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On the MRT demonstration by using MIL-HDBK-470A, Appendix B.4.2, Test Method 1, Test A

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ABSTRACT: In the framework of the SBB's SA-NBS project including integrated trackside and integrated trainborne sub-systems (based on the application of ALSTOM's ERTMS/ETCS ATC solutions), and the Package CH vehicle project (based on the application of the SIEMENS' ERTMS/ETCS ATC solution), the Mean Repair Time (MRT) demonstration for the main sub-systems has been requested, planed, organised and carried out as a part of the Maintainability Demonstrations (MDs).

In the invitation for tenders, the Customer (SBB/BLS) has requested from the Main Suppliers (ALSTOM & SIEMENS) to prepare in the final design phase, a detailed PBS into items up to the level of LRUs, with specification of predicted MTBF and MRT values for each LRU, as well as the quantity of each LRU in the overall system (e.g. train fleet).

The MRT demonstration has been carried out by the simulation of failures, and the application of the MIL-HDBK-470A, Appendix B.4.2, Test Method 1, Test A.

The main aim of the paper is to present precisely the applied procedure steps for the determination of the needed test parameters, based on the mentioned Customer's requirements and the application of the mentioned MIL-HDBK-470A method.

1 INTRODUCTION

Within SBB's ambitious SA-NBS project including integrated trackside and trainborne sub-systems, a total of 468 vehicles (total of 512 sub-systems) have been retrofitted with ALSTOM's ERTMS/ETCS ATC solution, and within the Package CH project, a total of 51 vehicles (total of 70 sub-systems) have been retrofitted with the SIEMENS ERTMS/ETCS ATC solution.

In the invitation for tenders for both mentioned projects, the planning and carrying out of the MDs for the main sub-system has been requested by the Customer (SBB 2005). Hence, in the corresponding RAMPPs, prepared by the Main Suppliers (ALSTOM 2007a & SIEMENS 2006), the requested MDs have been seriously planed, and later efficiently organized and successfully carried out as a part of system acceptance tests (ALSTOM 2007b, e, f & SIEMENS 2007b, 2008).

The MDs have been related to preventive and corrective maintainability aspects. The Main Supplier has been responsible for the planning, organisation and carrying out of the MDs. One of the Customer's mandatory RAM requirements was related to the preparation of detailed maintenance plans including detailed lists for preventive and corrective maintenance activities, based on the detailed PBS into items up to the level of LRUs, with specification of predicted MTBF and MRT values for all LRUs. Based on these requirements, and on the application of failure simulation for the MRT demonstration one can precise the procedure for determination of the needed test parameters by the application of the MIL-HDBK-470A 1997, Appendix B.4.2, Test Method 1, Test A. Hence the present paper is focused on the applied procedures steps, which have been applied standardised by the two mentioned projects and some new Customer's projects.

1.1 *Abbreviations*

General abbreviations

ATC	Automatic Train Control
BLS AG	BLS Lötschbergbahn AG (Railway company)
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
LCC	Life Cycle Costs
LRU	Line Replaceable Unit

MAPMT Mean Active Preventive Maintenance Time
MD Maintainability Demonstration
MRT Mean Repair Time
MTBF Mean operating Time Between Failures
MTBPM Mean Time Between Preventive Maintenance
NBS Neubaustrecke (New Swiss High Speed Line)
PBS Product Breakdown Structure
RAM Reliability, Availability and Maintainability
RAMP RAM assurance Programme
RAMPP RAM assurance Programme Plan
SA-NBS Signalling and Automation Systems on New Swiss High Speed Line (Mattstetten-Rothrist)
SBB AG Schweizerische Bundesbahnen AG (Swiss Federal Railway company)
SRU Shop Replaceable Unit (Unit which can be removed from the LRU in the shop, during corrective maintenance)

MRT demonstration relevant abbreviations/ list of symbols

λ the failure rate
RT Repair Time, defined as RT = (FLT + FCT + COT)
FLT Fault Localisation (diagnostic) Time
FCT Fault Correction Time including verification (including removing of faulty item, replacement with operating/ healthy one (including time to download the appropriate software, and adjustment times
COT Check-out Time (including verification)
λ_{pi} the predicted failure rate of the i[th] LRU ($i = 1, 2, \ldots, n$)
MRT_{pi} the predicted MRT of the the i[th] LRU ($i = 1, 2, \ldots, n$)
n_i the total quantity of the i[th] LRU in the considered system (sub-system/ equipment)
λ_{Sp} the predicted failure rate of the entire system (sub-system/equipment)
MRT_{Sp} predicted MRT of the entire system (sub-system/equipment)
f_i $n_i\lambda_{pi}/\lambda_{Sp}$ — estimated relative frequency of corrective maintenance tasks occurrence [weighing/contribution of the failure rate of n_i LRU_i to λ_{Sp}] ($i = 1, 2, \ldots, n$)
μ_1 the requested MRT value
μ_0 the MRT value as design goal ($\mu_1 > \mu_0$)
α the producer's risk; the probability that the system (sub-system/equipment) will be rejected when it has a true value equal to the desired value (μ_0)
β the consumer's risk; the probability that the system (sub-system/equipment) will be accepted when it has a true value equal to the maximum tolerable value (μ_1)
Z_α (Z_β) the standardised normal deviate exceeded with probability α (β)
H_0 (H_1) the hypothesis
σ^2 the prior estimate of the variance of the logarithm of maintenance time
X the random variable which denotes the maintenance characteristics of interest (e.g., corrective maintenance time, preventive maintenance time, etc.)
X_i the i[th] observation or value of the random variable X
d^2 the sample variance of X
m the sample size
σ_p^2 the predicted variance of the logarithm of MRT calculated using λ_{pi}, MRT_{pi} and n_i of the LRU_i ($i = 1, 2, \ldots, n$)
d_{Smeas}^2 the sample variance based on the measured RT values

2 DETAILED MAINTENANCE PLANS FOR TRACKSIDE AND TRAINBORNE SUB-SYSTEMS

2.1 *Maintenance concept and strategy*

In order to achieve requested RAM targets with acceptable maintenance costs, it has been requested from all Main Suppliers within the projects to consider existing Customer's processes for preventive and corrective maintenance, maintenance levels, skill level of operating and maintenance personnel, maintenance tools and other existing maintenance resources (Stamenković et al. 2008) — when planning maintenance strategy, procedures and tools for their systems/subsystems/equipment. Some of the main requirements were:

- Clear definition of three maintenance levels related to preventive and corrective maintenance activities on the trainborne and trackside sub-systems;
- Customer's operating and maintenance personnel shall perform the maintenance on the first and second maintenance levels;
- The Main Suppliers are responsible to provide the needed spare parts, appropriate operating and maintenance documentation, maintenance tools and trainings of operating and maintenance personnel; and
- Customer's personnel shall be trained as much as needed to be able to conduct the maintenance activities on the first and the second maintenance levels efficiently.

The mentioned documents are related to the responsibilities during the warranty period and support responsibilities have to be considered within separate trainborne and trackside sub-system support documents.

2.2 *Maintenance plans*

The detailed maintenance plans contain the following maintainability relevant elements:

- definitions of the basic maintenance relevant indices, such as MTBF, MRT, MTBPM, MAPMT, etc.;
- definition of three maintenance levels covering preventive and corrective maintenance activities;
- operator — driver, maintenance technician and system engineer basic profile descriptions;
- trainings provided by the Main Supplier for technical, maintenance and operating personnel, so that this personnel is able to use and maintain the system supplied by the Main Supplier with maximum efficiency and safety;
- maintenance strategy;
- specific Customer's processes by failure of trainborne/trackside sub-systems, the roles of existing ETCS hot line, operation centre, etc.;
- intervention undertaken by an Customer's service or the Main Supplier support technician;
- organisation and the roles of the Main Supplier's help desk and emergency services (picket services/duty) during the warranty period;
- self-tests and indicators;
- maintenance tools;
- relations to maintenance manuals;
- LRUs/SRUs flows; and
- spare parts management.

2.3 *Maintenance level definitions*

Three maintenance levels have been defined.

Maintenance level 1 is characterised by the following features:

- the corrective and preventive maintenance activities on the first maintenance level are carried out by operating personnel and vehicle driver or supervisor;
- it is an activity that takes place at the installation place (usage site), i.e. either on board of the train or on site for trackside equipment;
- as far as preventive maintenance is concerned, the 1st maintenance level consists mainly of servicing and inspections such as periodical visual inspections and controls, cleaning and periodical tests which can be performed without using complex tools or specified as self-tests at power on; and
- for corrective maintenance, the 1st maintenance level consists of immediate servicing actions on field by the operator such as restart of the system after a software fault caused by a failure.

Maintenance level 2 is characterised by the following features:

- the corrective and preventive maintenance activities on the second maintenance level are carried out by the line maintenance personal;
- it is an activity that takes place in depot for onboard system (facilities for under-frame examination, wheel exchange and pantograph examination) or on the line or trackside equipment;
- as far as preventive maintenance is concerned, the 2nd maintenance level consists mainly of the adjustment after some corrective actions, periodical tests requiring special tools (wheel diameter measurement, calibrations, etc.), some visual inspections and correct component functioning checking;
- as far as corrective maintenance is concerned, it consists mainly, for hardware, in diagnosing faulty line-replaceable units (LRUs), removing them, refitting healthy ones and checking correct operation; and
- the removed faulty LRUs are then shipped to a 3rd maintenance level facility to be repaired or replaced with healthy ones.

Maintenance level 3 is characterised by the following features:

- the corrective and preventive maintenance activities on the third maintenance level are carried out in a special Customer's workshop (trainborne sub-systems) or supplier/sub-supplier workshop facilities (trainborne and trackside sub-systems);
- as far as preventive maintenance is concerned, the 3rd maintenance level consists mainly of replacing some items with new ones, adjustment after some corrective actions, periodical cleaning, periodical calibration of some items and special tools, refreshment of long-term memories, upgrade of hardware and software and technology updates; and
- as far as corrective maintenance is concerned, the 3rd maintenance level consists of the following 2 stages:
  - stage A: replacing of failed SRU(s) – including diagnostic of failed SRU(s), removing failed SRU(s), refitting healthy ones and final testing; and
  - stage B: repairing of SRU(s) and simple LRU(s) (not consisting of SRU(s)).

During the warranty period the Main Suppliers are responsible for the 3rd maintenance level.

2.3.1 *Corrective maintenance*

The sub-system corrective maintenance tables with clearly specified PBS (ALSTOM 2007c, d & SIEMENS 2007a) have been prepared including the following headings:

- item code — a unique identifier specifying clearly item's hierarchical level according to PBS;
- item name — with the name and/or abbreviation of the item;
- LRU/SRU;
- quantity — on the first higher hierarchical level;
- description — specifying the main item's functions;
- train classes (for trainborne only);
- MTBF (hours);
- MRT (hours);
- maintenance level and skill — of the maintenance personal;
- technical documentation — which has to be used by the corrective maintenance activities; and
- spare parts.

The mentioned corrective maintenance tables have been prepared in order to organise easy corrective maintenance, but also to allow correct assessment of LCC.

2.3.2 *Training*

The needed training sessions provided by the Main Suppliers are intended for the technical, maintenance and operating personnel concerned about the ERTMS knowledge, so that this personnel is able to use and maintain the system supplied by the Main Suppliers with maximum efficiency and safety.

The training takes into account the maintenance, the operating and the driver's point of view.

Driver trainings have been organised directly by the Customer with support of the Main Suppliers.

The training courses have covered the following subjects:

- ERTMS principles;
- on-board ETCS platform (technical — maintenance — tools);
- on-board ETCS platform (Main-Machine-Interface); and
- short overview of some new trackside sub-systems/equipments, such as RBC.

Customer's maintenance instructors trained by the Main Suppliers have trained other Customer's maintainers.

3 MAINTAINABILITY DEMONSTRATION (MD)

The objectives of the MDs have been:

- to demonstrate the MRT contractual target achievement by means of statistical tests;
- to demonstrate the convenience, adequacy and user-friendliness features of operating and maintenance documentation, maintenance procedures and maintenance tools;
- to demonstrate the adequacy of the defined corrective maintenance concept based on the replacing of faulty LRUs;
- to assess the adequacy of maintenance personnel skill levels for the requested maintenance activities;
- to assess the experience achieved by the maintainer in carrying out specified maintenance tasks;
- to assess performing of selected representative preventive maintenance tasks selected for the MAPMT demonstration;
- to assess the carrying out of the selected representative corrective maintenance tasks for the MRT

demonstration according to LRUs contribution to the total sub-system predicted failure rate and determined sample size;
- to verify the statement "easy to maintain (easy of maintenance)";
- to modify, correct and/or improve some maintenance tasks and/or descriptions in maintenance manuals; and
- to check spare parts availability.

Additional benefits of MDs are:
- achieving of higher maintainer self-confidence; and
- giving a good guarantee to operator maintenance management, that all needed maintenance activities will be performed adequately.

The MDs have been considered as a part of system/sub-system acceptance. Hence, they have been organised during the commissioning phase and completed before the start of the official revenue service and the In Service Reliability Demonstration (ISRD).

3.1 *Organisation of the MD*

The MD organisation elements have been given in (Stamenković et al. 2008), including the management organisation of the MD and the role of preliminary logistic meetings.

The management organization of the MD is shown on Figure 1.

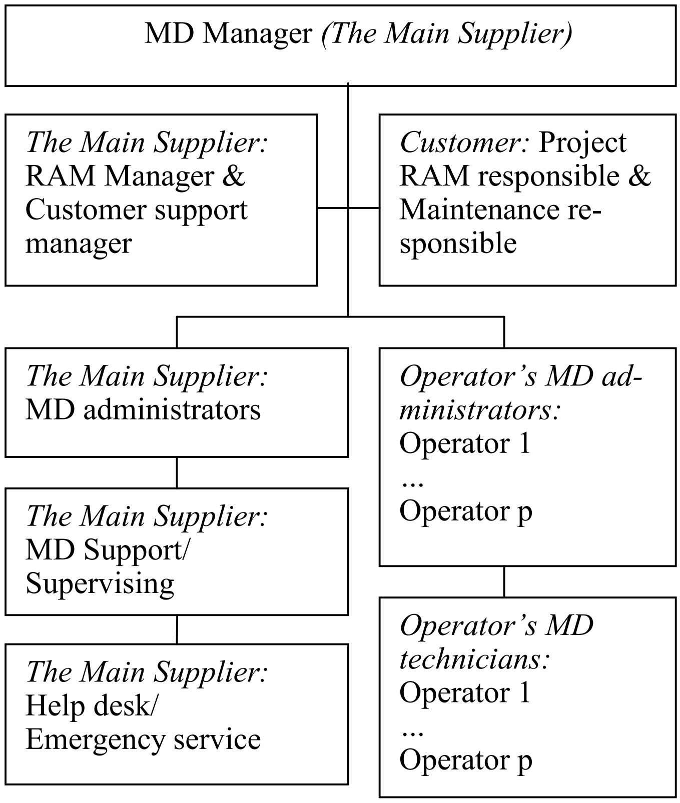

Figure 1. Organisation of the MD

4 MRT DEMONSTRATION AS A PART OF THE MD

4.1 *Statistical pass/fail test — methodology: Background*

Several statistical tests are given in (MIL 1997) for the MRT demonstration, mostly under the assumption (well verified in practice) that the time to restore follows a lognormal distribution.

The test which is proposed is defined in (MIL 1997), Appendix B.4.2, Test Method 1, Test A:

Hypothesis H_0: MRT = μ_0; and
Hypothesis H_1: MRT = $\mu_1 > \mu_0$

when the MRT requirement is stated in terms of both a required mean value (μ_1) and a design goal value (μ_0) (or when the requirement is started in terms of a required mean value (μ_1) and a design goal value (μ_0) is chosen by the Main Supplier).

The test is a fixed sample one (minimum sample size of 30).

The procedure steps are as follows:

- let μ_1 and μ_0 be specified;
- choose α and β, and then find Z_α and Z_β using existing tables, such as (Birolini 2007, Table A9.1 'Standard normal distribution');
- calculate the sample size m using Equation 1

$$m = [(Z_\beta \mu_1 + Z_\alpha \mu_0)/(\mu_1 - \mu_0)]^2 (e^{\sigma^2} - 1), \qquad (1)$$

  where σ^2 is the prior estimate of the variance of the logarithm of maintenance times;
- obtain a random of m corrective maintenance times X_i (i = 1, 2,…, m) corresponding to the i-th failure, and compute the sample mean using Equation 2

$$\overline{X} = (1/m)\sum_{i=1}^{m} X_i ; \quad (2)$$

- the sample variance

$$d^2 = [1/(m-1)]\sum_{i=1}^{m}(X_i - \overline{X})^2$$
$$= [1/(m-1)][(\sum_{i=1}^{m} X_i^{\,2}) - m\overline{X}^2]; \text{ and} \quad (3)$$

- the acceptance rule is — accept the hypothesis H_0, if

$$\overline{X} \le \mu_0 + Z_\alpha d m^{-0.5}, \quad (4)$$

otherwise reject it.

4.2 *Predicted MRT of the system (MRT_{Sp})*

Usually, in the final design phase, one needs as a mandatory maintainability requirement the detailed PBS with items up to the level of the LRUs, with specification of the predicted failure rates and the predicted MRTs of all LRUs, as well as the total number of each different LRU in the system. In this paper, the procedure steps are more detailed for the defined case, when a simulation of the failures for the system MRT (MRT_S) demonstration has to be applied.

Failure rate data sources — field data from existing identical or similar items in operation, reliability tests and some failure rate data handbooks, such as (MIL 1995), (IEC 2004) or (SN 2005), have been used for the failure rate prediction of the LRUs.

The predicted MRT values of LRUs are based on experience data of existing identical or similar items in operation.

4.3 *Determination of the demonstration test parameters*

Let the considered system be specified with a detailed PBS; and let the i-th LRU be characterised by the predicted failure rate, the predicted MRT and the total quantity in the system. Denote them with λ_{pi}, MRT_{pi}, and n_i (i = 1, 2,…, n), respectively. Then one defines the Worksheet 1 for the determination of the needed MRT demonstration test parameters. The column headings of Worksheet 1 have to be tabulated in the following order:

- LRU_i ident code (i = 1, 2,…, n) — a unique identifier specifying clearly item's hierarchical level;
- LRU_i name — name and/or abbreviation of the LRU which is subject of the corrective maintenance;
- LRU_i description (i = 1, 2,…, n);
- λ_{pi}, (i = 1, 2,…, n) — predicted failure rate of the LRU_i;
- MRT_{pi}, (i = 1, 2,…, n) — predicted MRT of the LRU_i;
- n_i, (i = 1, 2,…, n — total quantity of the i-th LRU in the system (entire train fleet, considering all different vehicle types where it is applied);
- $n_i\lambda_{pi}$, (i = 1, 2,…, n), and calculate λ_{Sp} using Equation 5

$$\lambda_{Sp} = \sum_{i=1}^{n} n_i \lambda_{pi}; \quad (5)$$

- f_i (i = 1, 2,…, n), defined by Equation 6

$$f_i = n_i\lambda_{pi}/\lambda_{Sp}; \quad (6)$$

- $f_i MRT_{pi}$, (i = 1, 2,…, n), and calculate MRT_{Sp} using Equation 7

$$MRT_{Sp} = \sum_{i=1}^{n} f_i MRT_{pi}. \quad (7)$$

Remark 1.1 *The column headings are given for an overview. Some of them are basic, and the other of them are only needed for some formula based calculations, which can be executed using existing efficient EXCEL tools to obtain only some final results (EXCEL array to multiply two columns and to find the resulting sums).*

In order to determine the sample size for test A, the following column headings are needed:

- $f_i\ln(MRT_{pi})$, (i = 1, 2,…, n); and calculate $\mu_{\ln}$ using Equation 8

$$\mu_{\ln} = \sum_{i=1}^{n} f_i \ln(MRT_{pi}); \quad (8)$$

- $f_i[\ln(MRT_{pi}) - \mu_{\ln}]^2$, (i = 1, 2,…, n); and calculate the predicted variance of the logarithm of maintenance times σ_p^2 using Equation 9

$$\sigma_p^{\,2} = \sum_{i=1}^{n} f_i [\ln(MRT_{pi}) - \mu_{\ln}]^2; \quad (9)$$

- for $\mu_1 = MRT_{Sr}$, $\mu_0 = MRT_{Sp}$, choose risks α and β, calculate Z_α, Z_β and sample size m using Equation 10

$$m = [(Z_\beta \mu_1 + Z_\alpha \mu_0)/(\mu_1 - \mu_0)]^2 (e^{\sigma_p^2} - 1); \quad (10)$$

- calculate $m_i = f_i m$ and specify the number of corrective maintenance tasks m_{effi} to be demonstrated for LRU_i as rounding of m_i, so that

$$m = \sum_{i=1}^{n} m_i = \sum_{i=1}^{n} m_{effi}. \quad (11)$$

4.4 *Test executing, measurement results and test decision*

Let m corrective maintenance tasks have been conducted. Then one defines Worksheet 2 for the determination of measured system MRT (MRT_{Smeas}), having the following column headings:

- RT_{measij} — being the j-th measured RT value for the LRU_i (i = 1, 2,…, n; j = 1, 2.,.., m_{effi}), and calculate measured MRT of the system (MRT_{Smeas}) using Equation 12

$$MRT_{Smeas} = (1/m)\sum_{i=1}^{n}\sum_{j=1}^{m_{effi}} RT_{meas\,ij} = (1/m)\sum_{i=1}^{n} m_{effi} MRT_{measi}, \quad (12)$$

where

$$MRT_{measi} = (1/m_{effi})\sum_{j=1}^{m_{effi}} RT_{measij}; \quad (13)$$

- define column $(RT_{measij}\text{-}MRT_{Smeas})^2$ and calculate the sample variance using Equation 14

$$(d_{Smeas})^2 = [1/(m-1)]\sum_{i=1}^{n}\sum_{j=1}^{m_{effi}} (RT_{measij} - MRT_{Smeas})^2; \quad (14)$$

and finally

- accept the hypothesis H_0: MRT = μ_0, if

$$MRT_{Smeas} \le \mu_0 + Z_\alpha d_{Smeas} m^{-0.5}, \quad (15)$$

otherwise reject it.

4.5 *On the recording of the relevant MRT times*

The selected test cases have been prepared by the Main Supplier and approved by the Customer. The Main Supplier, as responsible for the organisation and the executing of the MD, has been obliged to prepare the working sheets for the selected test cases, including the description of the failure simulation (such as the application of failed LRU, prepared disconnection in connectors, power supply, software failure, etc. Convenient EXCEL tables have also been prepared by the Main Supplier for the recording of all activities during the performance of the test, the relevant and non relevant times related to the FLT, FCT and COT, the calculation of the resulting RT, as well as the needed corrective actions related to a corrective maintenance procedure, maintenance documentation, etc.

4.6 *The MD report*

After completion of the MD, a MD report has been prepared by the Main Supplier, which has been subject of the Customer's review and approval.

The MD report shall include the following elements:

- Objectives of the MD;
- The goals of the MD related to preventive and corrective maintenance;
- Logistic elements (place, dates, durations, attendees, etc.);
- Test scenarios related to preventive maintenance tasks;
- Measurements of the MAPMT;
- Statistical parameters for the MRT demonstration, such as the test method, customer and producers risks, sample size, contractual and design target MRT, acceptance criteria;
- Test scenarios for corrective maintenance tasks (specified LRUs, the number of tests for each specified LRU, maintenance tasks, the method of failure simulation, etc.)
- Measurements of the MRTs according to sample size, calculation of the MRT for the considered sub-system and the test decision (pass/fail);
- Assessment of the maintenance documentation;

- The list of observed and recorded weaknesses which have been related to: the description of some maintenance procedures specified in the maintenance manuals; the optimality of some design solutions; the availability of appropriate maintenance tools; the maintainer's experience and the strict execution of specified maintenance procedures, etc. — has been included into the action plan, and the appropriate corrections/modifications have been performed and included into the MD report; and
- Conclusions.

5 CONCLUSIONS

A detailed procedure for the MRT demonstration has been specified for the following case:

- Customer requires from the Main Supplier to prepare in the final design a detailed PBS into items, with a clearly specified hierarchy up to the level of the LRUs, with specified and predicted MTBF and MRT values of each LRU, as well as the quantity of each LRU in the overall system; and

- The MRT demonstration is carried out by failure simulation and an application of (MIL 1997), Appendix B.4.2, Test Method 1, Test A.

The procedure steps have been applied by the two ambitious SBB's projects, and will be used by some new SBB projects.

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