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A Thermal Management Concept for More Electric Aircraft Power System Applications

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ABSTRACT

An innovative thermal management system (TMS) that provides both effective active heat transfer and high passive thermal energy storage capacity has been developed and successfully demonstrated. The TMS integrates the high latent heat advantages of a phase change material with an actively cooled cold plate design. The resulting TMS concept has direct use on many transient system applications, where the amount of heat dissipated varies over time. The example discussed in this paper is the transient operation of electric flight control actuator hardware that is proposed for the More Electric Aircraft (MEA) Initiative. The development of the TMS concept, the successful fabrication and validation testing on actual flight control electronic hardware is provided. The advantages of the Thermal Management System include: significant weight savings, high thermal performance, high thermal energy storage capability, high reliability and reduced maintenance.

INTRODUCTION

The waste heat rejection for many systems varies over time, with peak loads for short time periods substantially greater than the nominal operating loads. In conventional designs, the thermal management system is either; over designed for the peak heat rejection or under designed near the average heat rejection.

The over designed alternative results in a larger, heavier and more costly TMS. The advantage, however, is that it maintains component temperatures at or below their design values, resulting in improved electronic component performance and reliability. If the conventional TMS is designed for the average heat load condition it has the advantages of being smaller and lighter weight. The disadvantage, however, is that the components experience higher temperature excursions during peak load operation. This can significantly reduce the reliability of the temperature sensitive electronic components. The design of a TMS that synergistically couples the advantages of thermal energy storage and effective heat transfer can result in an overall system that has the advantages of maintaining component temperatures during the peak excursions, as well as, being smaller and lighter weight.

The goals presented by Cloyd (Ref. 1) for the MEA Initiative include improved reliability, maintainability, supportability as well as enhancements in aircraft performance, weight and volume. Correspondingly, the design requirements for thermal management systems utilized in MEA applications also need to incorporate these attributes. A TMS that can couple the advantages of both a smaller and lighter weight system with the ability to maintain component temperature excursions during peak operation is of paramount importance for the future development of hardware the MEA Initiative.

The electrically based aircraft is made feasible with the advent of improved power and power conditioning equipment. These developments allow replacement of the conventional centralized hydraulic system with a distributed electrical system. Replacement of the hydraulic system with a distributed electrical based system also eliminates the means for transporting and rejecting the waste heat. A distributed approach for the thermal management of waste heat from the electrically based components is needed for the MEA systems. Using a separate centralized fluid loop to handle the thermal loads from the distributed components would compromise the MEA system objective of reducing the complex fluid loops.

A new approach of dealing with the individual component heat loads at a local level was perceived to best achieve the goals of the MEA Initiative. This includes developing a distributed thermal management system to locally handle the component heat rejection. Many of the electric systems such as actuators for flight control operate at high powers during only certain portions (take-off, flight maneuvers and landing) of the mission. These transient systems have an average heat rejection load that is substantially lower than the short term peak power levels that can reach 40-50 kW. This type of duty cycle allows the size of the active TMS to be significantly reduced if thermal energy storage can be effectively employed to handle the peak power cooling loads. The electronic component temperatures associated with these systems is maintained during high power operation by diverting the excess thermal energy into storage. This is very important since electronic components are highly sensitive to temperature threshold values which effect their reliability and failure mechanisms.

The TMS presented allows a simple active system to be sized for the average heat load with enhanced passive capability to effectively store excess heat. The TMS concept can be easily tailored to match the thermal characteristics of a wide variety of components and transient operating cycles. This concept synergistically couples the advantages of the high latent heat capability of a phase change material (PCM) with an efficient thermal design of the cold plate. Typically integrating a PCM with a thermal system has been plagued by the very poor thermal conductivity of relevant PCM candidates. This meant that even though the latent heat capacity of the PCM was 5-10 times the sensible heat capacity of most materials it was difficult to exploit this advantage. Getting the heat into and subsequently out of the PCM was a slow and inefficient process. For applications where the thermal response time requirement is relatively short (approximately a minute) it has been difficult to effectively use latent heat energy storage. Also the integration of the low thermal conductivity PCM in a cooled structure will inhibited the transport of heat through the structure during its steady-state operation. Therefore, the nominal steady-state design of the cold plate requires special enhancement techniques to minimize the conductance path to the ultimate heat sink.

Schneider et. al. (Ref. 2,3) have also developed a thermal cooing system that incorporates a reflux cooler and the PCM. Although the system performance and weight is much improved over other conventional systems, the system complexity is increased by incorporating the fluid within the reflux loop. Utilizing a simple and passive thermal management system has distinct advantages over the more complex multi-working fluid systems.

The passive TMS described in this paper and the reported test results demonstrate a unique concept that addresses the deficiencies typically found in prior integrated thermal transport and storage systems. The TMS is directly applicable to many transient applications with varying duty cycles and local heat removal. The concept has been demonstrated on realistic hardware used for electric flight control actuators and their associated electronic components.

TMS TECHNICAL DISCUSSION

The TMS concept features, thermal design and analysis, fabrication, test results and future applications are provided in the following technical discussion.

TMS DESIGN DESCRIPTION – The thermal management system includes a high thermal conductivity finned structure that is light weight and highly effective in dissipating waste heat. This aspect is important during operation at nominal power levels. The heat source to sink conductance needs to be minimized in order maintain the electronic component temperatures. A high performance air cooled fin structure mounted on the cold side of the TMS provides the local active heat rejection into the air enthalpy stream. The phase change material (PCM) is integrated within the finned structure, providing thermal energy storage. The mass of the PCM is determined by the requirements of the application. The PCM placement and geometric fin configuration is determined by extensive optimization to achieve the required steady-state heat rejection capability, the thermal response to transients and overall energy storage characteristics.

Effective thermal transport to the PCM is derived from two features: use of a high thermal conductivity filler material and a PCM cell size that has a high heat transfer surface area to volume ratio. The optimal combination of these two features provides the effective conductive heat transport into the PCM cell. The small cell size (about 1.3 mm) reduces the conductance length into the low thermal conductivity phase change material and significantly reduces the thermal penetration time. The high surface to volume ratio of the cells allows for fast thermal response and efficient heat transfer of the overall structure. This design feature allows rapid and effective thermal transport into and out of the low thermal conductivity PCM.

The TMS concept has broad applicability to a number of transient applications. It represents a lightweight, thermally efficient, passive energy storage device that can be easily tailored to the specific duty cycle and component operating characteristics. In order to demonstrate the TMS concept the application to electro-mechanical actuators (EMA) systems in development for the MEA Initiative was selected. In particular, the EMA motor controller switch under development by Sundstrand Aerospace was selected as the representative application for the proposed TMS. This allowed realistic design requirements to be used, as well as, the ability to test the TMS on actual hardware.

The TMS illustrated in **Figures 1** and **2** which shows the full size hardware that offers operating simplicity, improved reliability, performance and weight advantages over competing approaches. The concept has been developed and analyzed to established its operating characteristics and performance. A testing program has validated the performance characteristics of the full size hardware under realistic operating conditions. The demonstrated hardware is ready for transition into hardware applications.

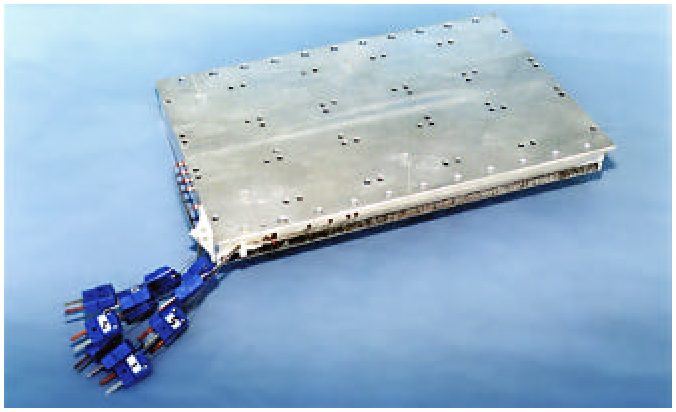

Figure 1. EMA Switch Cooler

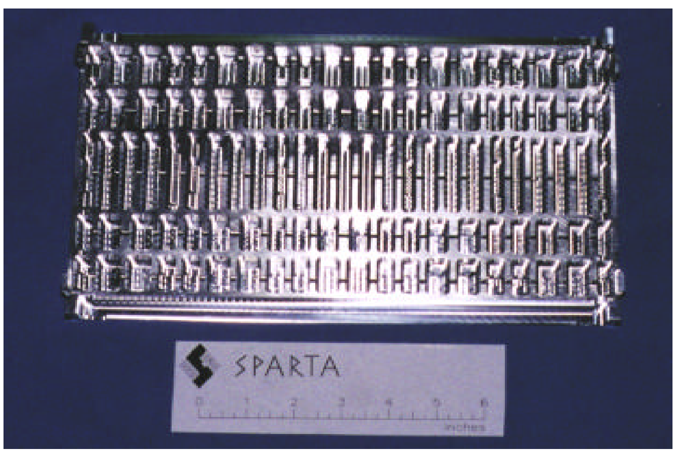

Figure 2. EMA Switch Cooler Internal Details

The design features and thermal requirements of the EMA switch cooler are provided in **Table 1**. A total of ten switches can be mounted on the surface of the TMS switch cooler. The back side of the cooler incorporates a plate fin heat exchanger for heat rejection to the air stream. The TMS configuration and design envelope were consistent to interface with the Sundstrand EMA switch locations. The TMS hardware measured approximately 29.5 cm by 17.5 cm by 2.5 cm and weighs a total of 2.37 kg including 418 gm of PCM. The material for the housing, internal fins and the plate fin heat exchanger was 6061-T6 aluminum alloy. The PCM cavities located between the housing internal fins were filled with a 6061 DUOCEL® aluminum foam fill with a volume void fraction of 88 per cent. The entire structure is brazed which provides good thermal contact between the various sub-elements. During the course of the study a variety of different PCM candidates were evaluated and tested. The PCM candidate selected was a fully refined paraffin wax (ShellWax 200) with a melting point of 50 C. The PCM was introduced through fill ports located on the ends of the housing.

Table 1. TMS Design Features

Parameters	
TMS Housing	
Material	6061-T6 Al
Dimensions	29.5 cm ×17.5 cm ×2.5 cm
PCM Mass	418 gm
Total TMS Mass	2.37 kg
Air Heat Exchanger	Wavy Plate Fin Design
Material	6061-T6 Al
Fins per inch	27 fins/inch
Fin Thickness	1 mm
Fin Height	9.5 mm
Fabrication Braze	4047 Al Braze Alloy

THERMAL DESIGN AND ANALYSIS – The thermal analysis evolved in complexity and sophistication as the program progressed. Earlier in the program a SINDA thermal model was used to assess the overall system performance and establish the design features based on extensive trade studies. An independent thermal study was also conducted by Shanmugasundaram, Brown and Yerkes (Ref. 4) using a commercial finite element based CFD code (FIDAP). Their study independently confirmed the sensitivity of the key design parameters that were established in the early design phase of the current work. Both studies confirmed that a high fin effectiveness coupled with a large heat transfer surface to volume ratio are required to achieve effective thermal transport into the phase change material.

The important aspect established in the current study was how this feature was implemented into the design. Our approach was to use an optimized straight fin design to effectively transfer the nominal thermal power from the heat source to the air cooled heat exchanger. In addition, the region between the straight fins is filled with an aluminum foam to enhance the thermal transport into the PCM by the high heat transfer surface area to volume ratio of the foam. The aluminum foam provides a very high (nearly 2000 m^2/m^3) heat transfer surface to volume ratio and a very small 1.27 mm cell size. These design features allow efficient thermal transport into the PCM and provides a fast thermal response.

Table 2 provides the thermal design parameters selected for the full size test TMS hardware based on extensive trade studies. Following the optimization of the final design features detailed thermal analysis was conducted. The fidelity of the thermal analysis included a full three dimensional transient model that incorporated the effects of the phase change transition, convective boundary conditions, complex internal conduction paths and the local heat input sources. **Figure 3** provides the schematic of the housing showing the overall structure and the locations of the switches. The cross hatched region is the representative section used in the detailed 3-D transient finite element thermal modeling.

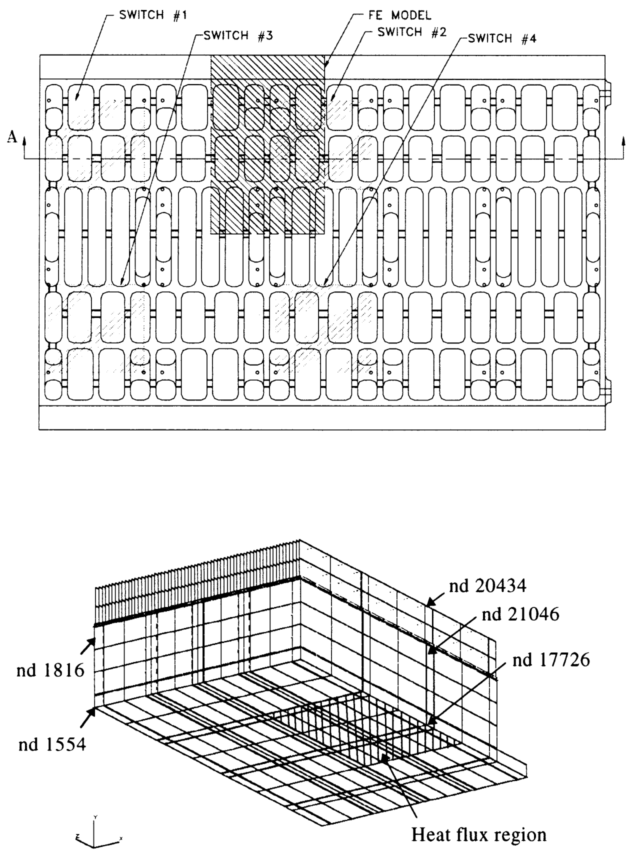

Figure 3. Switch Location, Internal Fin Structure and the Thermal Model Section

Table 2. TMS Thermal Design Parameters

Overall Storage Capacity	300 kJ
# of Switches	Ten
Peak Power	500 W/switch
Nominal Power	100 - 200 W/switch
Air-side	
Mass Flowrate	0 - 42 gm/sec
Inlet Temperature	20 - 30 C
Heat Transfer Coefficient	100 - 200 W/m^2-C
PCM	ShellWax 200
Melting Point	50 - 60 C
Latent Heat	240 kJ/kg-C
Conductivity	0.15 W/m-C
Cell Size	1.27 mm
Foam Cell Surface Area/Vol	1900 m^2/m^3
Housing Fins	6061-T6 Al
Fin Thickness	5 mm
Fin Length	20 mm
Fin Spacing	8-12 mm
Fin Conductivity	180 W/m-C

The thermal boundary conditions for the model section are adiabatic due to selected model symmetry and the insulated boundaries. The model represented by over 20,000 elements provides sufficient detail to evaluate the heat transfer from the localized input power beneath the switch into the housing fins, the PCM/foam core and the air cooled heat exchanger.

The thermal response characteristics are equally important as the energy storage capability in the design of the TMS. For the selected EMA application it was necessary to have a thermal time constant for the system on the order of 30-50 seconds. This allows the TMS adequate time to respond during the peak power excursions and effectively store the excess heat. **Figures 4** and **5** illustrates the predicted thermal response time characteristics for the selected TMS design. The calculated thermal time constant is approximately 50 seconds. **Figure 4** provides the response with no air flow to the TMS. The graph illustrates the ability of the TMS to effectively transport 200 W per switch into the structure and PCM for a period of 300 seconds before the junction temperatures exceed the design maximum of 100 C.

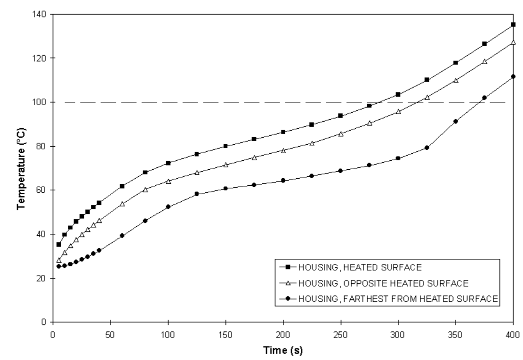

Figure 4. Thermal Response without Air Cooling

Figure 5 shows the same response with the design air flow to the TMS. The same 200 W per switch power level is effectively transported through the housing structure to the air cooled heat exchanger. The temperatures are maintained just slightly below the melting point of the PCM for this operating condition. The latent heat capability is not accessed and is still available for peak power thermal storage.

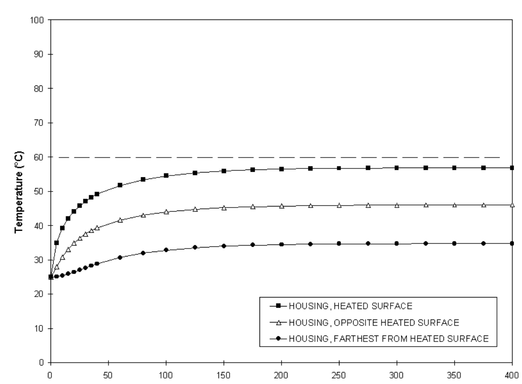

Figure 5. Thermal Response with Air Cooling

A thermal energy storage requirement of approximately 300 kJ was needed for the this application. This storage level allows the switch cooler to passively store the full power output (500 W per switch) from two switches for approximately 5 minutes without exceeding the temperature limits of the electronics. The overall effective storage capacity assumes the TMS is initially at 20 C and thermal storage continues until the junction temperature reaches 100 C. The available thermal storage includes: the sensible heat of the structure, sensible heat of the sold phase PCM, latent heat of the PCM and the sensible heat of the PCM in the liquid phase.

The selection of the thermal design parameters (fin thickness, fin height, fin spacing, cover thickness, foam pore size, foam void fraction, PCM type, PCM melting point, PCM mass, etc.) were made to optimize both the system performance and reduce the overall weight. The steady-state condition dominates the housing fin parameter selection since a high through-the-thickness structure conductance is necessary to maintain a low electronic junction temperature. During the low power mode of operation the PCM remains in a solid state and the latent heat storage capability is not accessed or utilized.

During the transient peak power operation the PCM must provide a sufficient amount of energy storage. The dominating design parameters include the mass of the structure and the PCM. These parameters also effect the low power steady-state performance. Adding more PCM mass with a proportional increase in the housing thickness or reduction in the number of internal fins will decrease the through-thickness conductance. Also the thermal response time may be adversely effected by the addition of more mass without the corresponding increase in heat transfer area to the PCM cells. These somewhat opposing design constraints were part of the trade-off studies in the selection of the overall design parameters for the selected application.

Figure 6 provides a snap shot of the transient temperature distribution as the peak thermal power penetrates into the TMS structure and the PCM. The relative symmetric temperature profile illustrates the effectiveness of the thermal design in achieving maximum penetration from the local heat source under the switch into structure. Detailed transient temperature profiles have been calculated showing the penetration of the transient peak power into the TMS structure for a variety of cooled and uncooled cases.

An alternative to achieve the same energy storage capacity is to use only the sensible heat of the structure. This would mean eliminating the PCM and increasing the structure mass to accommodate the same amount of thermal energy storage capacity. A calculation of this TMS alternative would result in a total mass of 4.44 kg compared to the 2.37 kg for the current system. This illustrates the effectiveness of the latent heat storage associated with the PCM design. The system weight is approximately one half of the purely sensible heat storage alternative.

TMS FABRICATION – The TMS hardware was fabricated by numerical control (NC) machining the internal fins into an aluminum base plate. The DUOCEL® aluminum foam was electro-discharged machined to closely fit into the fin spacing. The entire structure consisting of the housing, aluminum foam and the plate fin heat exchanger was all assembled and vacuum brazed in a single step. The fin locations were influenced by both thermal performance and the threaded insert locations required to mount the motor controller switches to the TMS cooler. Brazing was with a 4047 aluminum braze alloy in both sheet and paste forms.

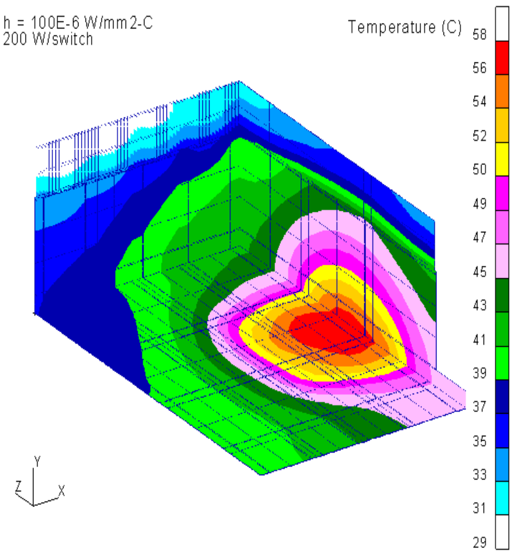

Figure 6.   Temperature Profile Distributions

Braze fixturing provided the proper alignment and loading to achieve a high quality, leak-tight braze close-out seal. The tolerances of the various TMS sub-elements were designed and fabricated to provide intimate contact of all surfaces upon completion of the braze cycle. The initial test article was cut and evaluated microscopically to validate the braze quality and thermal contact between the aluminum foam with the fins and cover plates. Two access ports were provided to leak check the housing and allow filling of the PCM.

A specialized procedure was developed to clean and evacuate internal foam structure prior to filling with the PCM in order to eliminate any potential contamination problems. The temperature at which the PCM was introduced to the housing was also evaluated and selected to result in the maximum amount of PCM mass and a minimum void upon cool down. Since the PCM has a over a 15 per cent density change between the liquid and solid state, filling at too high a temperature would cause significant shrinkage away from the foam and fin structure resulting in poor thermal performance. Filling at a too low of temperature would result in applying high internal pressure during peak operating conditions due to the constrained expansion. A fill temperature approximately

20 C below the expected maximum operating temperature was selected as optimum.

THERMAL TESTING – The TMS test hardware was fully instrumented with 12 thermocouples to measure temperatures at various locations throughout the structure and within the PCM/Foam cells. These locations were selected to measure and establish the thermal performance of the TMS, as well as compare and validate the analytical temperature predictions. Over thirty test runs were made at Sundstrand's Test Laboratory using actual motor controller switches mounted and powered on the TMS cooler. Tests were conducted for both cooled and uncooled conditions. A variety of air flow rates and switch power levels established the overall thermal performance of the concept under realistic operating conditions.

Figure 7 provides an example of the test data and its comparison to our predictions from the 3-D transient model. Both the measured temperatures and the thermal response characteristics are in reasonably close agreement (within 10%) with the predicted values. Considering the complexity of the mechanisms taking place (complex conduction pathways into the structure and phase change interfaces) the thermal results can be reasonably predicted with the models that have been established. The TMS was also demonstrated to be insensitive to orientation effects.

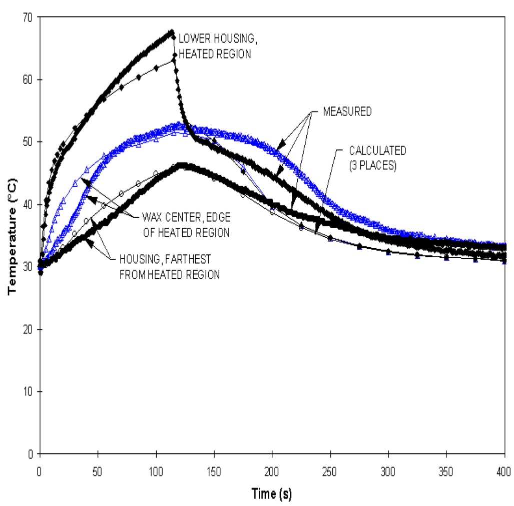

Figure 7. Transient Temperature Comparisons Between the Analysis and Actual Test Data

TMS APPLICATIONS – The TMS developed under this contract has application to a wide variety of applications for the MEA Initiative as well as other transient power applications. Direct application has been demonstrated for the EMA motor controller switch cooling. Other transient electronic power applications will require a simple tailoring of the design and configuration for the new set of thermal design requirements. The thermal model developed and validated in this program will assist in any redesign with a high degree of confidence.

CONCLUSION

The passive TMS described in this paper provides a unique concept that addresses the deficiencies typically found in prior integrated thermal transport and storage systems. The concept has been developed and analyzed to establish its performance capabilities and operational characteristics. Proto-type full size hardware was fabricated and successfully tested on realistic EMA components. Although the initial TMS has been validated for electric flight control actuator electronic components the concept has much broader applicability. The TMS with integral PCM provides a high thermal performance system with attributes of light weight, fast thermal response, high thermal energy storage capability, high reliability and low maintenance.

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