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Development of EUROFER97 database and material property handbook

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ABSTRACT

The current paper reports the work of the EUROfusion Material Database and Handbook group within the MAT-EDDI (Materials - Engineering Data and Design Integration) subproject of the EUROfusion consortium. A special emphasis is put on the building of the EUROfusion RAFM steel database accounting around 3000 raw materials data records. A data reviewing procedure is discussed for qualification of the data on EUROFER97 for material property handbook summarizing the material database content at a higher level and thus serving as a reference document for the structural design criteria development. Internationally recognized methodologies applied for the calculation of the average and minimum curves as well as for generation of the analysis data is presented and differences between different methodologies is addressed. The content and format of the material property handbook currently counting over 20 DEMO design relevant material properties on baseline steel EUROFER97 is summarized and discussed on the base of selected examples.

1. Introduction

The development of the DEMO Design Criteria (DDC) for in-vessel components of future fusion DEMOnstration (DEMO) and power reactors requires building of a sound database on structural, armour and functional materials comprising physical and mechanical properties under various conditions, in particular in unirradiated and irradiated states [1]. Raw material data cannot be directly used in the design due to large dispersion of the data. The reasons underlying the data dispersion might be different and originated in i) variation of the material properties among different products and heats; or ii) a sensitivity of a property to the test and evaluation procedure. Exemplarily, surface finish quality is expected to have different influence e.g. on Low Cycle Fatigue properties of ferritic/martensitic steels while using sub-sized and standard specimens [2]. Qualification of the collated raw data is a mandatory step for the development of Material Property Handbook (MPH) summarizing the material database content at a higher level and thus serving as a reference document for the structural design criteria development [3]. In addition to the quality of the underlying data the conservatism of the calculated design allowables will have direct impact on the reliability and conservatism of the design rules. The examination of different internationally recognized methodologies for allowable calculation e.g. the ones given in AFCEN RCC-MRx 2012 [4], ASME BPVC 2004 [5], ITER SDC-IC [6] is a mandatory step for identification of the methodologies suited for a given material under targeted operation conditions.

The current work summarizes the results of the EUROfusion Material Database and Handbook group as part of the MAT-EDDI (Materials - Engineering Data and Design Integration) subproject. The activities are currently focused on the Reduced Activation Ferritic/Martensitic (RAFM) steel EUROFER97 which is a European reference steel for ITER Test Blanket Module (TBM) and a potential candidate material for European DEMO. The article is organized as follows. First the status of the development of the EUROfusion RAFM steel database will be reported. In the subsequent sections the procedure for the qualification of the data for inclusion in MPH will be outlined and explained by selected examples. On the base of the tensile properties the application of different internationally recognized methodologies will be discussed aiming at the calculation of the average and minimum curves as well as analysis data. Finally, the format and structure of the MPH will be presented on the base of different examples.

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Nomenclature

AFCEN RCC-MRx French Design and Construction Rules for Mechanical Components of nuclear installations : high-temperature, research and fusion reactors
ASME BPVC The American Society of Mechanical Engineering - Boiler and Pressure Vessel Code
DEMO DEMOnstration power reactor
DDC DEMO Design Criteria
MAT EUROfusion Materials Project
EDDI Engineering Data and Design Integration
EFDA European Fusion Development Agreement
EN European Standard
EUROfusion The European Consortium for Development of Fusion Energy
ITER A world's largest tokamak under construction
ITER SDC-IC ITER Structural Design Criteria for In-vessel Components
LCF Low Cycle Fatigue
LM Larson-Miller parameter
MPH Material Property Handbook
PWHT Post Weld Heat Treatment
RAFM Reduced Activation Ferritic/Martensitic
$R_{p0.2}$ 0.2% offset proof stress
RT Room Temperature
RU Research Unit
S Allowable stress intensity as defined in RCC-MRx
SD Standard Deviation
S_m Allowable stress intensity as defined in RCC-MRx
S_{mB} Allowable stress intensity as defined in RCC-MRx
SSTT Small Specimen Testing Technology
S_t Time dependent allowable stress intensity as defined in RCC-MRx
TBM Test Blanket Module

2. EUROFER97 database

The European RAFM steel EUROFER97 has been developed in the course of the systematic optimization of 9%CrWTa alloys [7]. The current study is limited to the 1st and 2nd industrial batches of 3.5 and 7.5 tonnes with 10 different heats and 18 different semi-finished product forms produced by EU steel manufacturers Böhler Austria GmbH and Saarschmiede GmbH [8]. The last heat treatments applied by producer included normalization at 980 °C for 15–30 min and tempering at 760 °C for 90 min for plates and normalization at 960–980 °C for 110–120 min and tempering at 750 °C for 220–240 min for rods. The impact of different tempering and annealing conditions on the microstructure and mechanical properties has been thoroughly studied at laboratory scale, for the results on selected product forms from the 1st batch of EUROFER97 the reader is referred to [9]. Specified concentrations of main alloying elements and radiologically undesired elements of EUROFER97 are summarized in Table 1.

Extensive examination and characterization campaigns have been carried out by several European Research Units (RUs) in the framework of the course of implementing the Contract of Association under EFDA (2001–2013) and within EUROfusion grants (since 2014). The raw materials data generated by RUs were made available either as scientific reports and open publications or in form of private communications kindly provided by responsible investigators. The majority of the mechanical properties used for the development of the EUROFER97 database are compiled from the following data sources [9,11–39].

Dedicated data acquisition templates developed at CEA [40] and further standardized by the EDDI group have been utilized for the collection of tensile, low cycle fatigue, impact, fracture toughness and creep data. In addition, new templates have been developed for specific testing needs, e.g. for collection of the physical and mechanical properties data. All relevant information on the heat, product form, heat treatment, irradiation condition, specimen geometry, test and evaluation procedure as well as the testing results can be stored in the template thus allowing full traceability of the data from the results down to initial product. The EUROfusion EDDI RAFM steel database currently accounts around 3000 raw materials data records. Selected data have been reassessed aiming at completion of the required information or at judgment of the validity of the collected results according to the international testing standards.

3. Data qualification

A data reviewing procedure and quality thresholds have been elaborated for the exclusion and inclusion the data in the MPH. In the first step the integrity of the compiled data has been checked focusing on identification of i) material (manufacturer, heat/product, thermo-mechanical treatment …); ii) specimen (geometry, extraction direction, …); iii) irradiation condition; and iv) testing and evaluation procedure (testing standard, parameter, temperature, environment, results, validity …). The calculation of the design allowables for MPH has been performed with the data passing the quality thresholds. In the following the data qualification procedure will be exemplarily shown for selected properties obtained on base metal EUROFER97. Aged data and irradiated data have been excluded for the calculation of the design allowables in the reference unirradiated state.

Fig. 1 summarizes the results of 0.2% offset proof stress, R_{p02}, on the 1st and 2nd batches of EUROFER97. Totally six different product forms (plates of different thicknesses, bars) are considered in the current plot. With respect to the yield strength, the differences between different batches and product forms turned out to be within the scatter band of the data measured on single product forms. Based on this observation no differentiation of tensile data has been done between different products for the MPH.

For the case when the collated information was in-complete the influence of the missing parameter on the property under consideration

Table 1
Specified chemical composition of EUROFER97 in weight % (wt%), Fe is balanced [10]. ALAP = as low as possible. Table is divided in main alloying elements and radiologically undesired elements.

Alloying elements	C	Cr	W	Mn	V	Ta	N_2	P	S	B	O_2
min value (wt%)	0.09	8.5	1.0	0.20	0.15	0.10	0.015			ALAP	
max value (wt%)	0.12	9.5	1.2	0.60	0.25	0.14	0.045	0.005	0.005	0.002	0.01
target value (wt%)	0.11	9.0	1.1	0.40		0.12	0.030				

Undesired elements	Nb	Mo	Ni	Cu	Al	Ti	Si	Co	As + Sn + Sb + Zr
min value (wt%)	ALAP	ALAP	ALAP	ALAP	ALAP			ALAP	
max value (wt%)	0.005	0.005	0.01	0.01	0.01	0.02	0.05	0.01	0.05

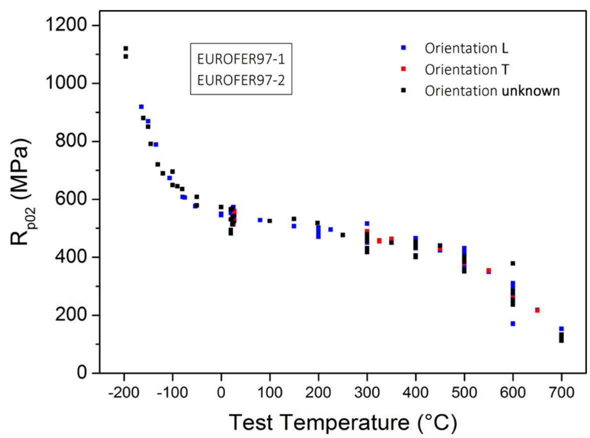

Fig. 1. R_{p02} proof stress of EUROFER97-1 and EUROFER97-2 for six different product forms [9], [11], [12], [19], [13], [14], [24], [20], [15], [17], [21]. The specimen orientations are indicated in the figure legend. (For identification of specimen orientations, the reader is referred to the web version of this article).

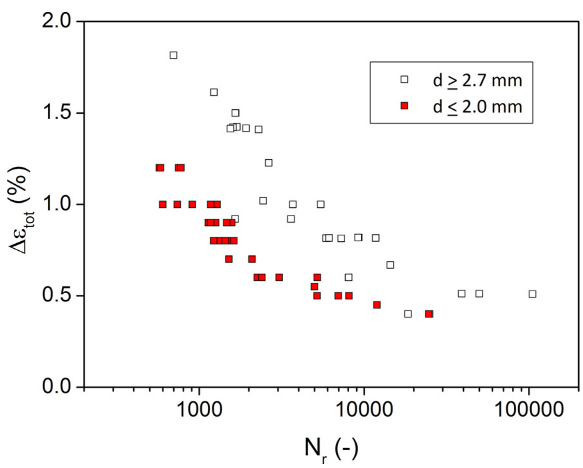

Fig. 2. Low cycle fatigue properties for EUROFER97 obtained by using SSTT type specimens (d ≤2 mm) and large (d ≥2.7 mm) specimens at test temperatures of T_{test} ≤350 °C [33], [34], [23], [24].

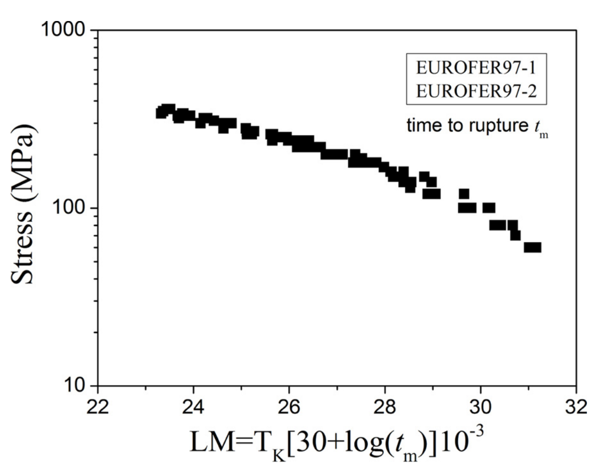

Fig. 3. Larson-Miller plot regarding the creep rupture time for four product forms from the 1st and 2nd batches of EUROFER97.

has been examined. The influence of the specimen orientation is exemplarily studied in Fig. 1. In additions to the results obtained in longitudinal and transverse orientations, the results available on specimens with unknown orientations are also included in the diagram.

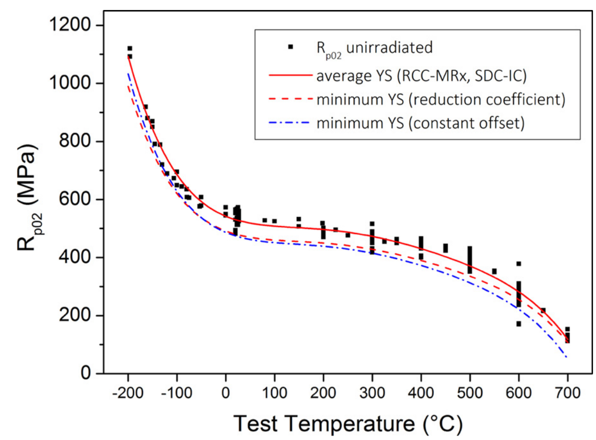

Fig. 4. R_{p02} yield strength along average and minimum curves calculated by means of different internationally accepted methodologies. The red solid line: an average yield strength curve determined by 5th order polynomial fitting to the data; the red dashed line: a minimum yield strength curve calculated on the base of Eq. (1) by using the minimum yield strength value determined by means of statistical methods; the blue dashed-dotted line: a minimum yield strength curve calculated following Eq. (2) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Table of content of EUROFER MPH, release 2017 [41].

1.	SHORT INTRODUCTION AND OBJECTIVES OF WORK, CHANGES FROM THE LAST ISSUE	6
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Specimen orientation is shown to have no measurable influence on the yield strength and consequently no differentiation has been done between different orientations for MPH.

The influence of the specimen geometry on the Low Cycle Fatigue (LCF) properties of EUROFER97 is shown in Fig. 2 for test temperatures below 350 °C. The use of SSTT type specimens with a diameter in the gauge section of 2 mm are found to strongly underestimate the lifetime of the material in comparison with the results obtained by using larger specimens. More pronounced influence of the surface imperfections (e.g. grooves introduced during the turning of the specimens in the workshop) on the lifetime for the SSTT specimens were attributed to the higher ratio of imperfection size to the specimen diameter in comparison with the larger specimens [2]. On the base of the assessment of the results in Fig. 2 the results obtained on the SSTT specimens have been excluded for the MPH allowable calculations. Similar to the tensile

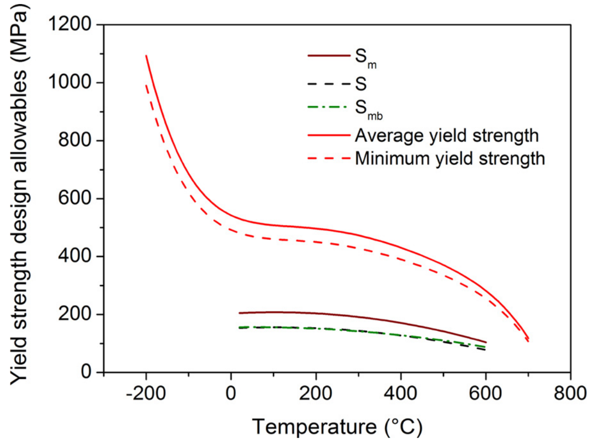

Fig. 5. The averaged and minimum values of the yield strength together with the S_m, S and S_{mb} allowables calculated according to the RCC-MRx methodology [41].

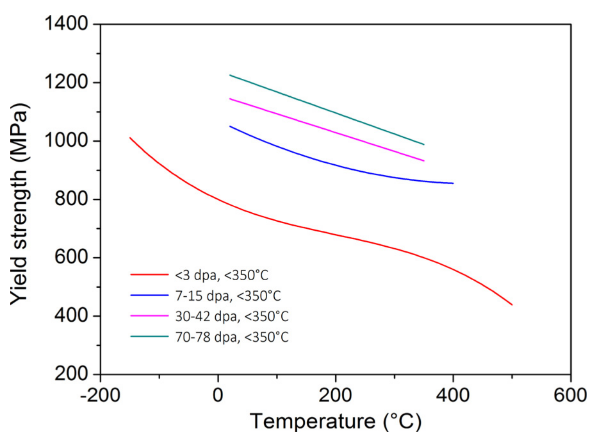

Fig. 6. The effects of irradiation on yield strength of EUROFER97, below 350 °C [41].

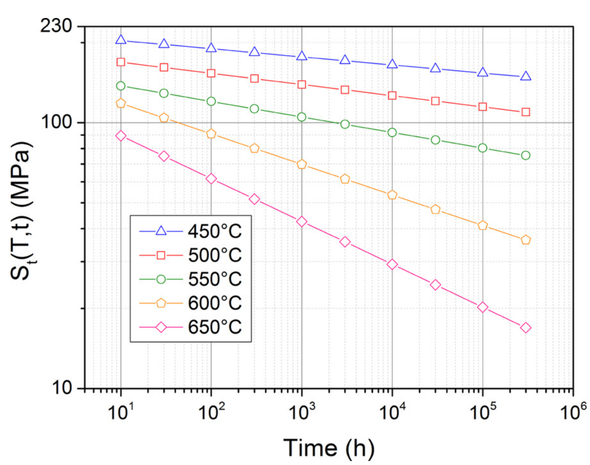

Fig. 7. Creep allowable stress [41].

properties no differentiation has been done between different product forms and between different orientations.

Approximately 140 original creep curves have been analysed with respect to the design relevant parameters e.g. onset of the tertiary creep, time to reach 1% total strain, time to reach 0.05% creep strain, etc. A Larson-Miller plot of creep properties constructed for the rupture time t_m is shown in Fig. 3 for the 1st and 2nd batches of EUROFER97. The results were found to follow common trend curve without substantial differences for the two batches and consequently no differentiation has been done between different heats for MPH.

4. Procedures for allowable calculation

Internationally recognized methodologies AFCEN RCC-MRx [4], ASME BPVC [5] and ITER SDC-IC [6] have been applied to the qualified data for calculation of the average and minimum curves as well as for the generation of analysis data. Independently from the design codes the average values of the properties are determined by a statistical method on the basis of the sufficient number of data on the representative samples. Fitting of the data with a polynomial function was found to describe fairly well the temperature evolution of most of the time independent mechanical properties. Exemplarily, the average curve obtained by 5th order polynomial fitting to the yield strength data is shown by red solid line in Fig. 4.

Within different design and construction codes different approaches are used for calculation of minimum mechanical properties at elevated temperatures [4–6]. One possible way is the application of constant reduction coefficient to the average curve $R_{p02,av}(T)$ according with the following equation:

$$\boldsymbol{R_{p02,min}(T)} = \frac{\boldsymbol{R_{p02,min}(RT)}}{\boldsymbol{R_{p02,av}(RT)}}\boldsymbol{R_{p02,av}(T)} \tag{1}$$

Here $R_{p02,min}(RT)$ is a minimum yield strength at RT which can either be specified within the material technical specification or calculated on the base of statistical analysis by $R_{p02,min}(RT) = R_{p02,av}(RT) - 1.96\cdot SD_{RT}$, with SD_{RT} being the standard deviation at RT.

Alternatively, minimum curve can be calculated on the base of the statistical analysis of the whole dataset according with the following equation

$$R_{p02,min}(T) = R_{p02,av}(T) - 1.96\cdot\mathrm{SD} \tag{2}$$

Here SD denotes the standard deviation obtained for the whole dataset in the procedure for the determination of $R_{p02,av}(T)$ curve. By definition Eq. (2) gives the 97.5% probability of sample exceeding the minimum.

Eq. (1) is conventionally used by ASME BPVC for determination of minimum yield strength at elevated temperatures by applying specified value of the minimum yield strength at RT, whereas Eq. (2) is typically used in ITER SDC-IC. As for AFCEN RCC-MRx code the minimum values of mechanical properties are given either by EN standards for the corresponding grades or determined by means of the statistical analysis or determined on the base of minimum values specified at RT. The example of minimum yield strength calculated by using Eq. (1) with RT minimum yield strength calculated by means of statistical methods is given by the red dashed line in Fig. 4. On the other hand blue dashed-dotted line in Fig. 4 shows the minimum value calculated on the base of the statistical analysis of the whole dataset following Eq. (2). It can be seen that minimum curve according with Eq. (2) yields more conservative results at elevated temperatures in comparison with the curve calculated according with Eq. (1). It has to be noted that application of Eq. (2) would require sufficiently large number of test results in the whole temperature range and consequently case by case study will be required in order to check whether Eq. (2) can be applied to the a given property for a given material. To determine the minimum values of yield strength and ultimate tensile strength for MPH we made use of Eq. (1) by using the minimum value of the RT yield strength calculated on the base of statistical methods, $R_{p02,min}(RT) = R_{p02,av}(RT) - 1.96\cdot SD_{RT}$. This procedure can be however revised in the future taking into account the needs of the European DEMO Design Criteria being currently under development. Variation of the confidence levels as well as subdivision of the temperature domains shall be investigated to determine reliable minimum curves and to avoid unnecessary conservatism.

5. EUROFER97 material property handbook

The EUROFER chapter of the MPH has been developed as the "pilot project" by the EDDI group. The format of the MPH is largely based on the format of ITER MPH. In contrast to the ITER MPH, however, the raw data points are not shown in the MPH in order not to violate intellectual property rights of data owner RUs. The data points are instead stored in the EUROfusion EDDI database and the procedures for the allowable calculations are justified in separate EUROfusion task reports. Table 2 shows the content of the EUROFER MPH. For the case when the material data were missing, e.g. for ratchetting behaviour, place holders have been introduced in the MPH. Currently, MPH summarizes over 20 DEMO design relevant material properties on base metal ERUOFER97.

Each property section provides identification of material, brief description of the property under consideration followed by relevant plots and tables. The influence of the irradiation is given in the *aged values* subsection of the property. Furthermore, in addition to the average and minimum curves selected allowables (e.g. S_m, S, S_{mb}) have been calculated by applying the RCC-MRx methodology [4]. Finally, at the end of each property paragraph a list of the references used for the calculation of the design allowables is given. This paper has no intention to report on the whole design allowables determined for MPH, instead aiming at giving the first insight into MPH selected examples will be briefly discussed below.

Fig. 5 is a reproduction of the yield strengths design allowables from MPH [41]. As already mentioned above in contrast to Fig. 4 the underlying data is removed from the MPH. This improves a readability of the document. Furthermore the tabulated values of the allowables together with the corresponding formulas given in MPH make the handling of the allowables straightforward for the designers.

Fig. 6 shows the effects of the neutron irradiation on the yield strength for low irradiation temperatures. Due to limited statistics of the irradiated data, only trend curves are provided for the data grouped according to their irradiation conditions. An adequate trend curve is also provided for high irradiation temperatures where the influence of the neutron irradiation is substantially supressed.

According to the RCC-MRx code [4] the $S_t(T,t)$ stress allowables are defined as the least of the following quantities: i) 2/3 of the minimum stress inducing fracture at a given temperature T and time t; ii) 80% of the minimum stress leading to the appearance of the tertiary creep and iii) the stress inducing total strain (elastic + plastic + creep) of 1%. Due to lack of the statistics 80% of the rupture stresses have been used as the estimate of the minimum values of the rupture stresses in the same conditions. The stresses leading to the onset of the tertiary creep stage have been evaluated from the original creep curves by using the 0.2% offset of the secondary creep stage. Also the stresses inducing total strain (elastic + plastic + creep) of 1% have been derived on the base of the analysis of the original creep curves and by taking into account initial elastic plus plastic strains. The determined values of $S_t(T,t)$ are summarized in Fig. 7. $S_t(T,t)$ values were found to be governed by 2/3 of minimum stress to rupture.

Concluding this section we would like to emphasize that actual release of MPH [41] is developed within a pilot project. This means that the current document will be further evolved in order to address the need of the DEMO Design Criteria as well as to close the known gaps in the design allowables. Dedicated experimental campaigns will be required for closing the database gaps particularly in fracture toughness, creep-fatigue, ratchetting, fatigue crack growth, etc. properties both in the unirradiated and irradiated states. Full qualification of the weldments exposed to the suitable Post Weld Heat Treatments (PWHT) compatible with the DEMO design will be required in addition for development and validation of the design rules with respect to the joints. Complete identification of the missing data and elaboration of the detailed testing matrices requires close collaboration between the experts from database, testing, design and technology areas from relevant EUROfusion projects and is currently under progress.

6. Summary

In the current work we reported on the development of EUROfusion material database and material property handbook on European reference RAFM steel EUROFER97. The EUROfusion EDDI RAFM steel database currently accounts around 3000 raw materials data records. The quality thresholds for the assessment of the data integrity have been introduced and the reviewing procedure for qualification of the data on EUROFER97 for material property handbook has been discussed. The application of different internationally recognized methodologies has been examined for calculation of the average and minimum curves as well as analysis data. The content and format of the MPH currently covering over 20 DEMO design relevant properties have been explained on the base of selected examples. The needs for the further optimization of the methodologies for calculation of the design allowables as well as the needs for the closing the gaps in the material database have been addressed.

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