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Will Pigs Fly Before Ceramics Do?

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Abstract
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PREFACE

In 2000, the Tactical Technology Office (TTO) of DARPA was directed to begin studies that could lead to the eventual construction and demonstration of a medium-sized supersonic aircraft that could be used for military reconnaissance roles. Called the Quiet Supersonic Platform (QSP) initiative, the technologies to be considered for such an aircraft would allow supersonic (Mn = 2.4) cruise capabilities with an unrefueled range of approximately 6,000 nmi. In addition, the "quiet" aspect of such an aircraft would enable prolonged supersonic flight over land, due to greatly attenuated sonic boom characteristics.

Although the detailed notional aspects, mission cycles, etc., of the QSP are yet to be determined as of this writing, the propulsion system is considered a vital area for the success of such an aircraft. The need for a lightweight, efficient engine with high flow characteristics will not only provide the needed power to fly the QSP, but also contribute toward the overall goal of reduced boom. Any propulsion system must presumably be able to operate at higher overall pressure and/or bypass ratios and temperatures than is now current practice in manned aircraft. Such conditions may tax current engine materials beyond their capabilities and require the use of developmental materials which have not been qualified for aircraft use.

For more than two decades, various U.S. Government agencies have funded the development of structural ceramics for potential use in gas turbine engines. Actual incorporation of ceramics into these engines (especially for aircraft) has been slow because of a number of fabrication, cost, and other issues. Yet advanced structural ceramics, whether in the form of monolithic materials or ceramic matrix composites (CMCs), have been cited as enabling technologies for advanced turbine engines to reduce fuel consumption and emissions while increasing performance.

DARPA/TTO asked IDA to conduct an assessment of the suitability of current ceramics technology for gas turbine engines such as those needed for the QSP, especially for higher risk rotating components such as the turbine. This assessment was expanded to include both CMCs and monolithic ceramics for both static and dynamic components in the hot section. Anticipated advances in the materials over the next few years were considered, although this was admittedly speculative. IDA will present its recommendations for addressing technical shortfalls in current ceramic materials such that they may eventually be applied to components in the QSP engine. Both shorter term actions that DARPA can address within a focused program and more global actions which the materials and design communities should address together will be explored.

This paper is a summary of the assessment and has been accepted for publication in the 2001 American Ceramic Society 25th Annual International Conference on Advanced Ceramics and Composites Proceedings.

WILL PIGS FLY BEFORE CERAMICS DO?

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ABSTRACT

For about 30 years, ceramic materials have been studied as possible candidates for static and rotating components in gas turbine engines. Some of the properties that make ceramic materials attractive in this application are their lower weight and higher temperature capability. Ceramic materials have found limited use in engines, however, because of low fracture toughness, erosion and lack of understanding of when and how the component will fail under real conditions.

In recent months, there has been a renewed interest in using ceramic materials in an advanced military aircraft. One of the envisioned features of such aircraft is an advanced turbine engine with high bypass/pressure ratios and a lightweight core. Ceramic materials are considered a critical part of an engine in order to meet performance goals. To advance the development of this concept, a realistic study of the capabilities and needs of advanced ceramics in this engine is required.

The objective of our task was to assess the feasibility of using current technology ceramic rotating components in an advanced turbofan engine core, to determine the associated risks of doing so, and to identify and recommend materials development activities which would best address those risks. Both monolithic and ceramic matrix composites (CMC) materials were considered and the study also took into consideration the use of ceramics in adjoining static components. The scope of this study included fact-finding discussions with knowledgeable personnel from the Military Services, NASA, the FAA, DOE, U.S. aeropropulsion and power turbine companies, advanced (ceramic) materials companies, and universities on advanced turbine engine cycle concepts, manufacturing processes and the current general state of acceptance of ceramics in turbine engines. An IDA-developed technology maturation assessment methodology was applied to the ceramics data where appropriate. This methodology will provide guidance in supporting efforts that will have the greatest impact in solving problems related to acceptance and qualification of

advanced ceramics in turbine engines for aircraft. The results of the assessment will be presented in a summary form.

INTRODUCTION

For more than two decades, various US Government agencies have funded the development of structural ceramics for potential use in gas turbine engines. The investment in this area is estimated to have been over one billion dollars since 1979. Actual incorporation of ceramics into these engines (especially for aircraft) has been slow, due to a number of fabrication, cost and other issues. Yet advanced structural ceramics, whether in the form of monolithic materials or ceramic matrix composites (CMCs), have been cited as enabling technologies for advanced turbine engines to reduce fuel consumption and emissions while increasing performance.

In recent months, interest in using ceramic materials in an advanced military aircraft has been renewed within the Tactical Technology Office (TTO) of the Defense Advanced Research Programs Agency (DARPA). One of the envisioned features of such aircraft is an advanced turbine engine with high bypass/pressure ratios and a lightweight core. Ceramic materials are considered a critical part of an engine in order to meet performance goals. To advance the development of this engine concept, a realistic, new assessment of the capabilities and needs for advanced ceramics in such an application was seen as necessary by DARPA/TTO. This assessment would identify what additional work should be done to build upon past DARPA and other government development work in engine-quality ceramic components. Therefore, the objective of the IDA study was to determine the feasibility of using rotating components made from current ceramic materials in an advanced turbofan engine core, to determine the associated risks of doing so, and to identify and recommend materials development activities which would best address those risks.

APPROACH

Two major types of ceramic materials were assessed: monolithic silicon nitride and ceramic matrix composites. Oxide-oxide systems such as Al_2O_3-Al_2O_3 were not considered in great detail because of their lower current temperature capability. Although there is work continuing to increase the use temperature for these materials, a number of issues make them less desirable for use in gas turbine engines within the next few years. It was also obvious that the number of companies that used to supply ceramic materials and components has decreased significantly in the last few years. The top companies identified in this study for ceramic materials suitable for gas turbine engines are Honeywell and Kyocera. IDA’s approach to this study was to first conduct a series of fact-finding discussions with knowledgeable personnel from U.S.

turbine engine companies, advanced (ceramic) materials companies, and universities on advanced turbine engine cycle concepts and the current general state of acceptance of ceramics in turbine engines. IDA covered not only aircraft propulsion engine companies but also aircraft power unit and ground-based turbine engine companies for this assessment, especially with ground-based systems having had significantly more field experience with ceramic materials. IDA also talked to D-Star Engineering, who has a very different engine design that may take better advantage of ceramic materials' inherent properties than conventional designs by the other companies.

A parallel series of discussions with personnel from Government agencies and the Military Services who are involved with materials qualification procedures for turbine engines, both for man-rated and unmanned aircraft, were also conducted. Previous, current, and planned Government-funded work in ceramic materials and engine component development were discussed in the context of the qualification process, especially for use in manned aircraft. The data gathered from these fact-finding activities were reviewed and the maturity of ceramics technologies was determined versus the risks and payoffs of using them in turbine engine systems. Faculty members from several universities familiar with these overall issues were also included in IDA's discussions. From questionnaires IDA sent to the all of the mentioned industry and government agencies and Services as well as through these discussions, IDA developed a list of common issues voiced in the community of materials researchers and engine designers. These issues as well as data IDA collected on materials properties, components and field testing experience were used in defining the maturity of the ceramic materials for gas turbine engines. These issues are given in Figure 1.

The technology maturity level analysis IDA used is based on a methodology described by Lincoln [1] and augmented by IDA to include important material parameters. IDA used a similar analysis in evaluating the state of the art of polymer matrix composites (PMCs), Honeywell's gel casting process for silicon nitride and single crystal piezoelectric materials [2]. In this assessment, however, the emphasis was on systems level maturity of ceramic components (both static and rotating types) rather than an individual material or process. Thus, the maturity factors used in assessing ceramic for gas turbine engines encompasses both the material and process maturity as well as the design and systems integration issues. These maturity factors are not ranked by importance; however, a deficiency in any one factor can prevent successful transition into production of a materials system. These maturity factors are listed in Figure 2.

The maturity level is often determined by a lack of information or experience that impedes further technical progress. A low maturity level indicates that there are a number of major deficiencies for a particular factor, whereas a higher maturity level indicates minor deficiencies but the system/component is more ready for full-scale production. The coding system for the degree of maturity is shown in Figure 3.

RESULTS OF THE ASSESSMENT

Figures 4 and 5 are a summary of the maturity status of both static and rotating ceramic components. In general, the most mature ceramic components are static ones; silicon nitride seals used in smaller propulsion engines or small nozzles in auxiliary power units (APUs). The least mature ceramic component for gas turbine engines are CMCs that would be used for rotating turbine blade applications. The following is a brief discussion of each of the ceramic component classifications.

Static Monolithic Components

Because silicon nitride seals and nozzles are currently being used in engines and APUs, the lab-scale devices and manufacturing scale-up maturity factors received a higher rating than the other maturity factors. Areas that were lacking data or still needed developed to some extent included most of the other maturity factors. For example, the characterization of the silicon nitride material has been well documented, however, the testing methodology was not consistent among the suppliers or end users. Environmental barrier coating (EBC) development has begun on monolithic components even though the environmental (water vapor erosion) issues have been known for quite some time. The coating work is only at a lab-scale level and no consistent formulations have been developed as yet. The materials and processes are relatively stable for silicon nitride but again, not for the coatings. Batch-to-batch variations in silicon nitride parts are still evident as shown by Weibull moduli in the 12-20 range. The gel casting process itself is much more consistent and mature than other processes such as solid freeform fabrication (SFF), yet there still is some "art" in the final finishing of the gelcast parts.

The lack of a sufficient database on materials property or component performance has adversely affected modeling efforts. Currently, life prediction models do not take into account coatings or real environmental issues, yet tend to be conservative. Although mechanical properties of the materials have sometimes been well characterized, components have not, including nozzles. Finite element models (FEM) that show component performance in simulated environments also use materials data. Given that the database for silicon nitride components is limited, so is the predictability of the overall performance of the component in an engine environment.

Non-destructive evaluation (NDE) techniques are limited when it comes to inspecting ceramic materials and thus, the parts that are used in APUs for example are 100% proof-tested. This is much more costly than more simple inspections and quality control procedures. Cost savings and design trades were not necessarily considered in using monolithic ceramics as static components in APUs; rather, this was a workable solution to a problem and one way to get real engine environment experience. Whether or not the static ceramic components are more affordable than similar parts may be more related to the life cycle costs than initial procurement costs. Systems integration issues were limited in scope since the current monolithic ceramic components are essentially drop-in replacements for their original metal counterparts. The maturity factor that received the lowest rating was in repairability, as no repairs have been developed for either the ceramic components or the coatings.

Rotating Monolithic Components

Similar arguments for static monolithic components held true for rotating monolithic components in the following maturity factors: characterized materials, stable materials and processes, and validated mechanical properties. Silicon nitride blades have been fabricated and tested in engine environments for short periods of time and thus, received a high rating in the lab-scale devices maturity factor.

However, most of the other maturity factors received much lower ratings because of a lack of test data on blades. The engine test times have been limited because of blade failures. And because of the failures, there has been a consequent reluctance to continue testing for fear of additional failures. Little effort has been evident in systems integration issues such as attachments, though some work has been done to address compliant layer and joint designs for ceramic blades in metal turbine disks

Static CMC Components

Under the NASA Enabling Propulsion Materials (EPM) Program and the Department of Energy's Advanced Turbine Systems (ATS) Program, several CMC combustor liners have been fabricated and two sets of CMC liners were tested in the ATS program. This accounts for the higher rating for the lab-scale devices fabricated and tested maturity factor. However, even though full-scale parts have been tested in an engine environment, areas such as characterized CMCs with coatings, stabilized materials and processes with and without coatings, validated FEM codes, life prediction models, systems integration and affordability still reflect shortfalls. The CMC liners that have been fabricated were drop-in replacements for metal liners and not optimized for design. Safety factors have been set by uncertainties in the materials properties. Most of the data that has been collected has been from coupon-sized samples that do not necessarily correlate with field-tests of full-scale components. The limited field data and relatively non-existent database for CMCs accounts for the very conservative FEM and life prediction models. In summary, the limited experience with CMC static components accounts for a lower maturity rating than for monolithic static components.

Rotating CMC Components

Very limited work has been done in developing CMC blades for gas turbine engines. There are a number of fabrication issues for these components, especially with regard to fiber weavability with respect to complex airfoil shapes and curvatures. Most of the current data is based on coupon samples, hence they do not necessarily represent the stress loads in complex blade shapes. Many of the other maturity factors have not even been considered at this time regarding cost studies, systems integration, etc.

SUMMARY AND CONCLUSIONS

The good news is that there are some ceramic components flying today even though they are in less critical static areas of gas turbine engines and APUs. Honeywell and Kyocera silicon nitride materials have been adopted for these applications, and Honeywell's AS 800 is a reasonable state of the art material for the static and limited number of rotating ceramic components that have been fabricated. Yet, there needs to be less variability in AS800's properties for designers to use monolithic ceramics in more critical areas as well as an adequate database and manufacturing consistency.

There are other efforts still underway to fabricate CMCs and monolithic ceramics for demonstration and eventual production for gas turbine engines. The DOE ATS program remains an important activity for getting CMC combustors and other components field-tested in actual land-based turbine engine conditions. However, the overall assessment is that ceramics are not ready for near term use in "high payoff" components in man-rated turbine engines. Nor are they likely to be, with a technology development approach that puts ceramic components as drop-in replacements for metal components, with little design optimization to take advantage of the ceramic materials' properties and their real payoff characteristics. Engine designers are conservative, so that they are more willing to use innovative cooled metal designs for turbine blades and other hot section parts, rather than ceramics which have higher use temperatures but which have insufficient design data to back up those attributes. . In recent years, there has been mostly sub-critical development and testing efforts for ceramic components, done on insufficient budgets. And, many of the problems identified with earlier generation ceramic components are still there, such as foreign object impact resistance, environmental durability, NDE, cost etc.

What is needed is a more radical, unconventional approach toward designing turbine engines that will take better advantage of ceramic materials properties. A consolidation of efforts is also needed to put more rotating ceramic components in full engine tests to update FEM and other prediction methods, in order that there are fewer failures in the future. Any results from the consolidation or coordination of such activity should be open to a wider community and minimize proprietary data generation in order to foster improved technology dissemination. Funding will continue to be an issue, but if the present mindpset in technology development continues, there may be more pigs flying than ceramics in the future.

ACKNOWLEDGEMENT:

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REFERENCES

[1]J.W. Lincoln, "Structural Technology Transition to New Aircraft", Proceedings from the 14th Symposium of the International Committee on Aeronautical Fatigue, Ottawa, Canada, 1987.

[2]W.S. Hong and L.C. Veitch, "Toward more Successful Evolution of New Materials and Technologies", Paper No. S-K-013-99, presentation given at the 101st American Ceramic Society Annual Meeting and Exposition, April, 1999.

- FOD for monolithic ceramics
- Low design stress limits for CMCs
- Thermal gradients
- Erosion (environmental) effects-additional environmental barrier coatings (EBC) needed which also complicate fabrication issues
- Integration/attachments to metals
- Design-quality database doesn’t really exist (other data are restricted)
- Standard testing practices
- Life prediction models
- NDE for ceramics does not exist
- COST

Figure 1. Common issues related to ceramic materials

•Characterized materials available (includes coatings)
•Stabilized materials and processes includes coatings)
•Design details and allowables determined
•Lab-scale devices (subcomponents) fabricated & tested
•Manufacturing scale-up determined
•Life prediction models available; mechanical and electrical properties valid for materials and components
•FEM validated for designs with materials data
•Design trades and cost studies determined and integrated with functional databases, quality assurance procedures developed and validated
•Systems integration issues for full-scale systems are addressed in device (component) development
•Devices (components) can be produced in multiple units; statistical test data is available
•Multiple repair trials (if feasible) are performed with critical details
•Supportability
•Demonstrated affordability

Figure 2. Maturity factors.

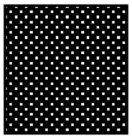
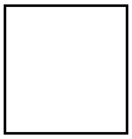
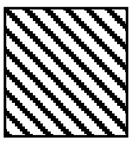
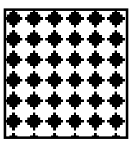
	Materials not available; devices or components not built; integration issues not addressed; design codes not valid; test data not available; designs incomplete
	Materials available but properties are not reproducible; testing is not complete; no subsystem or full-scale system built; design and cost models not validated for full-scale systems; little to no information on manufacturing practices
	Limited testing available with large error bars; subsystems built but testing is incomplete; full-scale components built but not tested under true conditions; cost and design model validation incomplete
	Materials and processes well-characterized; database for materials as well as component performance is available for different conditions; reproducible subsystems and full-scale systems are built and tested under real conditions; design, life prediction and cost models validated; manufacturing scale-up addressed with QC

Figure 3. Maturity rating scale

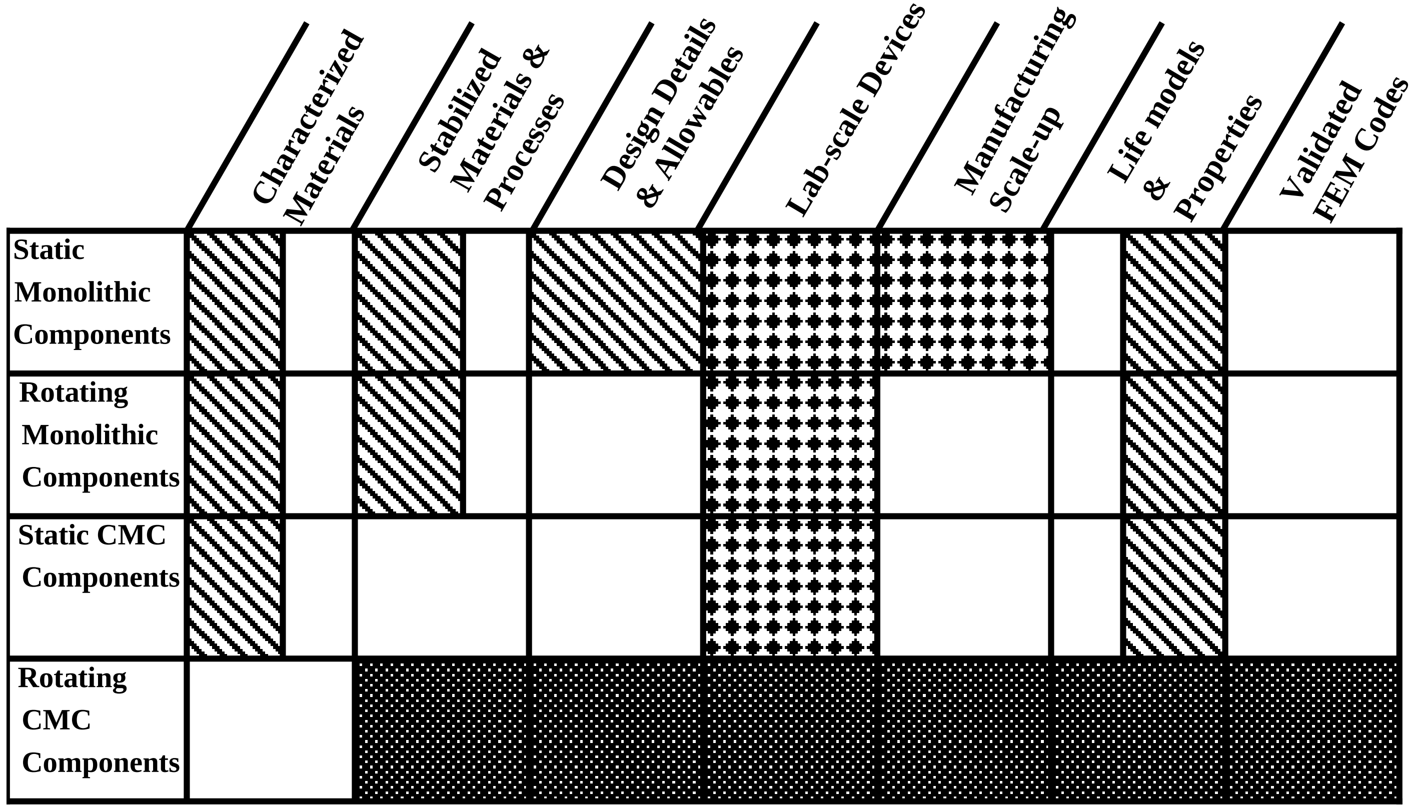


Figure 4. Maturity status for ceramic components.

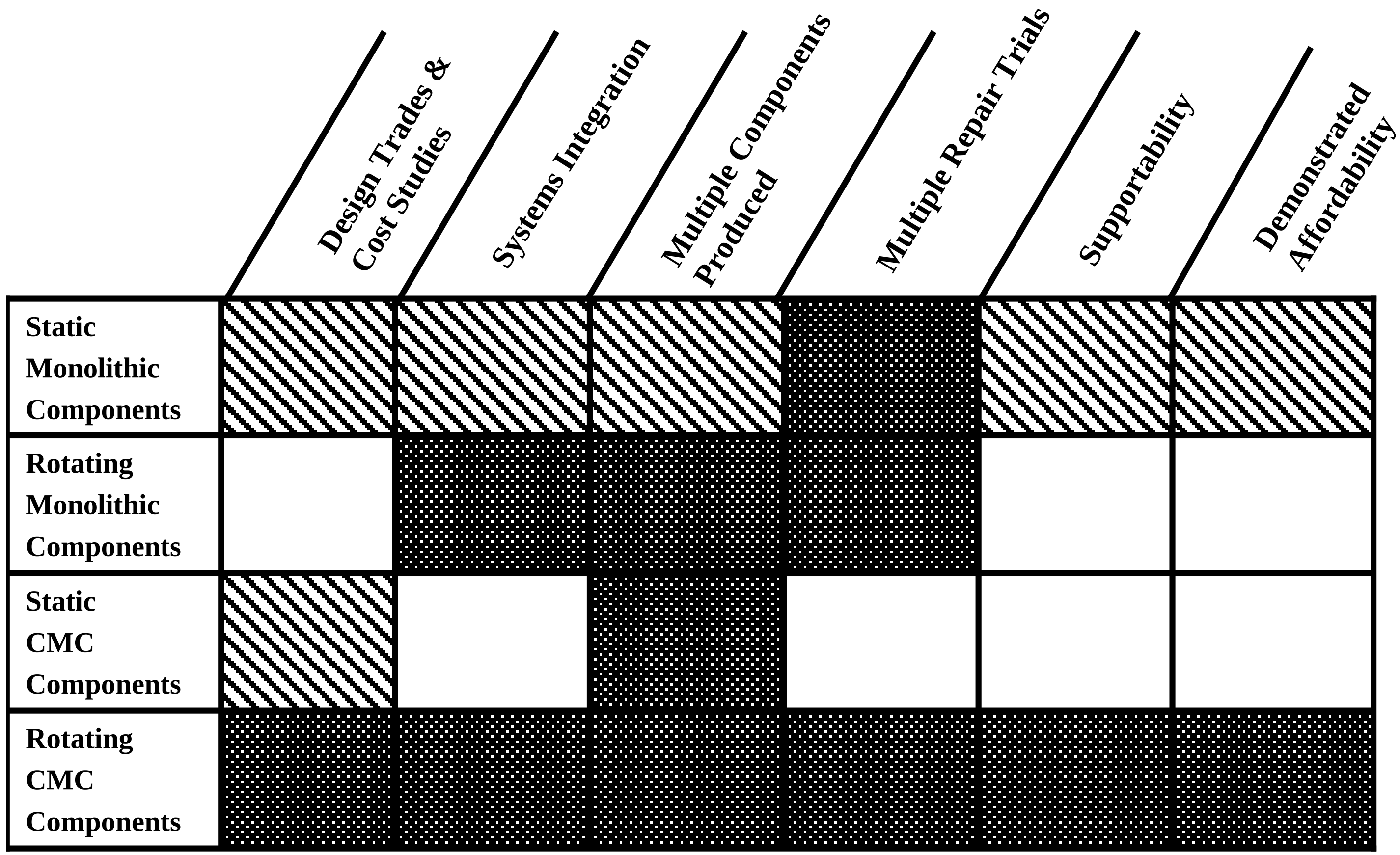


Figure 5. Maturity status for ceramic components (continued).

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