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Computer-aided tester for non-destructive determination of material properties

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Summary. This article presents a newly developed equipment system for computer-aided, magneto-inductive testing of metals for material properties. The advantages of ultra-modern computer technology over conventional test methods are illustrated, in particular the greatly simplified equipment adjustment and the extended possibilities of test data evaluation. The characterisitics of the new system of equipment are demonstrated by way of practical testing examples.

Introduction

Non-destructive testers for quality control of semifinished and finished products are now essential in any modern industrial plant. These testers can basically be divided into two groups: devices for flaw testing and devices for determining material properties.

In this article, a tester belonging to the latter group is described, based on the magneto-inductive testing method. This method enables high testing speeds, as are necessary for example when inspecting massproduced parts in the automobile industry.

To date, this advantage over conventional testing methods did, however, involve the disadvantage of complex tester adjustment because it is a comparative testing method and not an absolute one. Adjustment mainly involves determination of the optimum tester setting, i. e. the setting which provides the best correlation between measured value and sought test piece parameter.

The tester described here, the Magnatest S 3.625, is characterized by the fact that the tester adjustment process has been considerably simplified by means of advanced computer technology and that extended evaluation of the physical characteristics of the test pieces is performed to determine the technological parameters.

The tester's many different qualities will be demonstrated later by means of practical testing examples. First, however, there follows a short description of the tester.

Tester design and operating data

Figure 1 shows the Magnatest S, consisting of the controller (top section) and the test channel (bottom section) and a test coil, as well as the keyboard for alphanumeric entries and a printer to produce hardcopies of the VDU displays.

In brief, the most important features of the tester are:

- frequency range from 2 to 130 kHz,
- single-coil operation (absolute method),
- large choice of coil field strengths (up to approximately 500 A/cm for coil with a diameter of 50 mm and with optional booster),
- high measuring resolution (16 bit),
- determination of the measuring signal's harmonic up to the 7th harmonic,
- menu-type software structure,
- rapid calibration by means of 24 parameter sets,
- test operation with 8 parameter sets simultaneously,
- manual and statistical formation of sorting limits,
- ideal for use in production lines thanks to storage of tester and test parameters and control for external sorting and/or marking equipment,
- dialogue possible with a higher-level computer and
- optional multi-coil and multi-channel operation.

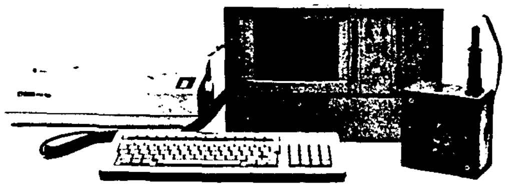

Figure 1. Magnatest S 3.625 (top: controller, bottom: test channel) with keyboard, test coil and printer

Extended evaluation of physical parameters

The task of a magneto-inductive tester is to determine the sought test piece property, such as
- alloy type,
- core or surface hardness,
- surface or case hardening depth

using the physical parameters of
- magnetic permeability and
- electrical conductivity.

If a ferromagnetic part is placed in the test coil with sinusoidal generation of the magnetic field, then the measured voltage contains both the frequency of the exiting field and the odd harmonics of this field, if measurement is performed without constant field superimposition, as a result of the non-linear behaviour of the materials' magnetic properties.

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In the Magnatest S, these harmonics are measured up to the 7th harmonic, whereby the real and imaginary components in respect of the excitation current are measured in addition to the magnitude. For simplicity's sake, however, only the magnitude is indicated on the VDU, **figure 2.**

If the dynamic range of the exciting field is sufficiently high, then the modulation range of the hysteresis curve which is affected particularly strongly by the sought material parameter in respect of its magnetic characteristic can be selected.

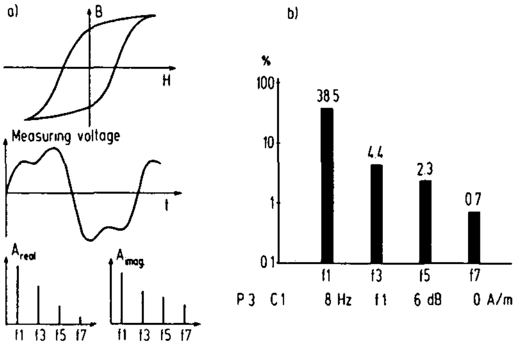

Figure 2. Magnatest S spectrum; a) origin of the harmonic, b) display of the harmonic magnitudes on the VDU of the Magnatest S

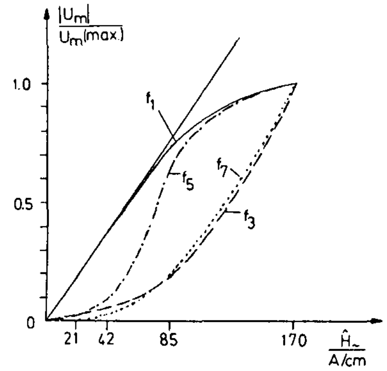

Figure 3. Principle dependence of the measuring signal's harmonics on the field strength of the test coil for a ferromagnetic test piece

This is extremely beneficial, since different mechanical or thermal treatment processes for ferromagnetic materials can influence different ranges of the magnetization curve[1][2][3].

Figure 3 clearly shows the dependence of the harmonic amplitudes on the excitation field strength. In addition, it can be seen that a sufficient field strength is necessary to obtain the information linked to the harmonics, for example, by means of the sought test piece parameter. Further details can be seen in [4] and [5] for example.

The harmonics have the advantage that they enable information to be obtained from the deeper material layers, in spite of their increased frequency compared with the carrier, since they are generated in the material itself. The results of a measurement test provide evidence of this, **figure 4.**

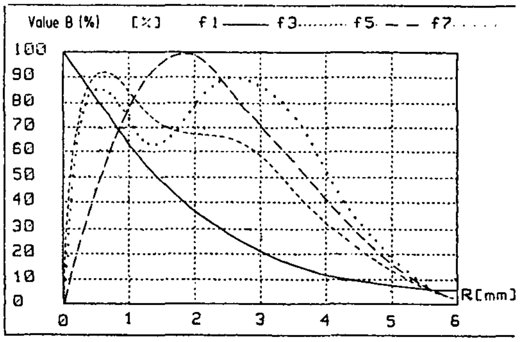

Figure 4. Depth-dependence of the amplitudes of the magnetic induction harmonics in a ferromagnetic cylinder with a diameter of 32 mm

A further advantage of the harmonics is that changes in test piece geometry, such as in length or diameter, affect the measured value less than is the case for the carrier.

As far as the influence of length is concerned, this can be explained, for example, by the fact that test piece sections further away from the coil center supply a lower proportion of the total signal than they would for the carrier, due to the field decay in a surrounding coil in the throughput direction and the square-law dependence of the harmonic signal, figure 3. The effective width of the coil is therefore reduced in the case of the harmonics.

Testing examples

Sorting according to alloy. This classical testing task will be demonstrated by sorting the alloys C 45, C 60 Pb and 9 SMn 28 into 3 groups. Sorting is possible for a maximum of 7 groups.

Tester setting. As required by the task in hand, measured value evaluation is performed by means of group anal-

Table 1a. Tester adjustment with various parameter sets

	Coil	Frequency	Harmonic	Field att.
P 1	C 1	8 Hz	f 3	0 dB
P 2	C 1	8 Hz	f 1	0 dB
P 3	C 1	8 Hz	f 1	6 dB
P 4	C 1	8 Hz	f 1	12 dB
P 5	C 1	8 Hz	f 1	18 dB
P 6	C 1	16 Hz	f 1	0 dB
P 7	C 1	16 Hz	f 3	0 dB
P 8	C 1	16 Hz	f 3	6 dB
P 9	C 1	16 Hz	f 3	12 dB
P 10	C 1	32 Hz	f 1	0 dB
P 11	C 1	32 Hz	f 3	0 dB
P 12	C 1	64 Hz	f 1	0 dB
P 13	C 1	64 Hz	f 3	0 dB

Table 1b. Structure of an individual parameter set

Parameter set	7
Frequency	16 Hz
Harmonic	3
Field att.	0 dB
Coil input	1
Coil indent.	
Coil current maximum	41 %
Sensitivity	15.0 dB
Const. current source	ON

Table 3. Printout of the test results for group analysis

Piece	Number	Parameter set		Class	Output	Sort.
		1	2			
T	47	R	R	C	1	1
T	46	R	R	C	1	1
T	45	R	R	C	1	1
T	44	R	B	B	1	1
T	43	R	B	B	1	1
T	42	R	B	B	1	1
T	41	R	B	B	1	1
T	40	R	B	B	1	1
T	39	A	R	A	1	1
T	38	A	A	A	1	1
T	37	A	R	A	1	1
T	36	A	R	A	1	1
–	31	C	C	C	1	1
–	30	C	C	C	1	1
–	29	C	C	C	1	1
–	28	C	C	C	1	1
–	27	C	C	C	1	1
–	26	C	C	C	1	1
–	25	C	C	C	1	1
–	24	C	C	C	1	1
–	23	C	C	C	1	1
–	22	C	C	C	1	1
–	21	C	C	C	1	1
–	20	C	C	C	1	1
–	19	B	B	B	1	1
–	18	B	B	B	1	1
–	17	B	B	B	1	1
–	16	B	B	B	1	1

Table 4. Printout of the correlation factors for assessment of the parameter sets in the "regression" evaluation mode

	Coil	Frequency	Harmonic	Field att.	Correlation
P 1	C1	4 Hz	f 1	0 dB	97.4 %
P 2	C1	4 Hz	f 3	0 dB	99.0 %
P 3	C1	4 Hz	f 5	0 dB	99.4 %
P 4	C1	8 Hz	f 1	0 dB	96.7 %
P 5	C1	8 Hz	f 3	0 dB	98.3 %
P 6	C1	8 Hz	f 5	0 dB	99.5 %
P 7	C1	8 Hz	f 5	6 dB	87.9 %
P 8	C1	8 Hz	f 5	12 dB	95.9 %
P 9	C1	16 Hz	f 1	0 dB	97.2 %
P 10	C1	16 Hz	f 3	0 dB	98.9 %
P 11	C1	16 Hz	f 5	0 dB	96.5 %

sible, even if there is no differentiation in one of the parameter sets.

Figure 8 shows a model example of this for the material types used here. Clear differentiation of all three materials is not possible either in the 1st or 2nd parameter sets selected here (not identical with the previous ones). Nevertheless, correct group allocation is possible by means of logical combination of the measured values, as is shown in table 3.

In addition to the tabular display of the test results, an overview is also offered on another menu page in the form of a bar chart, **figure 9.** This is extremely useful in obtaining a rapid overview of the batch quality during continuous production testing.

Strength measurement. In the case of such a testing task (e. g. also measurement of case or surface hardness thickness), there is continuous variation of the sought test piece parameter. For this reason, the "regression" evaluation mode must be used.

In the example here, the strength of bars with a diameter of 18 mm and made of 42 CRMo 4 is measured in the range between 750 and 1 250 N/mm², whereby the given conventionally determined strength values are accurate only to within ± 50 N/mm. Compared with the group analysis, only 3 menu pages basically change. The procedure described above for carrying out a testing task remains otherwise applicable.

Table 5. Continuous output of the estimated values for the sought technological parameter

Piece	Number	Meas.val	Deviation	Class	Output	Sort.
T	9	811.8	68.7	A	1	1
T	8	960.5	64.2	A	1	1
T	7	1 059.8	62.2	A	1	1
T	6	788.8	67.2	R	1	1
T	5	918.6	66.4	A	1	1
T	4	1 081.9	62.7	A	1	1
T	3	1 008.3	63.7	A	1	1
T	2	790.8	67.2	R	1	1
T	1	1 172.2	68.7	B	1	1
C	12	800.0	0.0	R	1	1
C	11	1 050.0	0.0	R	1	1
C	10	900.0	0.0	R	1	1
C	9	1 150.0	0.0	R	1	1
C	8	800.0	0.0	R	1	1
C	7	800.0	0.0	R	1	1
C	6	1 100.0	0.0	R	1	1
C	5	1 200.0	0.0	R	1	1
C	4	950.0	0.0	R	1	1
C	3	1 055.0	0.0	R	1	1
C	2	1 000.0	0.0	R	1	1

In this evaluation mode, the correlation factor between the measured value and the sought technological parameter, calculated in accordance with a 2-dimensional linear regression, is given to enable assessment of the suitability of the parameter sets selected for calibration, **table 4.**

In the example, parameter set 6 produces the best correlation factor with a value of 99.5 %. The measured values obtained on the complex signal plane with this tester setting are shown in **figure 10.** Lines with the same parameter values have been drawn in to enable rapid estimation of the value of the sought parameter.

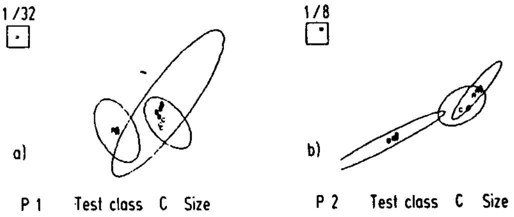

Figure 8. Locigal combination of the measured values of two parameter sets

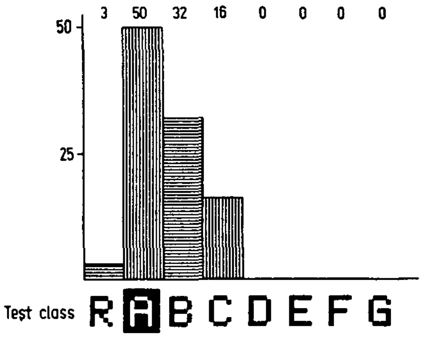

Figure 9. Display of the results of one test batch in bar chart form

ysis. This evaluation method is used in case the sought parameter, here the alloy composition, changes discretely.

As shown by the corresponding menu page in **table 1a**, a total of 13 parameter sets (a maximum of 24 are possible) are selected in a range which is physically appropriate for the testing task in order to enable test adjustment. An individual parameter set **table 1b** basically comprises the probe identifier (for coil multiplex operation), the frequency of the excitation field, the harmonics to be evaluated, the field strength and the measuring signal gain.

Calibration. Tester calibration for the testing task can be carried out after tester adjustment, which was performed after selection of a suitable test coil (good space factor). To do this, the calibration specimens, where the group membership is already known, are placed in the test coil. After measurement triggering, all the parameter sets, of which there are 13 in this example, are set successively by the integrated computer and the measured values are stored.

After the results have been recorded, the sorting limits for the individual groups can be determined. **Figure 5** shows the measurement results with the statistically determined limits in parameter set 2.

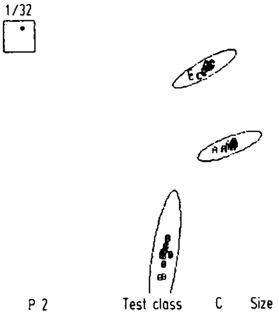

Figure 5. Display of the measured values and the sorting limits; pieces are identified by the respective group letters

Normal distribution of nominal value deviations (percentages of the individual alloy components) of the sought parameter and/or noise variables (fluctuations in geometry, temperature, etc. of the test piece) is assumed when determining the sorting limits. The limits are obtained in the form of ellipses since the measured value has two dimensions. Arbitrary selection of the statistical certainty of testing is also possible. Here, the number of calibration specimens is also taken into account, so that the tester can rapidly see whether sufficient calibration specimens are available on the basis of the size of the sorting ranges obtained.

Table 2. Overview of the calibration results, including selectivity values

	Coil	Fre-quency	Har-monic	Field att.	Separ. A	Separ.
P 1	C 1	8 Hz	f 3	0 dB	100 %	72 %
P 2	C 1	8 Hz	f 1	0 dB	100 %	100 %
P 3	C 1	8 Hz	f 1	6 dB	97 %	97 %
P 4	C 1	8 Hz	f 1	12 dB	36 %	36 %
P 5	C 1	8 Hz	f 1	18 dB	72 %	72 %
P 6	C 1	16 Hz	f 1	0 dB	100 %	100 %
P 7	C 1	16 Hz	f 3	0 dB	100 %	100 %
P 8	C 1	16 Hz	f 3	6 dB	86 %	86 %
P 9	C 1	16 Hz	f 3	12 dB	81 %	81 %
P 10	C 1	32 Hz	f 1	0 dB	97 %	97 %
P 11	C 1	32 Hz	f 3	0 dB	74 %	74 %
P 12	C 1	64 Hz	f 1	0 dB	81 %	72 %
P 13	C 1	64 Hz	f 3	0 dB	85 %	85 %

Using statistical methods, the computer now calculates 2 selectivity values in order to enable the operator to rapidly assess the suitability of the inidividual parameter sets. The first value describes the differentiation of all groups in respect of the most interesting group A, whereas the 2nd value states the worst differentiation between 2 arbitrary groups.

The values calculated in this way are displayed as shown in **table 2.**

The suitable parameter sets can now be selected using this list. If we assume in this example that all groups have to be differentiated as well as possible, then both selectivity values must be taken into account. In this case, the parameter sets P 2, P 6 and P 7 supply the best results.

We have already seen the results of P 2 in figure 5. This good result at 8 Hz was obtained due to the high field strength. A comparison with the results obtained at half this field strength, **figure 6a,** shows that good differentiation is possible only after driving into the extremely non-linear area of the hysteresis curve.

Although sorting is also possible here using manually-created rectangular sorting limits, the probability of incorrect part identification is higher, **figure 6b.**

Astonishingly, differentiation in the 3rd harmonic is better than in the carrier at 16 Hz, whereas exactly the reverse is true at 8 Hz; this can be seen if **figures 7a and 7b** are compared.

It would now be advisable to select parameter P 7 for testing since the test speed possible in physical and hardware terms is higher at 16 Hz.

Testing. When testing parts during production where the value of the sought technological parameter is unknown, it is possible to test with up to 8 parameter sets. The results are continuously output on a menu page as shown in **table 3.**

The measured values are logically combined if there is more than one parameter set. This often makes sorting pos-

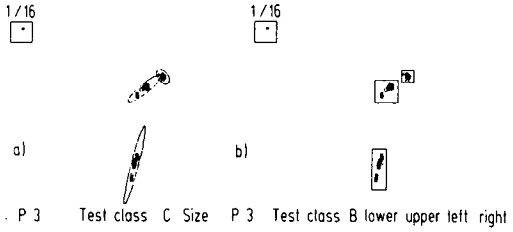

Figure 6. a) Measured values with excitation field strength reduced by half compared with figure 5; b) formation of manual, rectangular sorting limits

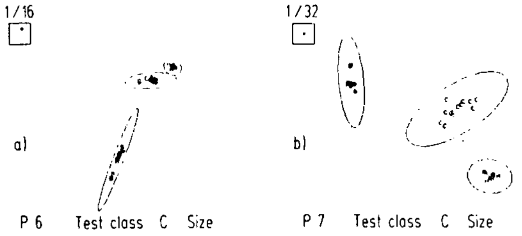

Figure 7. a) Measured values at 16 Hz, carrier; b) measured values at 16 Hz, 3rd Harmonic, same excitation field

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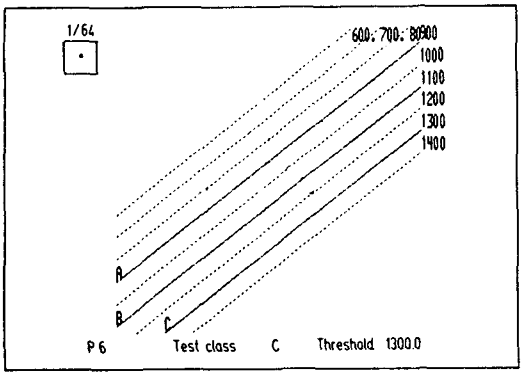

Figure 10. Depiction of the measured values on the complex signal plane with lines of the same value for the sought parameter

If it is sufficient to know the membership of a certain value range and not the individual value in each case when pieces are sorted, then it is also possible to set value thresholds, A, B, C etc. to enable sorting into groups.

The menu page shown in **table 5** is particularly suitable for displaying results on production lines. Here, the test pieces are continuously numbered and the respective estimated value for the sought parameter is output together with the estimate error factor obtained for the chosen statistical certainty.

There is naturally also a rather large estimate error factor in this example, since the number of calibration specimens was relatively small. This estimate error factor decreases if the number of specimens is correspondingly increased. However, this value has nothing to do with the hardware-related accuracy of measured value determination. In this table, the calibration specimens are identified by C, their class membership by R (remaining class: it is not yet possible to define any other class membership during calibration) and the test pieces by T.

The data of up to the last 100 tested specimens can be stored in a RAM. This menu page can be printed out continuously for logging purposes.

A further advantage of the computer technology used here is seen in the possibility of initially allocating a fictitious value to the sought parameter of the calibration specimen. After destructive determination of the actual technological value (e. g. the case-hardened depth), this can subsequently be entered for determination of the statistical correlation.

Semi-finished product testing

The examples given above referred to the testing of separate items. An optinal software package enables testing of long parts, such as pipes or bars.

The sought technological parameter here is usually the material type or the heat treatment state. In the case of these test pieces, values are measured for different sections because the physical properties may fluctuate over the length of the specimen due to mechanical pretreatment. The statistical mean value of these measured values is then used for evaluation.

Since there are mostly no calibration specimens available for such testing tasks, a "self-learning" evaluation system is used. The first test pieces are assumed "good", and the sorting limit is automatically created statistically using these measured values. If necessary, this sorting range is automatically corrected after a greater number of measured values have been obtained. This procedure is possible since experience has shown that there is only an extremely low percentage of defective test pieces. These can therefore be easily recognized by means of statistical evaluation.

Use in the production line

As mentioned at the beginning, the Magnatest S was designed for use in production lines. The most important features for this application will now be briefly described.

Storage of tester settings. This makes it possible for tester settings obtained in the laboratory for a certain testing problem to be stored in the controller archive or in an external mass store together with the corresponding evaluation parameters. The operator on site can call up one of these evaluation programs at any time by entering the test piece designation.

Recalibration. If differences should occur on site between the calibration specimens and the test pieces in uninteresting parameters which nevertheless influence the measured value (e. g. temperature), then the position of all sorting ranges can be corrected by means of simple recalibration with one of the original calibration specimens.

Key switch. The different setting procedures for the tester are divided hierarchically. Only the person authorized to perform a certain task can make the corresponding change in the setting. In this way, for example, the local operator cannot manipulate the setting parameters when the key is set to a practical position for this application.

I/O module. This convenient interface enables exchange of information with external components, such as marking or sorting devices, **figure 11.** The functions of the module

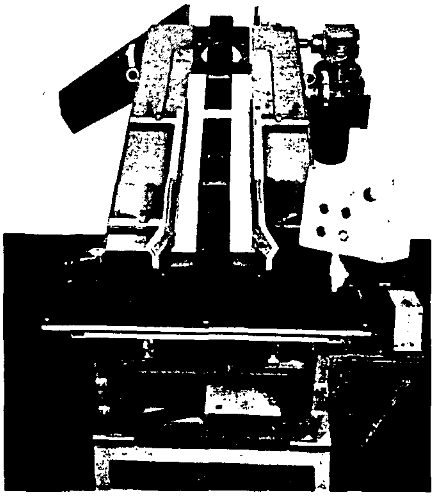

Figure 11. Sorting system for operation with the Magnatest S

Table 6. Determination of the I/O module functions for driving external mechanisms

Magnatest S	Testing line		
Date/time	15. 10. 86. 17:03		
	Number	Assignment	
		R A B C D E F X	
P-outputs	1	1 2 3 4 5 6 7 8	
S-outputs	1	1 2 3 4 5 6 7 8	
R-outputs	1	1 2 3 4 5 6 7 8	
System parameters			
Number 1	Designation:	I/O-bus operating mode	
Value: 0			
I/O-bus check			
Signal address	0	Level	high
Self-test			
Test stage	0	Test result	

inputs and outputs are defined on one of the menu pages, **table 6.**

Host computer connection. The results obtained on the production line may be passed on to a higher-level computer. Thus, in the case of a hardening plant, for example, the central computer can use the data provided by the Magnatest S to control the furnace temperature for heat treatment.

Logging. All tester parameters and measured values may be logged using an optional printer.

Conclusion

The Magnatest S enables everyday non-destructive testing tasks to be carried out better, more rapidly and more economically. Better because a solution to a testing problem can in some cases only be found using the extended physical parameters, which in turn then provide a more reliable result in the majority of cases. More rapid due to the computer-aided setting procedure and measured value determination and to the possible data exchange with external equipment via the RS interface.

The pressure on the person responsible for solving the testing task is relieved, enabling him to concentrate on the important work, while the qualifications required of the local operator are at the same time reduced.

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