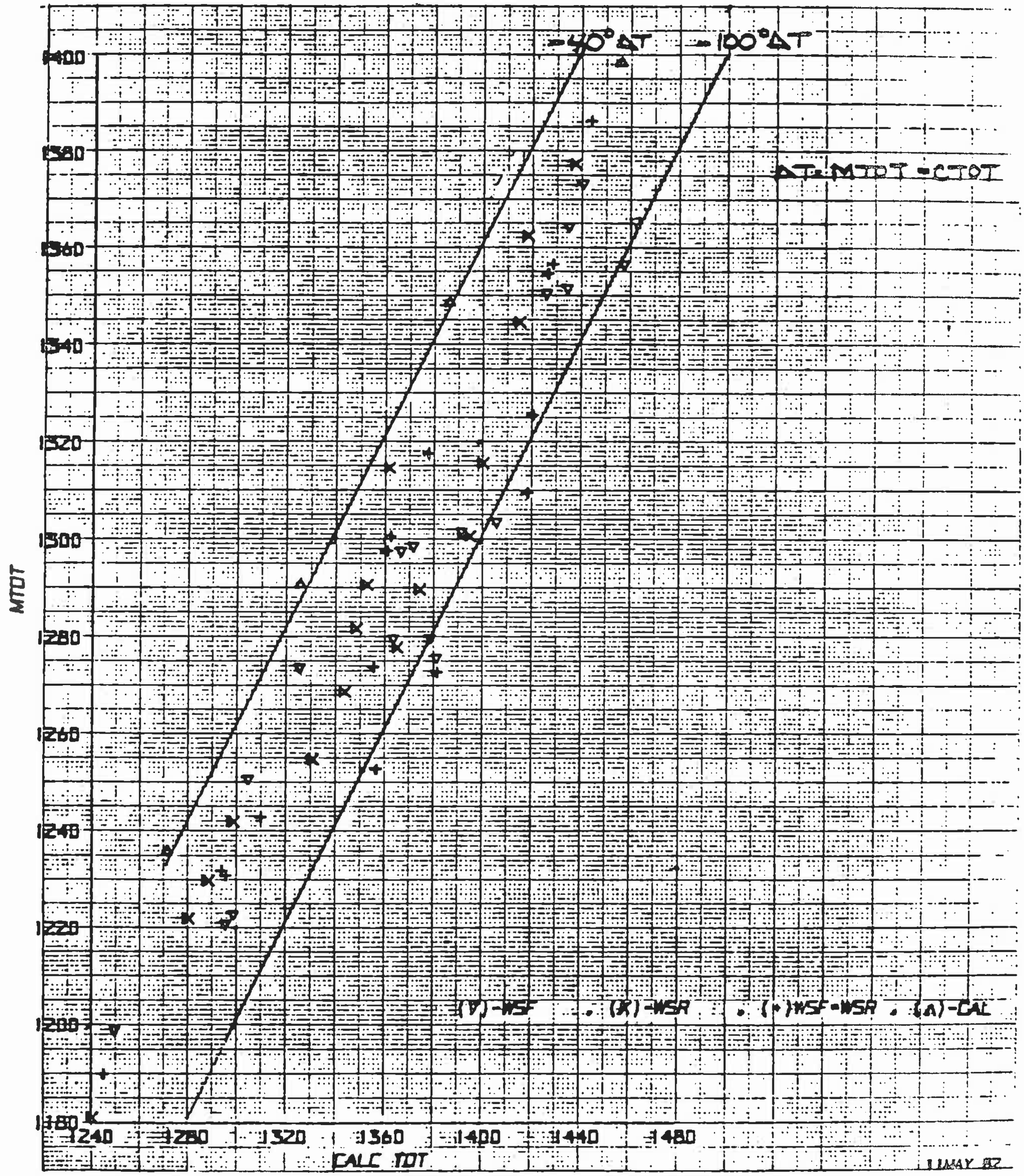

Figure 10 501 steam injection test data - Measured TOT vs calc TOT

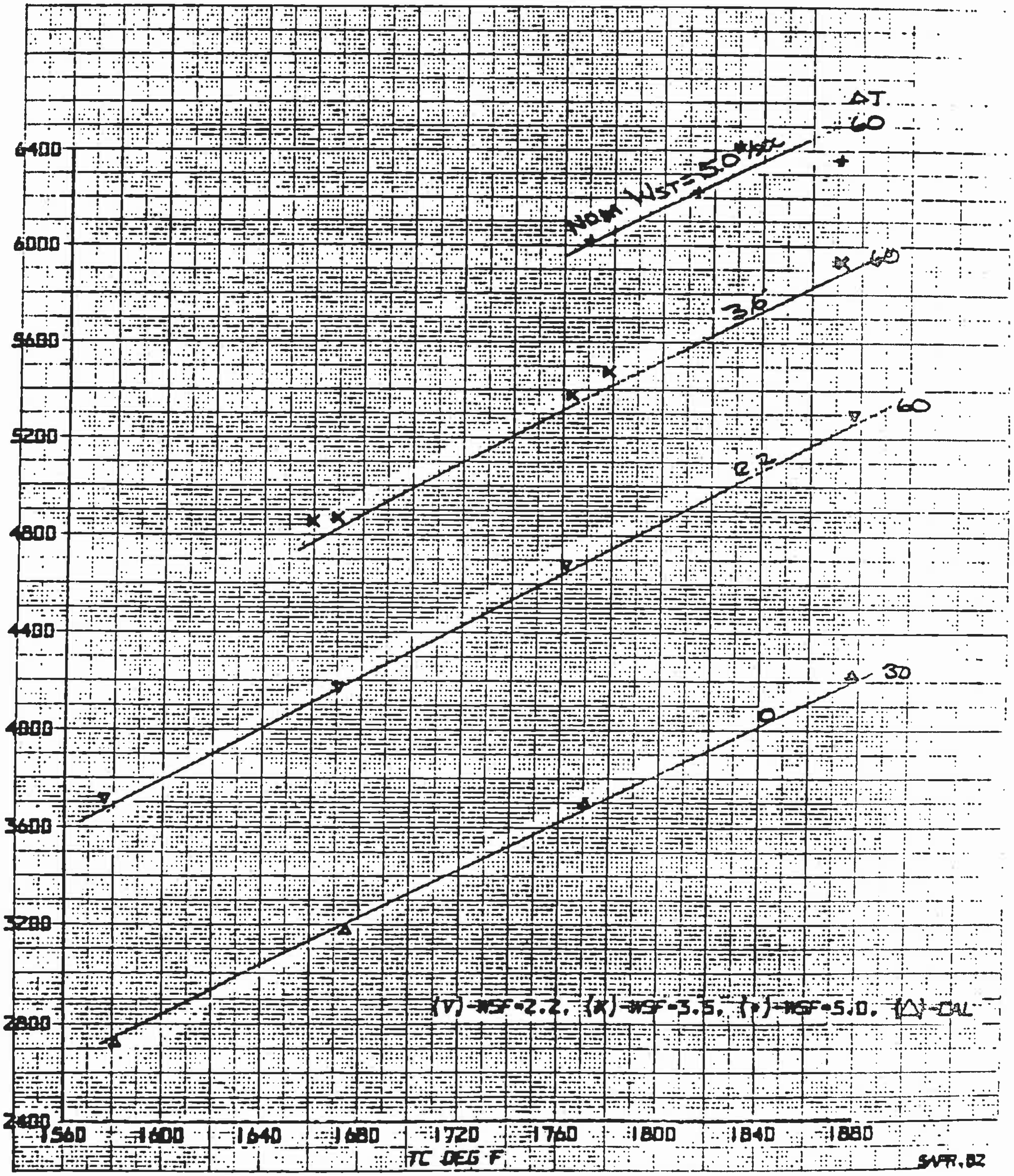

Figure 11 501 steam injection test data - T_C vs SHP with no steam through rear manifold

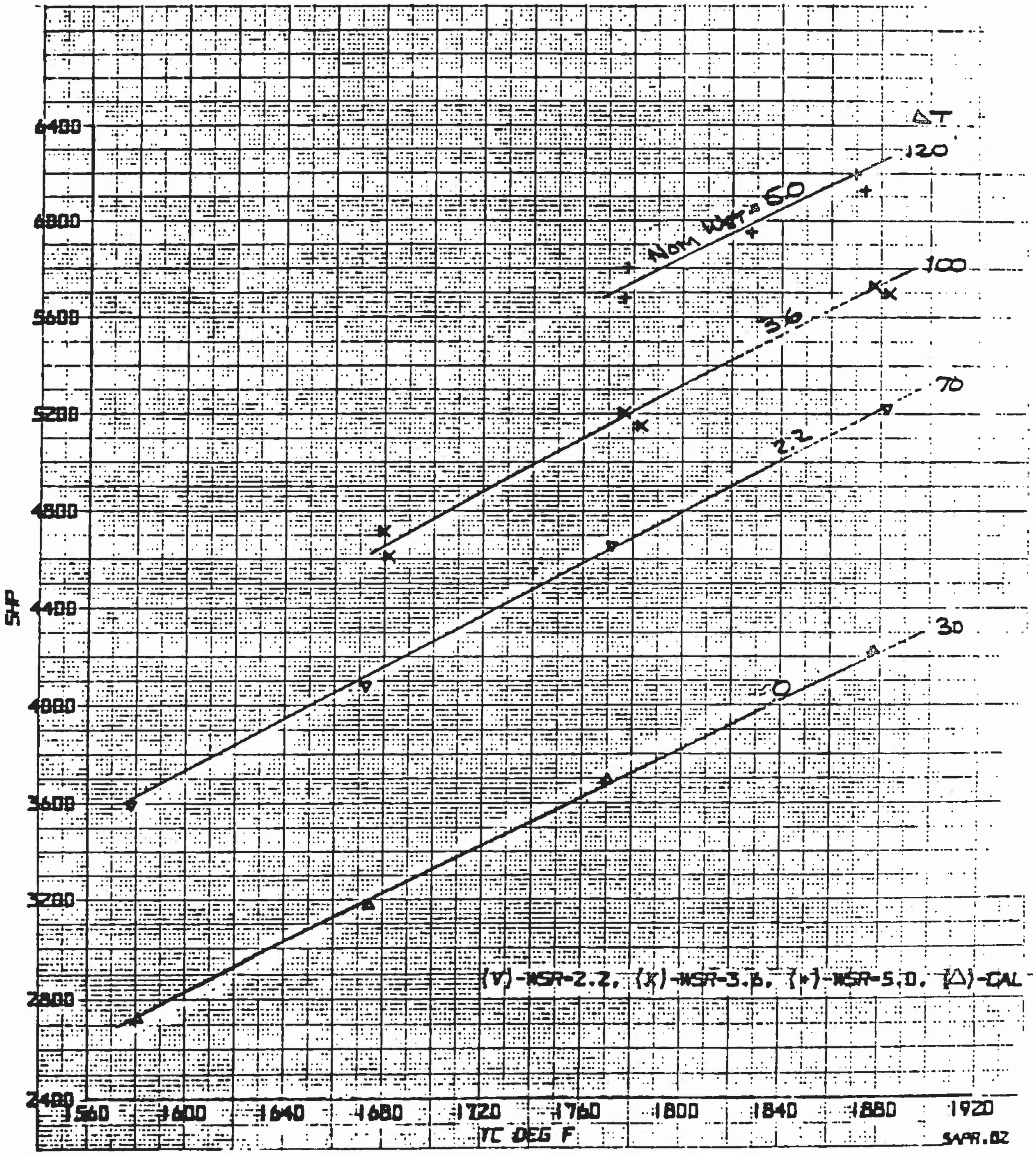

Figure 12 501°steam injection test data - T_C vs SHP with no steam through front manifold

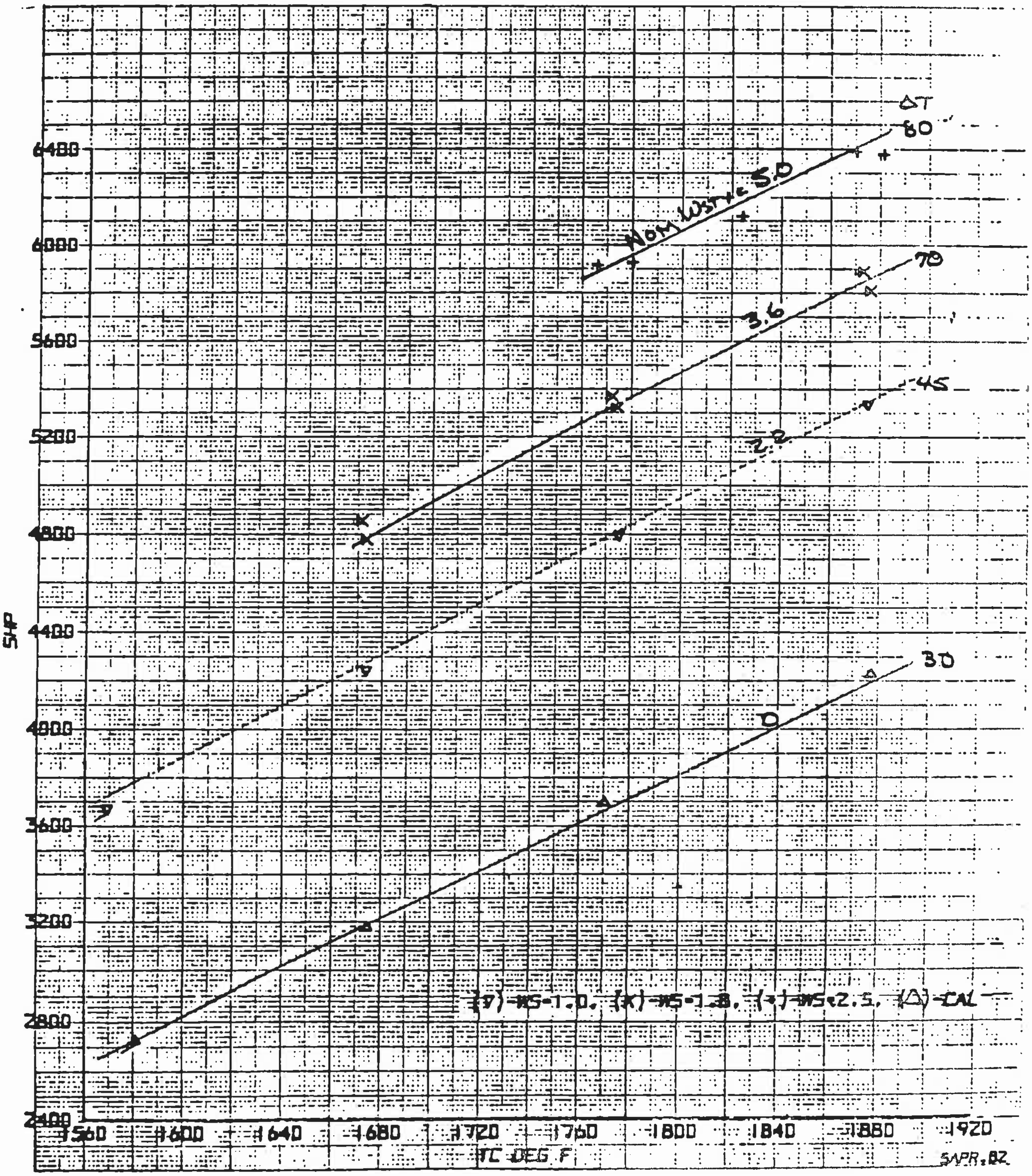

Figure 13 501° steam injection test data - T_C vs SHP with equal steam flow through both manifolds

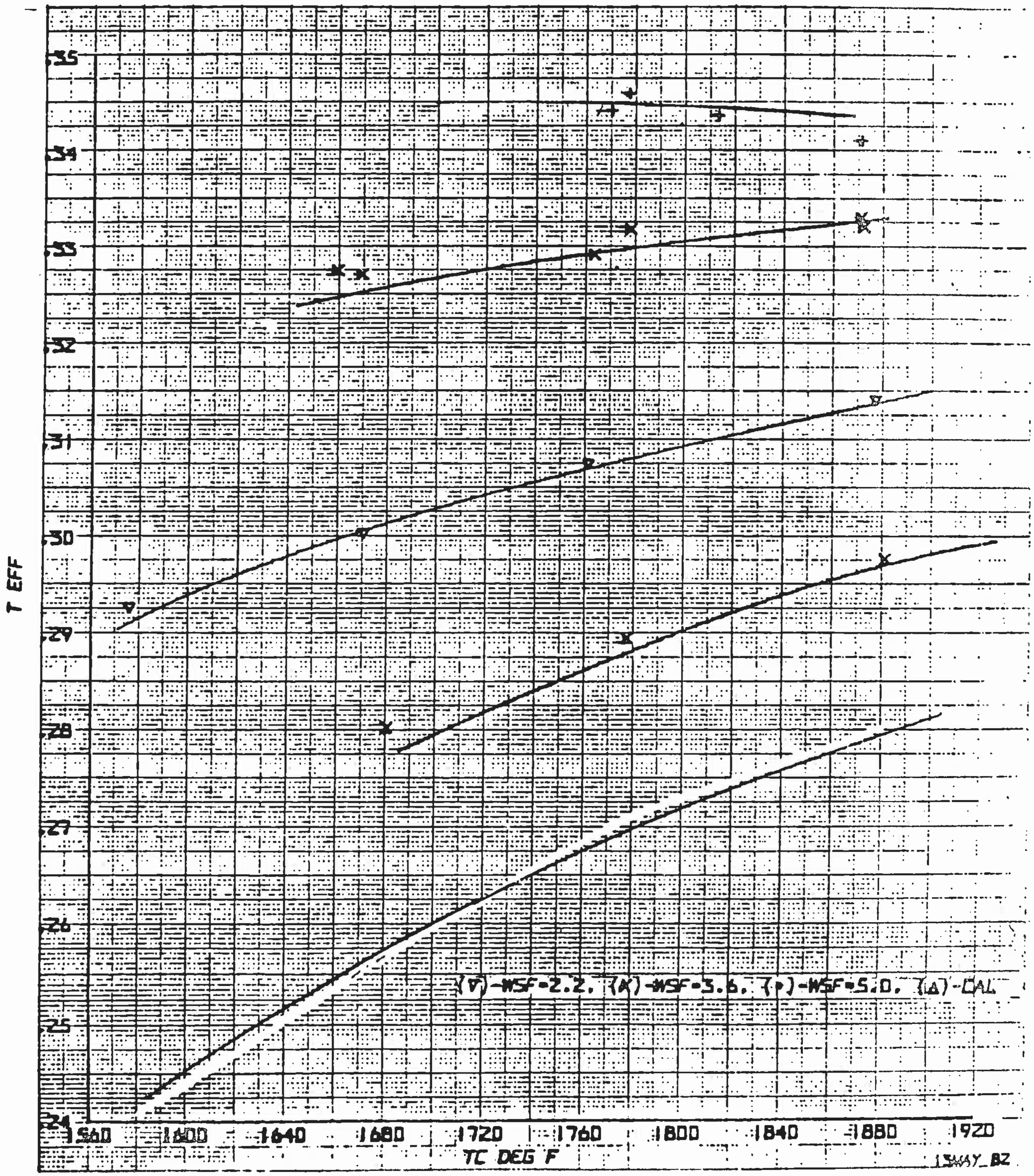

Figure 14 501 steam injection test data - Thermal eff vs T_C with no steam through rear manifold

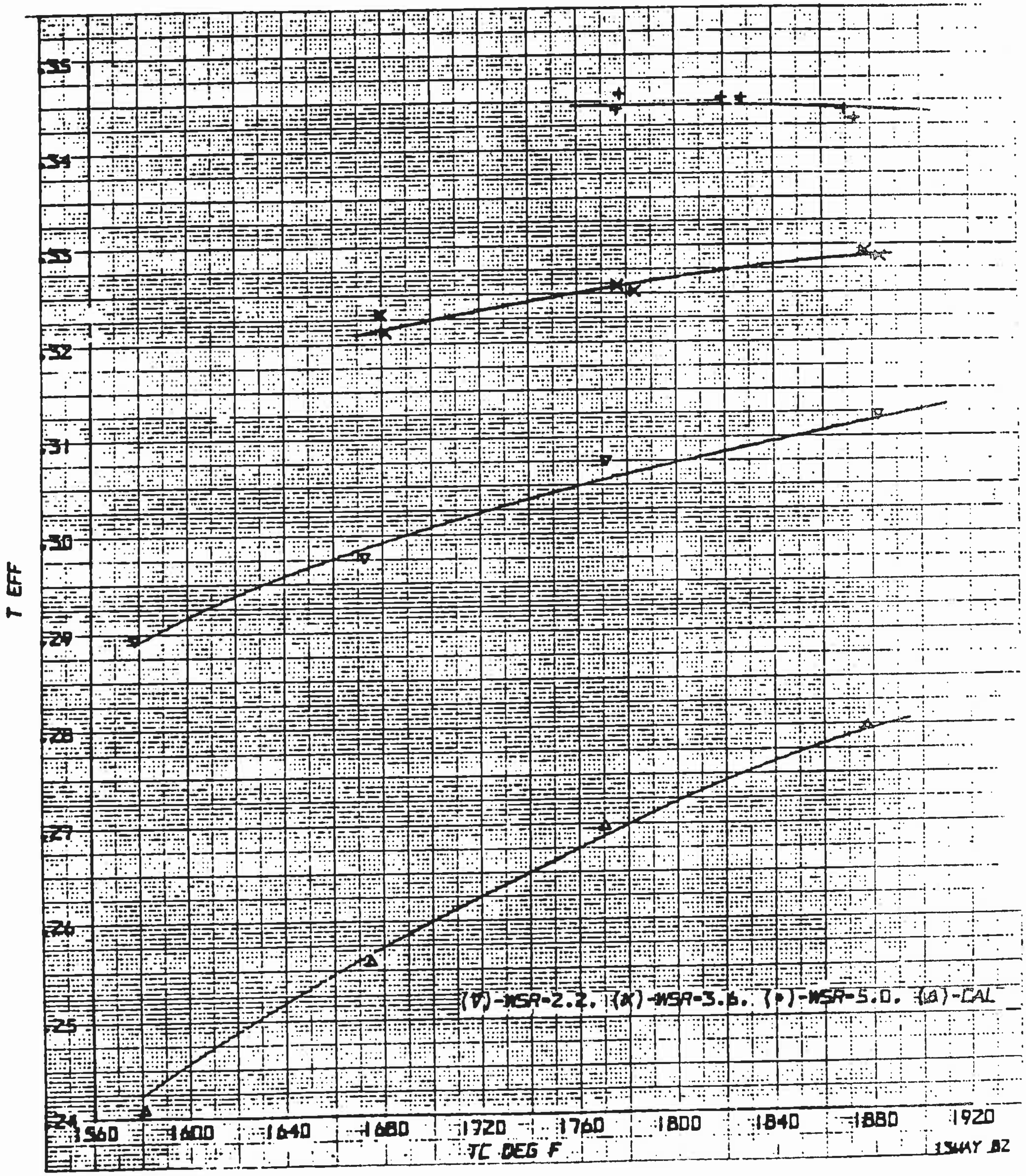

Figure 15 501 steam injection test data - Thermal efficiency vs T_C with no steam through front manifold

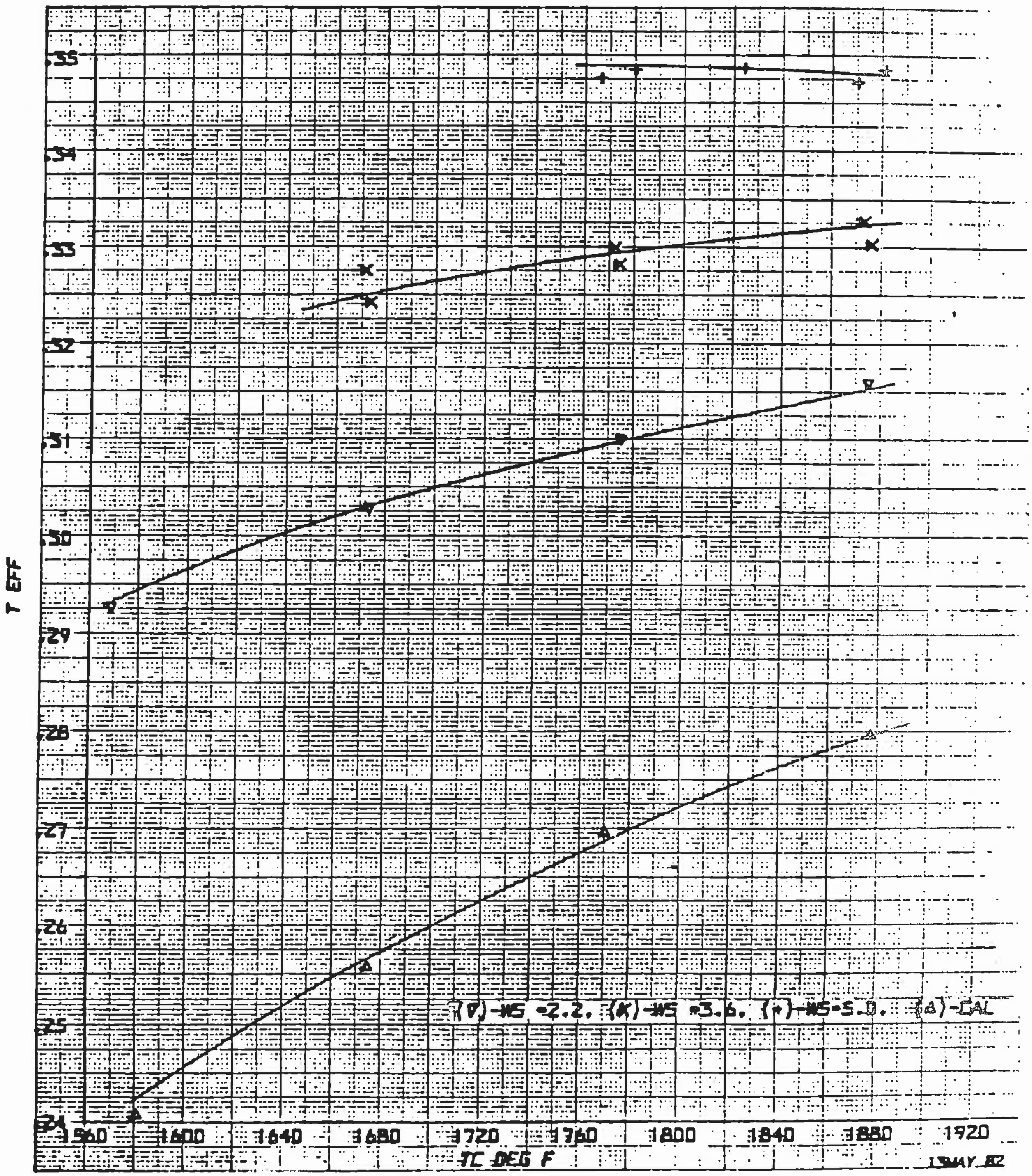

Figure 16 501 steam injection test data - Thermal eff vs T_c with equal steam through both manifolds