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" The Efficiency Measurement at Kalan Power Plant: Results and ideas "

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Résumé

Comme Le rendement des turbines dans les stations hydro-électriques est l'un des plus improtants" valeurs de garantie " , La méthode de mesure et de calcul des quantités correspondantes devront donc être prise en considertion d' une maniére trés attentive.
Cet article est essentiellement consacré aux essais de mesure du rendement des turbines dans la station hydro-électrique de KALAN et á la comparaison des résultats avec des " valeurs de garantie".
D́ ailleurs, quelques recommandations concernant ĺ augmentation de l la précision des mesures et du calcul du rendement réel des hydro-turbines seront présentées.

Summary

As the efficiency of the turbines in hydro electric power plants is one of the most important guarantee value, then the measuring method of the relevant quantities and calculations should be considered quite well.
This paper will mainly deal with the tests of measuring the turbines efficiency of the kalan hydro power plant and comparison of the tests results with the guarantee values.
Also, some recommendations towards increasing the accuracy of the measurements and calculation of the actual efficiency of the hydro turbine are presented.

1. Introduction

The kalan hydroelectric plant is owned and operated by Tehran regional water board (TRWB) . The owner awarded the contract for the electromechanical equipment of kalan power plant (3*38.5 MW) to the GIE co., Italy.

The studies of the plant was done originally by Sir Alexander Gibb & partner, England and the supervision of the works and commissioning was done by Lar Consulting Engineers, Iran.

The project was completed in late 1988, and since that time the units are in operation according to the reservoir level and requirements of the network .

During 7 years of operation, the O & M staff of the plant haven't reported any serious problems.

The delayed efficiency tests of the units was done in 1992 by a specialized team from the Riva Hydroart s.p.a., Italy.

2. Description of kalan power plant

The kalan hydro plant is approximately 30 km northeast of Tehran, the capital of Iran. Its purpose is to divert a part of the impounded water of Lar earthfil dam into the existing Latyian reservoir, in order to augment the supply of drinking water to Tehran as the demand increases.

A low pressure tunnel (approximately 19.9 km long) connects the Lar reservoir to a surge chamber from which a high pressure tunnel and penstock (approximately 1600 m long) leads to a distributing manifold, which supplies three hydro - electric generating sets (each 38.5 MW) and bypass valve(The layout is shown on figure No.1-1). Hydraulic conditions preclude the operation of more than two units at any one time and the additional unit is intended for standby purposes only in order to assure security of water supply to Tehran .

The units are capable of operating as synchronous condensers.

The three turbines are equipped with pressure relief valves, preventing excessive pressure rise during load rejections .

A spherical valve of 900 mm diameter is located at the ahead of each turbine.

Each vertical shaft Francis turbine is rated at 39.49 MW at 750 rpm with nominal discharge of 9.25 m^3/s at a net head of470.5 m.

The generators are vertical shaft, direct coupled (via an intermediate shaft) to the turbine, salient pole, synchronous type, generating (each) 38.5 MW at 50 HZ, 13.8 KV and power factor of 0.85.

The units are intended to operate as peaking units , but could operate continously for prolonged periods at maximum output and discharge.

The average annual generation of the plant is 200 Gwh.

The output of each generator is transmitted through a 45 MVA three - phase transformer to the 230 KV switchgear station for interconnection with the national network.

3. Measuring Systems

3.1. Discharge measurement

According to the contract, the discharge was measured by means of currentmeters in the penstock having a 2.1 m diameter. In compliance with the IEC codes 41-1963, 13 currentmeters (SIAP currentmeters) with diameter of 120 mm were used. The current meters were located on a rectilinear portion of the penstock.

The currentmeters were calibrated at the calibration laboratory of the waters federal service of Bern and were provided with the relevant calibration certificates.

The arrangement of the currentmeters and relevant information are indicated on the figure No.1-2

3.2. Head measurement

In compliance with the IEC codes 41- 1963, measurement of upstream pressure was done by means of a dead weight manometer (Neyrpic accuracy manometer) connected to the pressure taps at the inlet of spiral casing (four taps, which enables to measure the pressure mean value) and measurement of downstream level was done by means of a graduated bar. Before and after the tests, The dead weight manometer was statically calibrated according to the above mentioned IEC codes.

3.3. Differential pressure measurement

The differential pressure on winter kennedy taps was measured by means of a differential mercury manometer, utilizing the taps provided on the sprial case.

Arrangement of the measuring systems described at para. 3.2 and 3.3 are indicated on the figure No.2

3.4. Measurement of the electric power

The electric power at the terminals of generator was measured by means of three wattmeters with precision class of 0.2.
Also three ammeters with precision class of 0.5 and one voltmeter with precision class of 0.5 were used. The mentioned instruments were connected according to IEC codes 41-1963 for generator with grounded neutural.
All the utilized instruments were provided with the relevant calibration certificates.

4. Test procedure

In order to check the results of the tests against contractual guarantees, the tests was performed on each unit separately(only one in operation) and then on two units(each of two units in operation).

4.1. One unit in operation

The tests were performed at net heads between reference heads of 470.5m (gross head of 485.5 m) and 449 m (gross head of 464 m) as indicated in the contract.

On the hill diagram of figure No. 3 the relevant reference points are shown as C and B.

The measured values were subsequently converted to the reference net heads with the guarantees, as stated in the IEC codes 41-1963.

Besides of the guarantee discharge of 9.25 m^3/s, the tests was performed at various decreased discharges.

The above mentioned tests were alternately extended to two units by the measuring systems as already indicated.

4.2. Two units in operation

The tests were performed with two units in operation and a total discharge of 18.5 m^3/s was flowing through the penstock.

As the net head of the tests was differ from the net indicated in the contract (404.04 m), the measured values were converted to the referenc net head with the guarantee as stated in the IEC codes 41-1963 on the hill diagram of figure No. 3, the relevant reference point is shown as point A.

5. Results Processing

5.1. Discharge calculation

The signals at the outlet of each currentmeter (1 pulse every 1/2 turn) were routed by cables to a multichannel pulse counter (visualized on LCD) At the same time the signals were stored by a computer and processed for discharge calculation in real time.

The number of turns of each currentmeter, duration of the test and processins for calculation of the water velocity for each currentmeter was tabulated by a printer.

Finally, in compliance with the IEC codes 41-1963 for the procedures of graphic integration of $\int vdr^2$ and $2\int vrdr$, the relevant graphs were recorded by a plotter (HP) , piloted by a computer.

5.2. Head calculation

The head was calculated by the formulas specified in the IEC codes 41-1963 (chapters II and IX).

5.3. Turbine input(Pd)

The turbine input was calculated by the formula indicated in IEC codes 41-1963.

5.4. Turbine output(Pt)

The turbine output was determined by the following formula:

$Pt = Pr + Pa$

Pr: Active power measured at the terminals of generator by the instruments mentioned at para.3, with the due correction of the errors attributable to the instruments and relevant instrument transformers.

Pa: Mechanical and electrical losses measured during generator efficiency tests by means of calorimetric tests.
According to the contract, the generator losses includes the thrust bearing losses attributable to the turbine.

5.5. Efficiency calculation

- One unit in operation

The turbine efficiency was calculated as ratio of the trubine output (Pt) to the turbine input (Pd).

- Two units in operation

The output of each turbine(Pt1,Pt2) was measured by means of relevant set of instruments.

on the basis of the above mentioned measurements, the mean efficiency of the two turbines was determined by the following formula:

$$\eta_m = \frac{Pt1 + Pt2 \cdot 102}{\gamma \cdot 1000 \cdot \frac{H1+H2}{2} \cdot Q}$$

5.6. Calculation of winter kennedy taps constant

The constant of the winter kennedy taps was determined as the ratio of the discharge (measured by the currentmeters at various load) to the root of the differential pressure (measured by the differential manometer) at the same load, thus given by the following formula:

$$K = \frac{Q}{\sqrt{\Delta h}}$$

Q :discharge in m^3/s

Δ h : differential pressure mm Hg^1/2

on the figures No.4-1 to 4-13 samples of calculations and tests relevant to para. 5.1 to 5.6 and also other information for the specific condition are shown.

6. Comparison of the tests results against contractual guarantees.

The samples of the tests results (calculations and curves) for one unit and two units in operation are indicated on figures No.4-1 to 4- 13 .in compliance with the IEC codes 41-1963 (chap V.II) the tabulation of the measurements and test results are indicated on figures No.5-1 to 5-2 for one unit (unit No.1) and two units (units No.1 and No.2) in operation.

According to the contract, " the efficiencies of the model turbine, full size turbine , generator and the complete generating set shall not be less than the values stated below for operation at normal speed, rated voltage and rated power factor overexcited, under the mean gross head of 464 m, the turbine discharging 9.25 m^3/s".

Item	No. of operating set	
	1	2
output (MW)	36.75	33
Discharge (m^3/s)	9.25	9.25
Net head (m)	449	404.04
Model turbine efficiency(%)	90.33	90.29
Full size turbine efficiency (%)	92.08(92.10) *	92.04 (92.16) *
Generator efficiency(%)	97.48	97.32
Efficiency of complete set (%)	89.76	89.57

* Obtained from the turbine efficiency tests results.

As the model was made at a scale of 1/4 and the scaled - up efficiency calculated from the model peak efficiency by the moody formula (IEC 193 for Francis turbine):

$$\frac{1-\eta_p}{1-\eta_m} = (1/4)^{0.2}$$

giving $\eta_p = \eta_m + 2.3$ percent

And with regard to the test results, which showes comparatively higher peak efficiency on the prototype turbine, Finally it was comfirmed that the mentioned guarantees (relevant to the turbines) has been fulfilled.

7. Ideas

The efficiency of the turbine is dependant on its hydraulic design as well as its present condition.

In addition to the turbine design, the actual efficiency loss is caused by several factors.

A number of these factors and also recommendations are presented as follows:

7.1. For field testing of hydro turbines, using of modern technology (computrized) should be noticed quite well.

Modern technology provides real time recording of measured data, immediate control and evalution of the measurement, high accouracy and reduced error frequency of the measurements. Good post - processing of the data is also necessary to achieve a clear presentation of the results.

Of course, proven software and qualified test personnal are needed for successful measurement.

7.2. If the tests are done after a long period of operation of the units, then some matters should be noticed. For example, water quality can be an important matter. Experiences showes that abrasion from quarts - sand is often found in hydro turbines and can greatly reduce efficiency.

7.3. During the tests, it is better to check the situation of the frequency of the unit (connected to the network). In weak and unstable networks, mostly the frequency of the system is lower than the nominal value, which causes serious problems in the cooling system of the unit and finally increases the losses of the unit.

7.4. If both of generator and turbine efficiency tests at site are foreseen in the contract, then in order to increase the accuracy of the tests, simultaneous performing of the above mentioned tests (as far as possible) is recommended.

7.5. In order to measure the output power of the generator (during the tests) , mostly the existing instrument transformers in the switchboards are used. As the precision class of such instrument transformers are not suitble, using of instrument transformers with higher precision class (for example 0.2) is recommended.

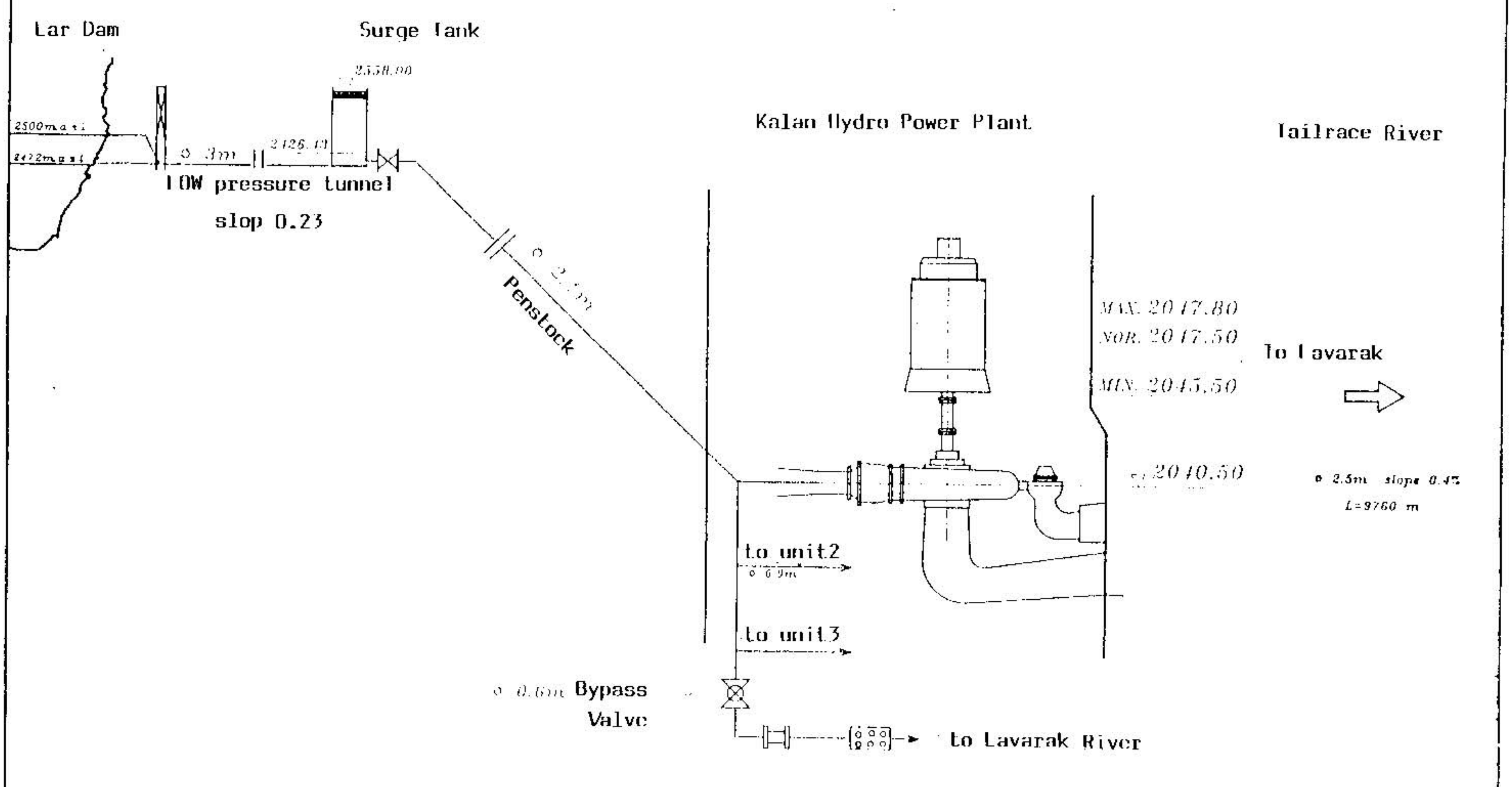
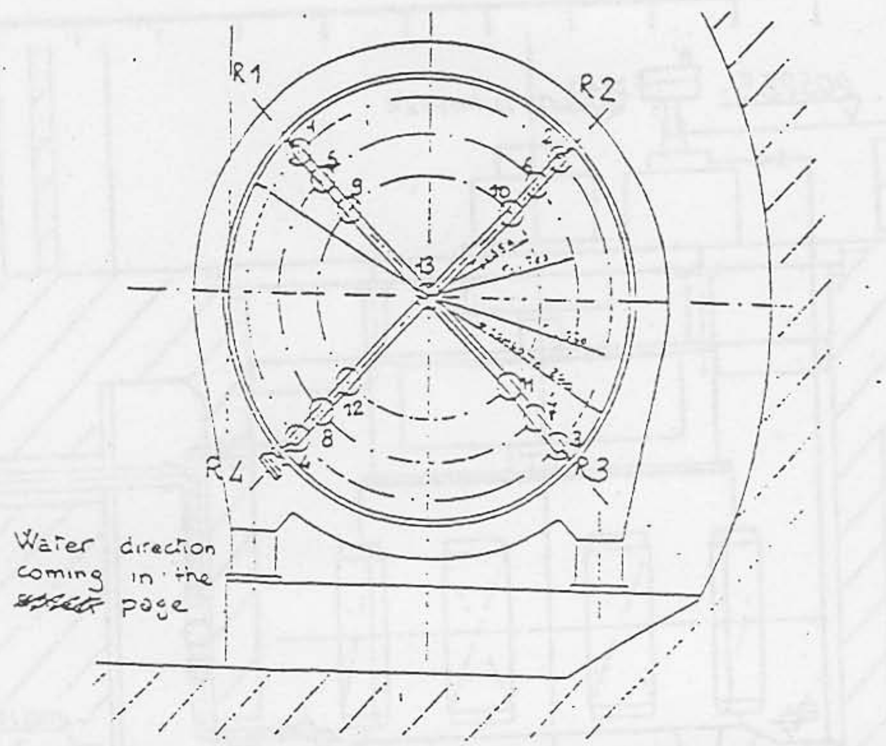


Fig. 1-1 : layout of Kalan Hydro plant

Fig. 1 -2 : Arrangement of the currentmeters



Average penstock diameter = 2101.5 mm

[illegible] HYDROELECTRIC POWER STATION
TURBINES EFFICIENCY TESTS
CURRENT METERS INSTALLATION SHEET

[illegible]

POSITION	SERIAL NO.	INSTALLATION RADIUS mm.	DISTANCE FROM WALL mm.
1	6608	961	90
2	6945	963	89
3	6954	961	88
4	6951	961	90
5	6607	785	266
6	6395	784	268
7	6606	783	266
8	6394	783	268
9	6955	554	497
10	6391	554	498
11	6393	554	495
12	6932	555	496
13	6096		R_1 = 1051
			R_2 = 1052
			R_3 = 1049
			R_4 = 1051

Fig. 2 : Arrangement of the measuring systems

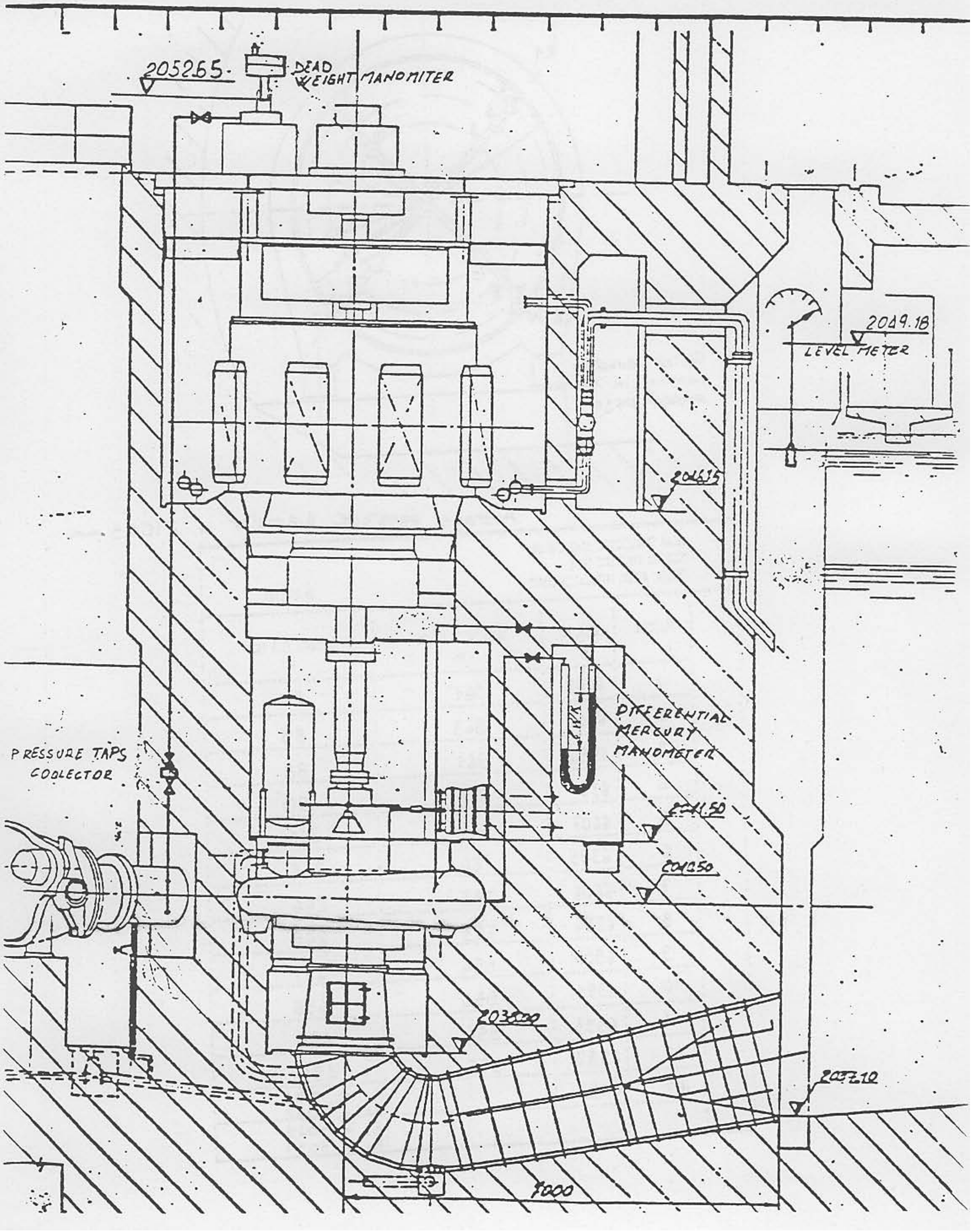


Fig. 3 : Hill diagram

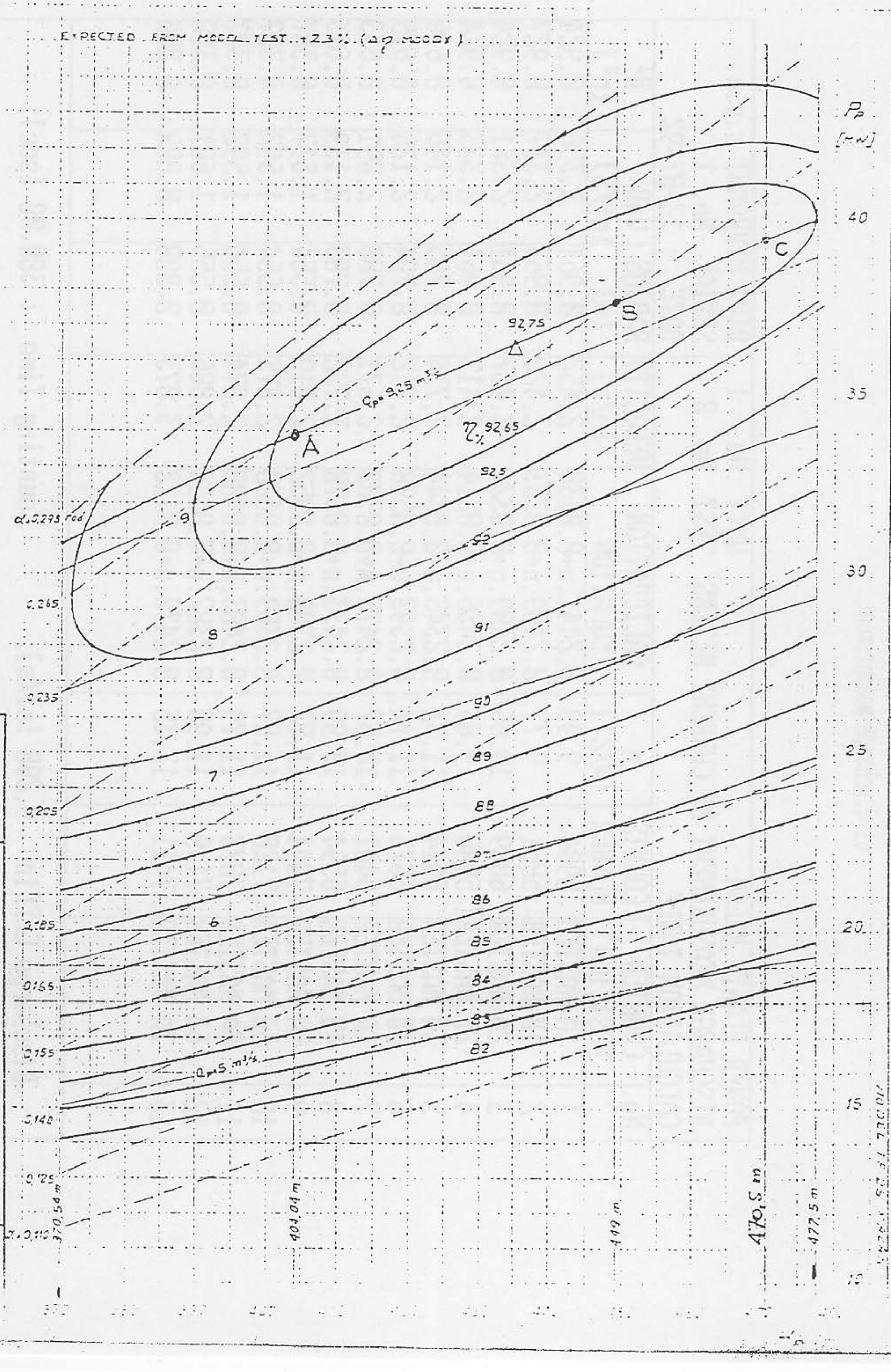


Fig. 4-1 : One unit in operation - Calculation of discharge measurement

POWER PLANT: KALAN
UNIT No. 1 SERIAL No. 1
DISCHARGE MEASUREMENT BY CURRENT METERS

13-07-1992

POWER PLANT: KALAN — UNIT No. 1 — RIVA HYDROART s.p.a.
DISCHARGE MEASUREMENT BY CURRENT METERS — TEST No. 8 — SERIAL No. 1
CALCULATION TABLE — DATE : 12-07-92

No.	COUNTER POSITION	COUNTS NUMBER	n [N/2T]	CALIBRATION EQUATION	VELOCITY [m/s]	RADIUS [m]	V*R [m²/S]	R² [m²]
1	1A MASTER	5994	9.99	0.2441.n+0.0130	2.452	0.961	2.356	0.924
2	1B MASTER	5861	9.77	0.2409.n+0.0733	2.426	0.963	2.337	0.927
3	2A MASTER	6039	10.06	0.2409.n+0.0324	2.457	0.961	2.361	0.924
4	2B MASTER	5900	9.83	0.2436.n+0.0214	2.417	0.961	2.323	0.924
5	3A MASTER	6914	11.52	0.2343.n+0.0344	2.734	0.785	2.146	0.616
6	3B MASTER	6673	11.12	0.2393.n+0.0508	2.712	0.784	2.126	0.615
7	4A MASTER	6401	10.67	0.2475.n+0.0302	2.671	0.783	2.091	0.613
8	4B MASTER	6594	10.99	0.2433.n+0.0578	2.732	0.783	2.139	0.613
9	5A MASTER	7094	11.82	0.2388.n+0.0952	2.919	0.554	1.617	0.307
10	5B MASTER	7120	11.87	0.2369.n+0.0620	2.873	0.554	1.592	0.307
11	6A MASTER	7073	11.79	0.2403.n+0.0408	2.874	0.554	1.592	0.307
12	6B MASTER	7139	11.90	0.2382.n+0.0514	2.886	0.555	1.601	0.308
13	7A MASTER	7411	12.35	0.2478.n+0.0122	3.073	0.000	0.000	0.000

Discharge Coffin 9.298 [m3/s]; Counting Time : 300.00 [sec];

POWER PLANT: KALAN SERIAL No. 1 UNIT No. 1 DISCHARGE MEASUREMENT BY CURRENT METERS	4RS Data: 16-07-1992	Pagina

TEST No. 8

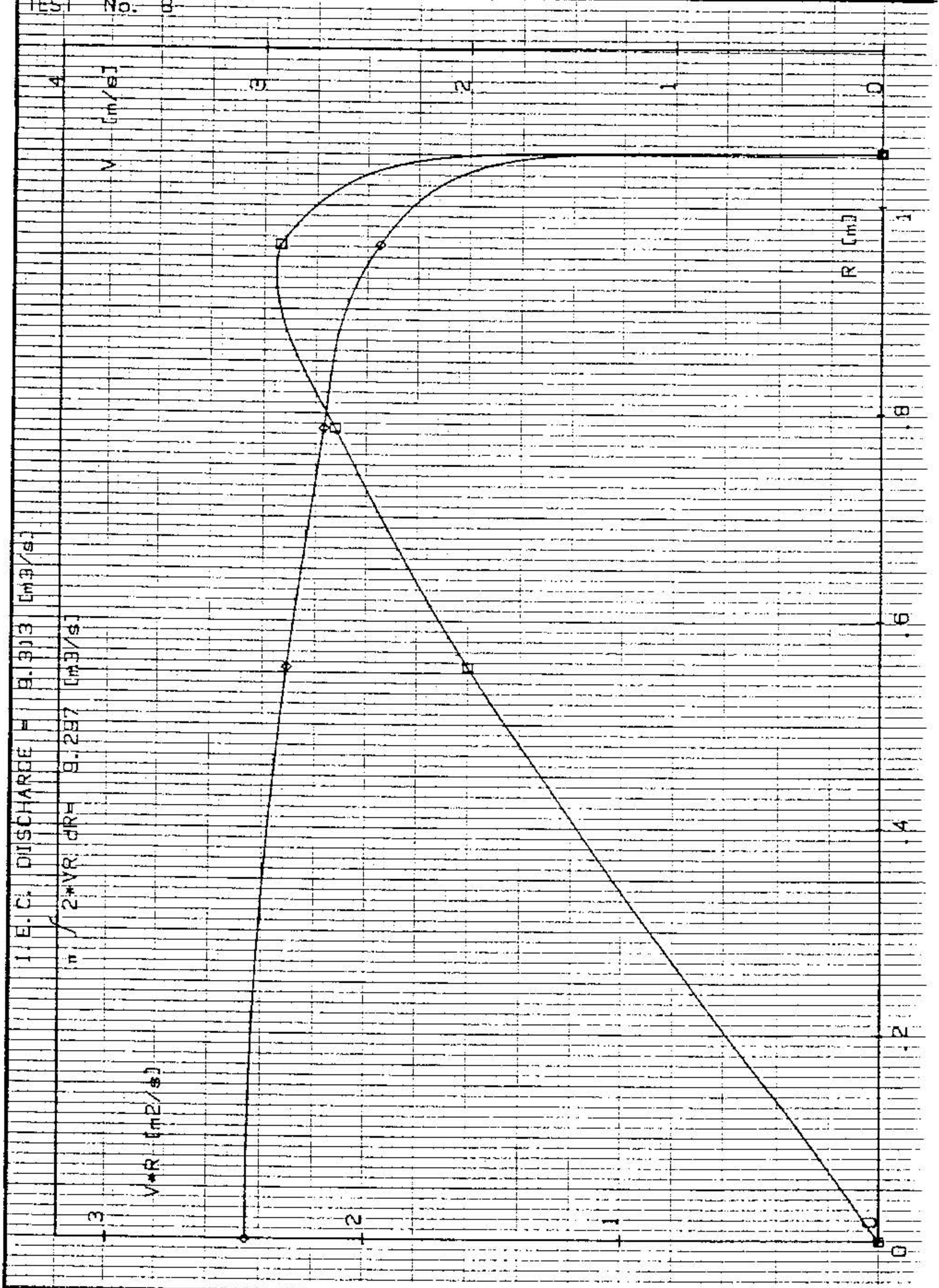


Fig. 4-2 : One unit in operation - Discharge measurement by graphic integration

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Fig. 4-3 : One unit in operation - Test results

RIVA HYDROART S.p.A. 21-07-92

POWER PLANT : KALAN - UNIT N°.1 - EFFICIENCY TESTS

Test number 8

FINAL RESULTS

1- WATER DENSITY AT 27.5 [°C] =	ro1 =	996.449	kg/m3
2- WATER DENSITY AT 9 [°C] =	ro2 =	999.798	kg/m3
3- STATIC PRESSURE UPSTREAM THE TURBINE	P1 =	43.573	bar
4- STATIC PRESSURE DOWNSTREAM THE TURBINE	P2 =	0.558	bar
5- TOTAL DISCHAGE THROUGH THE PENSTOCK	QT =	9.313	bar
6- DISCHARGE THROUGH THE UNIT UNDER TEST	Q =	9.313	bar
7- WINTER KENNEDY TAPS COEFFICIENT T	KWK =	0.479	
8- TOTAL CINETIC TERM	TC =	1.035	bar
9- NET HEAD	H =	450.072	m
10- HYDRAULIC POWER	Ph =	41025.078	kw
11- MEASURED ACTIVE POWER (*)	Pa =	36890.574	kw

(*) taking into account 34.87 kW of turbine and governor losses

12- POWER FACTOR	pf =	0.852	
13- GENERATOR LOSSES	Pb =	887.538	kw
14- MECHANICAL POWER AT TURBINE SHAFT	P =	37778.113	kw
16- HYDRAULIC TURBINE EFFICIENCY (**)	Eta'=	92.616	%

(**) taking into account the obstruction effect of current meters

17- TURBINE EFFICIENCY (***)	Eta =	92.035	%

(***) caculated as stated by the contract

18- REFERENCE NET HEAD	H'=	449.000	m
19- POWER AT REFERENCE HEAD	Pu'=	37643.180	kw
20- DISCHARGE AT REFERENCE HEAD	Q'=	9.301	m3/s

POWER PLANT : KALAN
UNIT NUMBER 1 SERIAL 1
EFFICIENCY TESTS BY CURRENT-METERS

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Pagina

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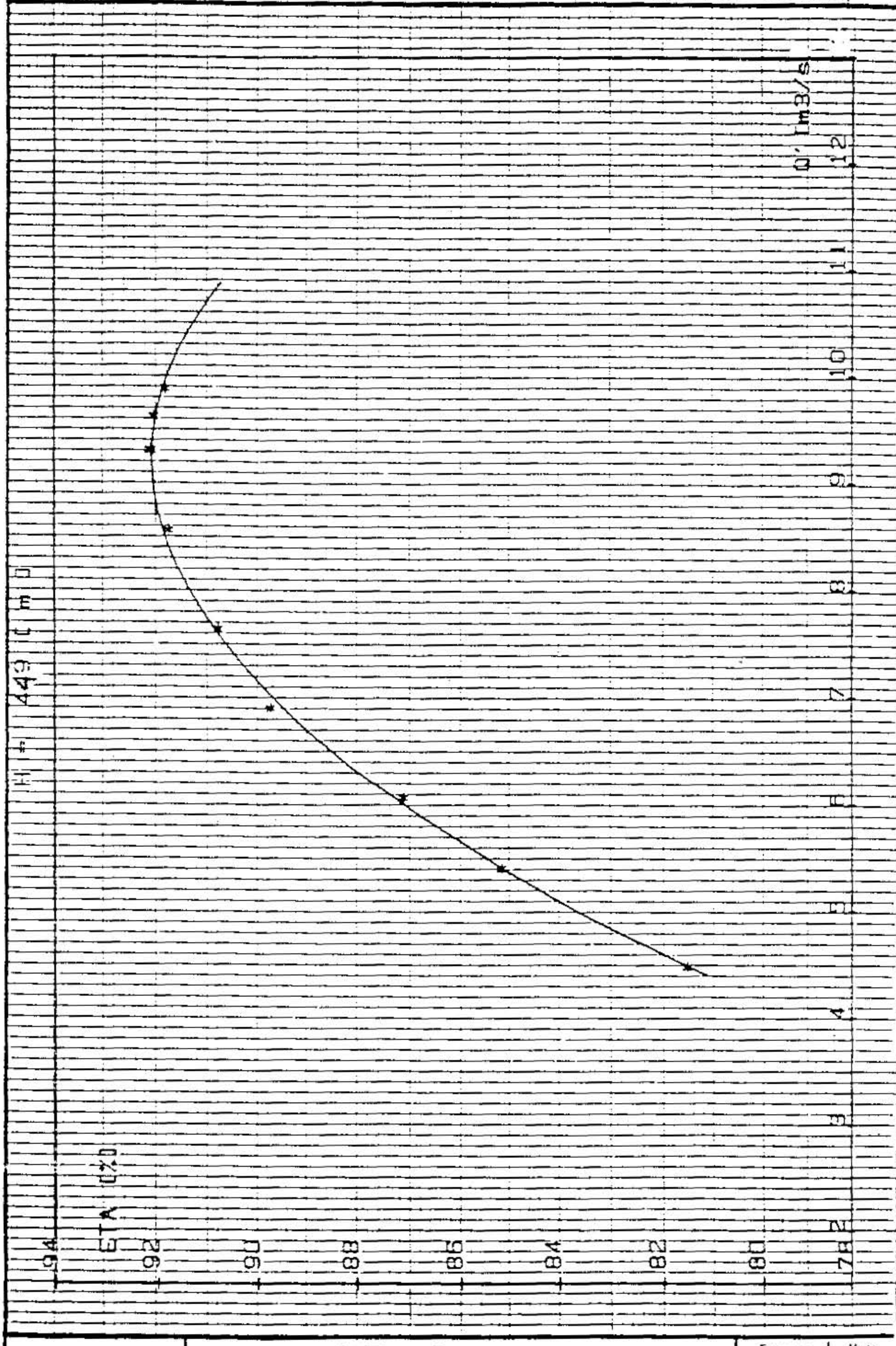

Fig. 4-4 : One unit in operation - Efficiency versus discharge

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POWER PLANT : KALAN

UNIT NUMBER 1 SERIAL 1

EFFICIENCY TESTS BY CURRENT-METERS

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Data: 18-07-1992

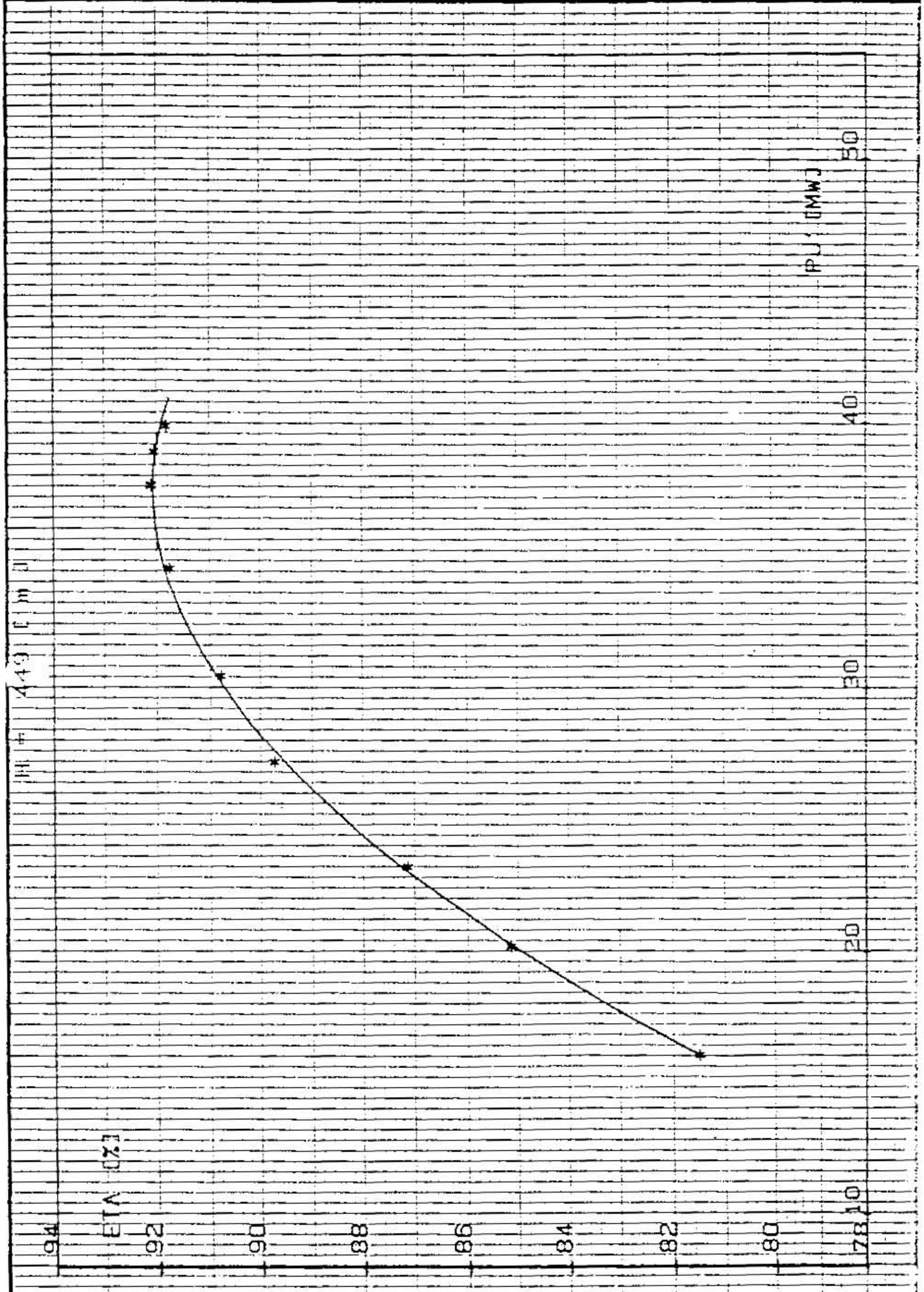

Fig. 4-5 : One unit in operation - Efficiency versus power

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POWER PLANT : KALAN
UNIT NUMBER 1 SERIAL 1
EFFICIENCY TESTS BY CURRENT-METERS

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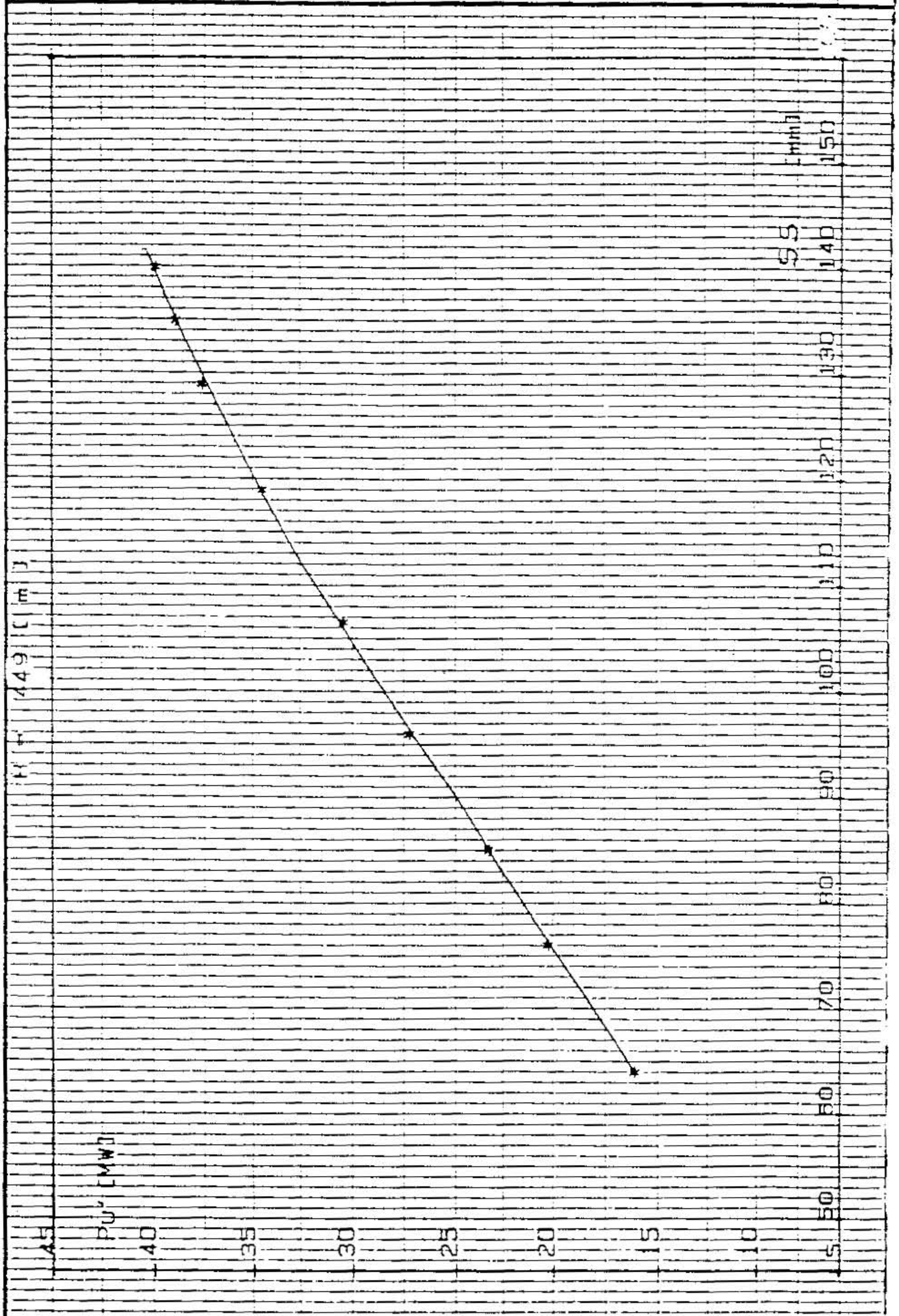

Fig. 4-6 : One unit in operation - Power versus servomotor stroke

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POWER PLANT : KALAN
UNIT NUMBER 1 SERIAL 1
EFFICIENCY TESTS BY CURRENT-METERS

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Data: 18-07-1992

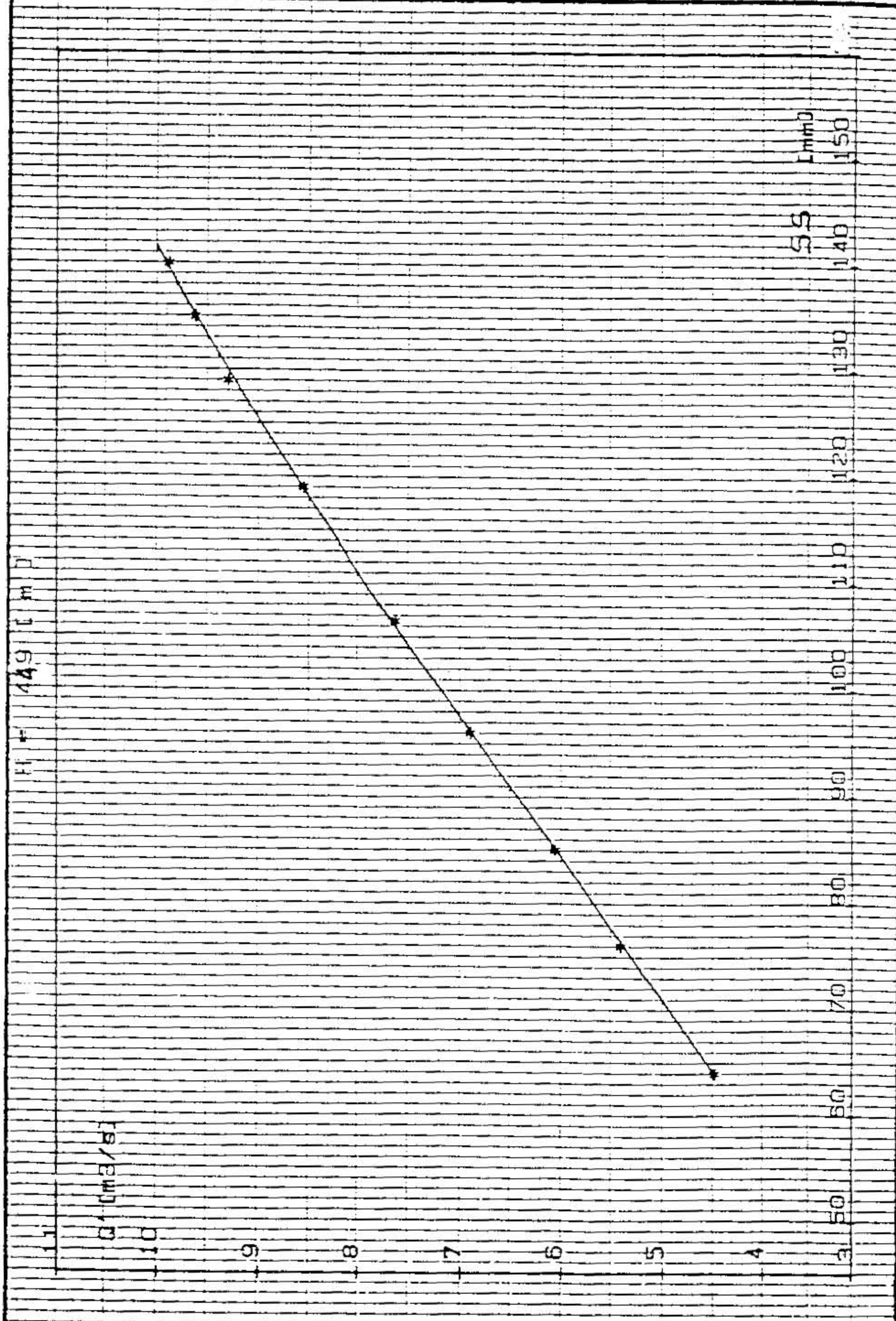

Fig. 4-7 : One unit in operation - Discharge versus servomotor stroke

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Fig. 4-8 : Two units in operation - Tests results

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POWER PLANT : KALAN - UNIT N°.1 - EFFICIENCY TESTS

INPUT DATA

Test number : 2

WATER DISCHARGE	[m3/s]	18.4850
WEIGHT ON PISTON MAN.	[kg]	36.2100
DOWNSTREAM FREE LEVEL	[m]	1.9900
WINTER KENNEDY PRESS.	[mm]	324.0000
POWER METER Phase R	[div]	87.5000
POWER METER Phase S	[div]	89.7000
POWER METER Phase T	[div]	83.5000
AMPERE METER Phase R	[div]	1.6500
AMPERE METER Phase S	[div]	1.6900
AMPERE METER Phase T	[div]	1.7000
VOLTS METER Phase R	[div]	64.2000
SERVOMOTOR STROKE	[mm]	138.0000
WATER TEMPERATURE	[°C]	8.0000
AIR TEMPERATURE	[°C]	26.5000
OTHER UNIT RUNNING	Y=1 N=0	2.
TEST STARTING TIME	[h.m]	11.0000

Fig. 4-9 : Two units in operation - Tests results

RIVA HYDROART S.p.A. 22-07-92

POWER PLANT : KALAN - UNIT N°.1 - EFFICIENCY TESTS

Test number 2

FINAL RESULTS

1- WATER DENSITY AT 26.5 [°C] =	ro1 =	996.717	kg/m3
2- WATER DENSITY AT 8 [°C] =	ro2 =	999.883	kg/m3
3- STATIC PRESSURE UPSTREAM THE TURBINE	P1 =	40.382	bar
4- STATIC PRESSURE DOWNSTREAM THE TURBINE	P2 =	0.656	bar
5- TOTAL DISCHAGE THROUGH THE PENSTOCK	QT =	18.519	bar
6- DISCHARGE THROUGH THE UNIT UNDER TEST	Q =	9.312	bar
7- DISCHARGE THROUGH UNIT No. 2	QWK =	9.207	bar
8- TOTAL CINETIC TERM	TC =	1.038	bar
9- NET HEAD	H =	416.427	m
10- HYDRAULIC POWER	Ph =	37958.738	kw
11- MEASURED ACTIVE POWER (*)	Pa =	34210.707	kw
(*) taking into account 34.87 kW of turbine and governor losses			
12- POWER FACTOR	pf =	0.842	
13- GENERATOR LOSSES	Pb =	865.203	kw
14- MECHANICAL POWER AT TURBINE SHAFT	P =	35075.910	kw
16- HYDRAULIC TURBINE EFFICIENCY (**)	Eta' =	92.936	%
(**) taking into account the obstruction effect of current meters			
17- TURBINE EFFICIENCY (***)	Eta =	92.405	%
(***) caculated as stated by the contract			
18- REFERENCE NET HEAD	H' =	404.300	m
19- POWER AT REFERENCE HEAD	Pu' =	33554.895	kw
20- DISCHARGE AT REFERENCE HEAD	Q' =	9.175	m3/s

POWER PLANT : KALAN
UNIT NUMBER 1 SERIAL 2
EFFICIENCY TESTS BY CURRENT-METERS

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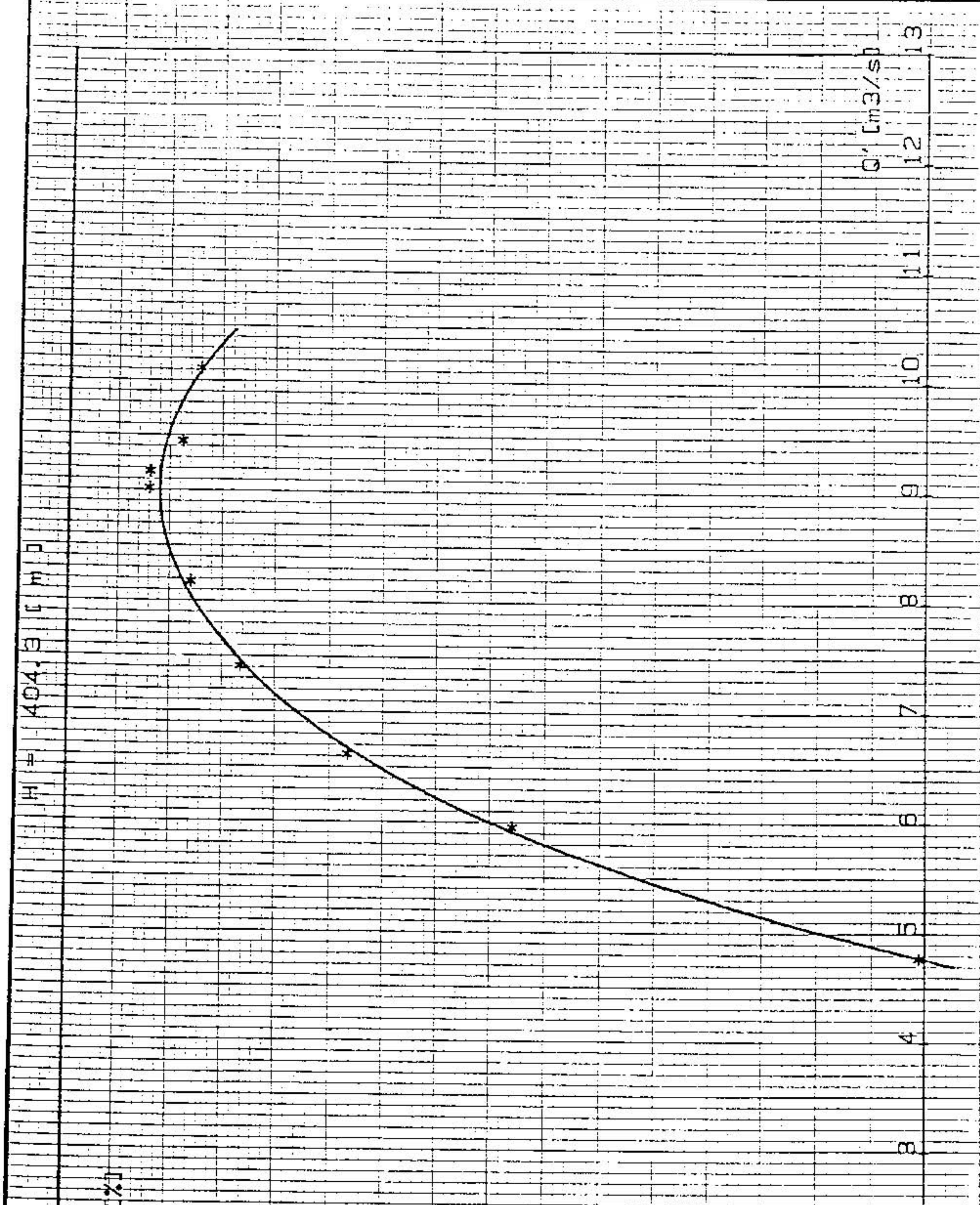

Fig. 4-10: Two units in operation - Efficiency versus discharge

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POWER PLANT : KALAN
UNIT NUMBER 1 SERIAL 2
EFFICIENCY TESTS BY CURRENT-METERS

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Data: 21-07-1992

Pagina

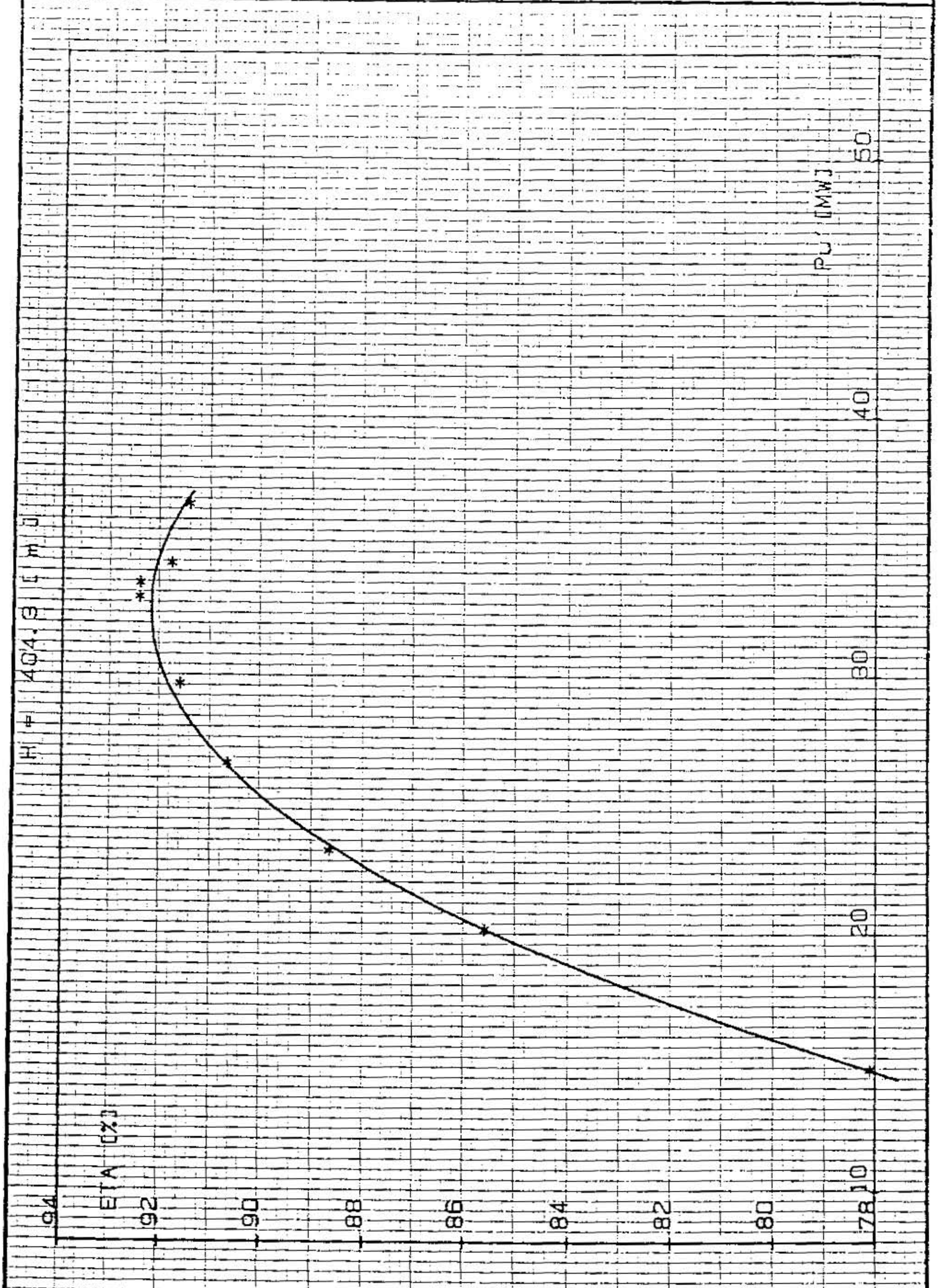

Fig. 4-11: Two units in operation - Efficiency versus Power

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UNIT NUMBER 1 SERIAL 2
EFFICIENCY TESTS BY CURRENT-METERS

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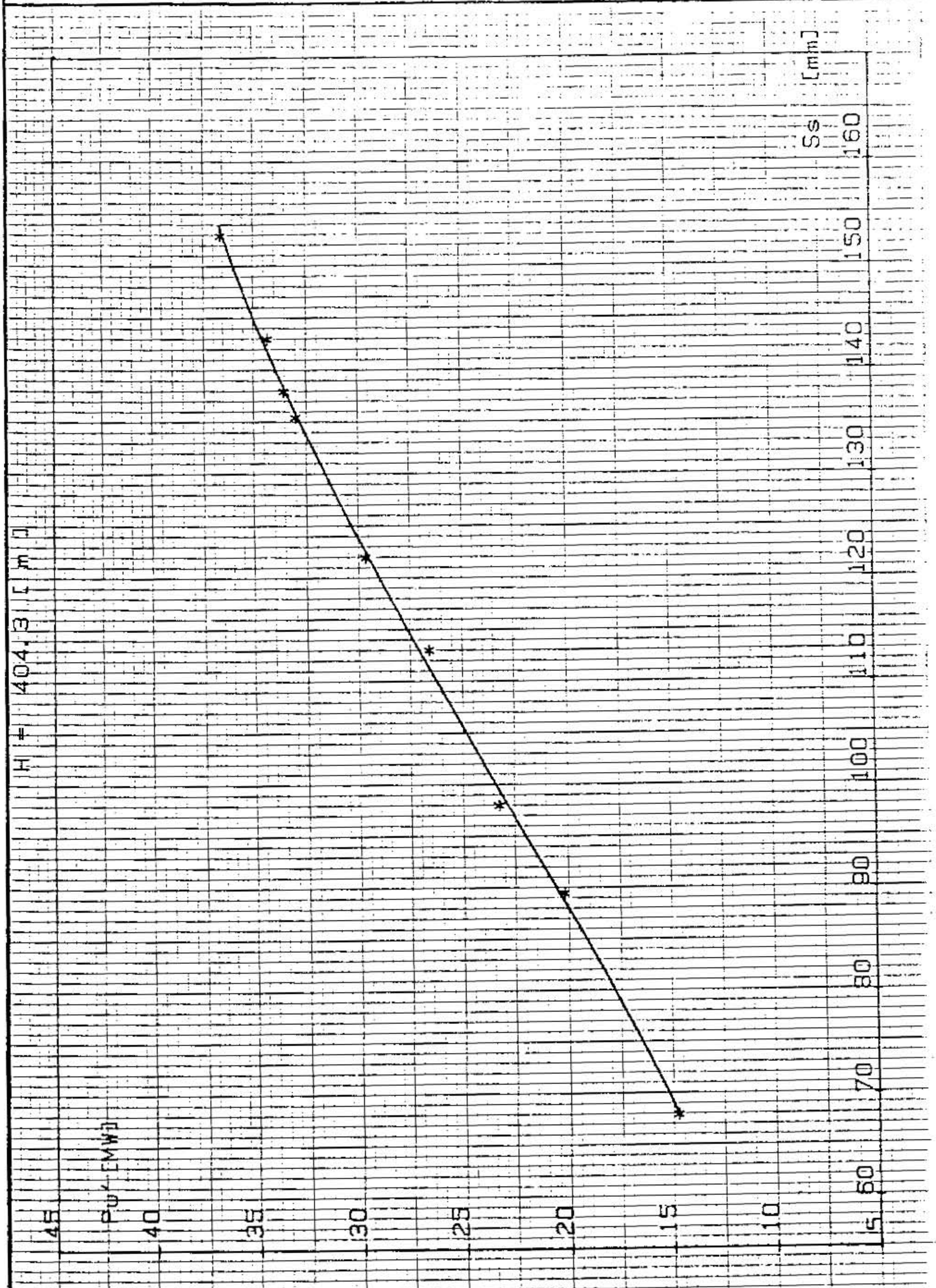

Fig. 4-12: Two units in operation - Power versus servomotor stroke

POWER PLANT : KALAN
UNIT NUMBER 1 SERIAL 2
EFFICIENCY TESTS BY CURRENT-METERS

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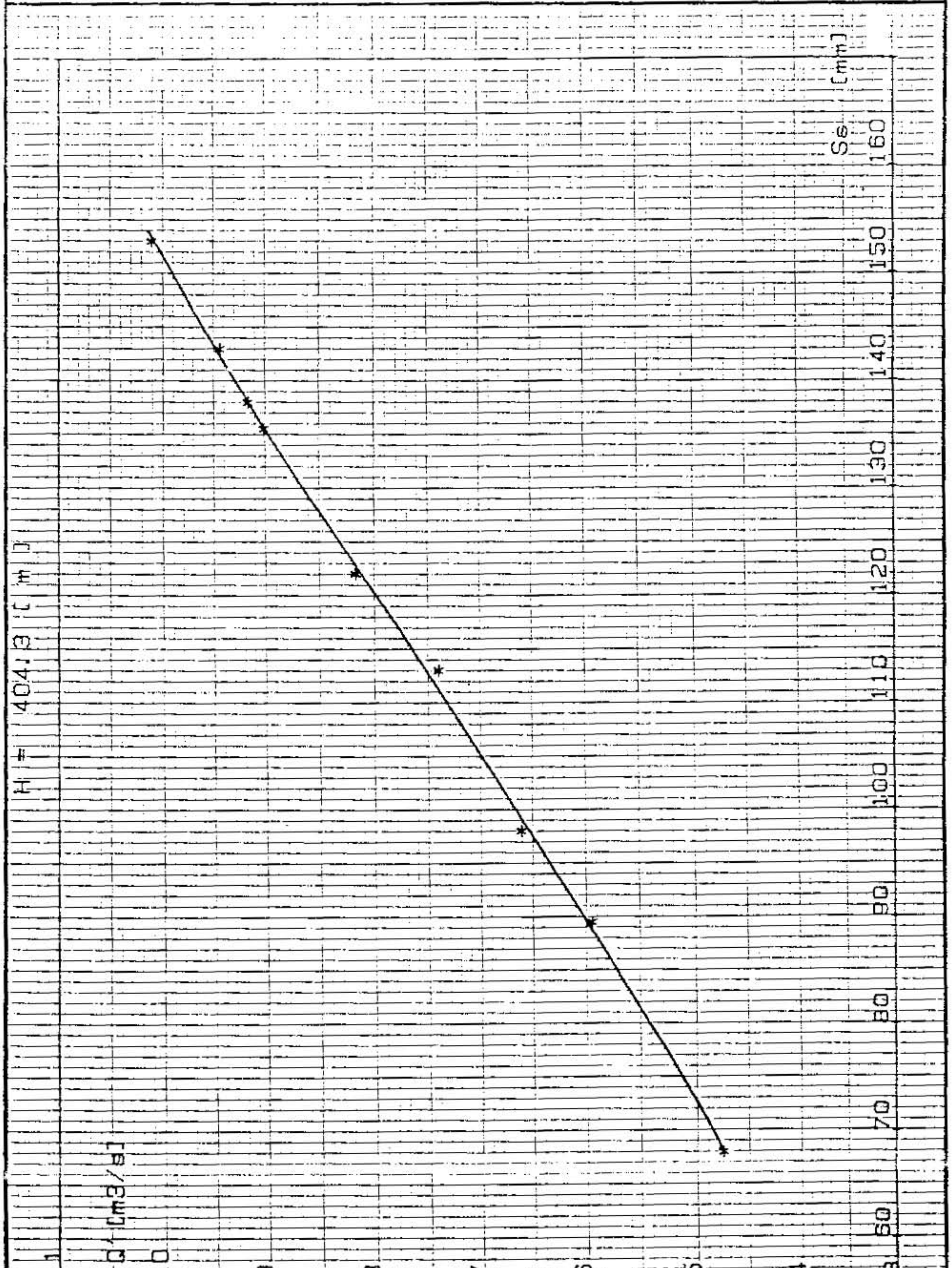

Fig. 4-13: Two units in operation - Discharge versus servomotor stroke

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No. of Test	Counting time (sec)	Servomotor stroke (mm)	Flow (m^3/s)	Net head (m)	Turbine input (KW)	Gen. Output (KW)	Gen. Losses (KW)	Turbine Efficiency (%)	Turbine Efficiency stated by (%)contract
1	300	106.5	7.629	454.393	34142.83	30229.56	824.006	91.483	90.952
2	300	119	8.534	452.640	38040.91	34068.98	860.410	92.352	91.821
3	300	135	9.565	450.070	42396.95	38088.78	903.244	92.500	91.969
4	300	96	6.913	456.293	31067.04	27163.18	798.397	90.535	90.004
5	300	85	6.084	457.230	27398.37	23207.80	764.516	88.026	87.495
6	300	76	5.425	457.897	24465.21	20205.84	744.330	86.163	85.632
7	300	64	4.515	459.876	20449.38	16159.10	729.702	83.119	82.588
8	300	129	9.255	450.072	41025.09	36890.57	887.538	92.616	92.085
9	300	140	9.816	449.136	43420.93	38926.24	915.609	92.288	91.757

Fig. 5-1 : Tests results for one unit in operation

No. of Test	Counting time (sec)	Servomotor stroke (mm)	Flow (m^3/s)	Flow through other unit (m^3/s)	Net head (m)	Turbine input (KW)	Gen.Output (KW)	Gen.Losses (KW)	Turbine Efficiency (%)	Turbine Efficiency stated by (%)contract
1	300	122	8.290	9.136	420.455	34335.87	30628.97	827.51	92.145	91.614
2	300	138	9.254	9.150	416.427	37958.74	34210.71	865.20	92.936	92.405
3	300	143	9.509	9.222	414.451	38823.27	34764.72	867.91	92.313	91.782
4	300	153	10.171	8.766	413.811	41459.67	37019.41	890.28	91.969	91.438
5	300	113	7.516	9.807	421.244	31187.89	27476.41	804.35	91.210	90.679
6	300	98	6.753	9.350	426.393	28362.81	24380.24	773.32	89.216	88.685
7	300	89.5	6.103	9.294	429.830	25840.52	21365.39	752.45	86.125	85.594
8	300	68	4.921	9.063	435.546	21113.99	15769.85	723.46	78.647	78.116
9	300	135.5	9.140	8.428	420.174	37828.86	34107.64	856.82	92.959	92.428

Fig. 5-2 : Tests results for two units in operation