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# DEVELOPMENT OF ULTRA HIGH TEMPERATURE MULTI-HOLE PROBES

**G. BIDAN**
Safran – Etablissement Paris Saclay
Magny-Les-Hameaux, France

**J.-L. CHAMPION**
Safran – Etablissement Bordes
Bordes, France

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## ABSTRACT

SAFRAN TECH is developing a specific kind of multi-hole probe adapted to high temperatures measurements in turbomachinery. The probes are designed to be inserted in the inter-grid space of a gas turbine high pressure core. In this severe environment, metallic probes rapidly become unsuited due to elevated temperatures, high aerodynamic drag and limited available space. The proposed probe design is of a hybrid kind including a ceramic measurement head and a high strength metal body. The current paper proposes insights in the design process including 1-dimensional and 3-dimensional computations used for probe sizing. Steps of the development process are also discussed, including maturation of the production of the ceramic head, preliminary design, materials and assembly choices. The design, production and testing of the first complete prototype are also discussed.

## NOMENCLATURE

$N_u$ : Number of upstream blades
$N_d$ : Number of downstream blades
$N_G$ : Gas generator rotation speed
$N_{TL}$ : Power turbine rotation speed
$f_s$ : Vortex shedding frequency
$r$ : Radial direction
$\theta$ : Azimuthal direction

## INTRODUCTION

The high pressure core of aero gas turbine engine is a complex region to predict due to multi-physics phenomena and inter-modular interactions. Our understanding of the physics taking place in this region is usually limited partly because of our inability to obtain test data in relevant, representative test conditions. While combustion test rigs may produce relatively decent overall aerothermal conditions, representative of engine operations, they lack the interactions with downstream turbine stages and aero-acoustic boundary conditions they can produce. Turbine test rigs are at a greater disadvantage in terms of accuracy in operating conditions. Linear cascades allow for increased accessibility, at potentially high Mach numbers and operating temperatures. However they lack three dimensional effects of annular test sections and the characteristic secondary flow structures they produce that are predominant in turbine flow patterns. But most of all, they lack the physics associated with rotating stages and their interactions with adjacent stators though some attempts have been made to increase the representativeness of such rig with moving rods or plates [1] [2]. “Cold” turbine rotating rigs are more expensive to operate and provide reduced access compared to linear cascade rigs. Several levels of complexity can be found in the literature with various associated measurement types. Open loop low speed rigs such as the ones presented in [3] [4] [5] or [6] provide reasonably good accessibility and dimensions, but usually low Mach numbers. Close loop turbine rigs such as the ones in [7] or [8] allow for higher Mach numbers, often supersonics, but with decreasing access. Blow-down facilities such as the ones presented in [9] [10] and [11] are transient facilities with highly representative engine like conditions, but with limited resolution measurements due to extremely short testing duration, preventing detailed flow measurements. Finally, industry-owned cold turbine test rigs are used to validate engine, airfoils geometries and performances, but are often constrained by engine development programs, preventing exhaustive measurement campaigns. Noticeable is the NG-TURB test rig used in particular in the FACTOR FP7 project proposing semi-representative integration interactions between combustor and turbine, although in low temperature operating conditions [12].

In this context, Safran through its research center Safran Tech took upon itself to use a full scale engine as base for aero-thermal and thermo-mechanical investigations in order to better characterize and understand the physics in HP core sections. Using high resolution measurements, the BEARCAT program (for Banc d’Essai Avancé pour la Recherche en Combustion et Aérothermique des Turbomachines) will provide steady and unsteady flow measurement database to be used in future CFD codes validation steps or as realistic boundary conditions for such computations.

In the frame of this project, heavy engine modifications have to be carried out, and new measurement equipment, adapted to engine operation have to be developed. Such is the case for the ultra-high temperature multi-hole probes which will be used in very severe conditions.

## BEARCAT RESEARCH ENGINE

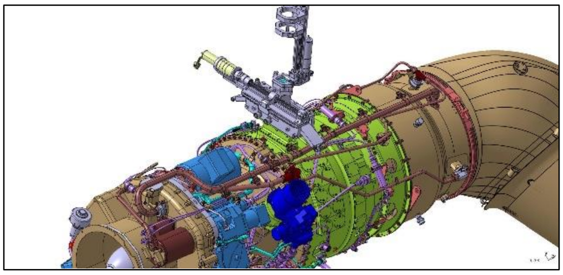

*Figure 1: BEARCAT research engine*

### Generalities

The BEARCAT engine is based on a MAKILA engine, a turboshaft developed by Safran Helicopter Engines and powering H215 and H225 Airbus Helicopters. BEARCAT allows both steady and unsteady flow measurements (velocity, static or dynamic pressure, temperature, chemical species…) coupled with mass temperature or local stress. A classical metrology allows the determination of detailed engine performances as well as the knowledge of the average experimental conditions generating investigated flows. Moreover, in order to characterize the turbulence, a specific attention is given to unsteady measurements such as, 2D/2C velocity measurements with LDA (Laser Doppler Anemometry), local temperature measurements by means of fine unsheathed thermocouples, pressure measurements with dynamic transducers, flame light intensity in the primary zone. These time-resolved measurements can be completed with time averaged measurements performed with multi-hole probes. Both types of data will be used to calibrate advanced CFD Models.

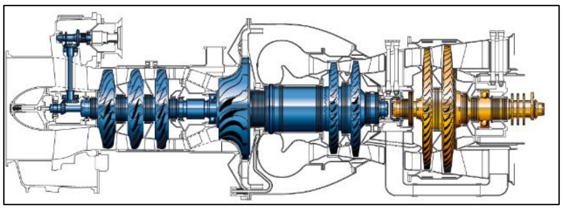

*Figure 2: SAFRAN HELICOPTER ENGINES MAKILA engine architecture*

### Architecture

The BEARCAT engine preserves the Makila engine architecture (Figure 2). The Makila 2 engine consist of an annular air intake, a gas generator, a two stage axial power turbine, an exhaust pipe and rear power transmission off-take. The gas generator has a three stage axial compressor and a single stage centrifugal compressor, driven by a two stage axial turbine, and an annular combustion chamber with centrifugal fuel injection.

### SAS and standard instrumentation

The BEARCAT engine carries out secondary air system instrumentation to provide purge flow data (pressure, temperature, flow rate) from all major contributors (cavities, shrouds…). Additional measurement points are added to increase engine aerothermal and thermomechanical understanding (Figure 3). The NGV1, NGV2 and inter-turbine duct are equipped with extra thermocouples and pressure taps while the HP turbine stage 2 is equipped with tip clearance sensors. The combustion chamber wall is fitted with thermocouples and pressure taps for aerothermal measurements, while the casing carries out high frequency pressure taps.

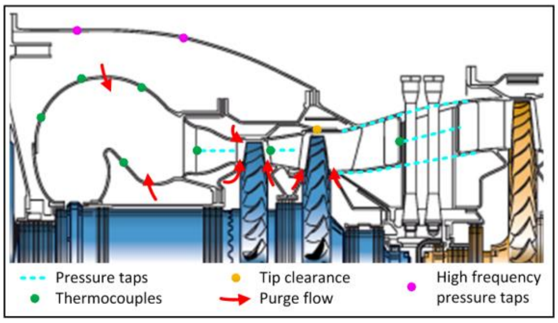

*Figure 3 : BEARCAT SAS and standard instrumentation*

### Innovative measurements

Innovative measurement methods are implemented in the BEARCAT test rig to obtain spatially and temporally high resolution data (Figure 4). Physical access is provided to three major engine planes (3020, 3950 and 4400) in such a way that measurements are possible on 20° annular sectors. In these planes, total temperature, total pressure and flow direction are measured using 5-hole probes while 2 components Laser Doppler Anemometry (LDA) is carried out in order to obtain high frequency velocity measurements to better characterize turbulent length scales. In the combustor primary (3250) and dilution (3760) zones, 10 physical accesses (5 in each plane) are provided to carry out temperature measurements and chemical species analysis through radial explorations to better characterize physics associated with combustion. Finally, in the 4140 and 4340 inter-stage planes, 10 physical accesses (5 in each plane) are provided for 3-hole probe and temperature measurements through radial explorations to acquire total pressure and total temperature profiles.

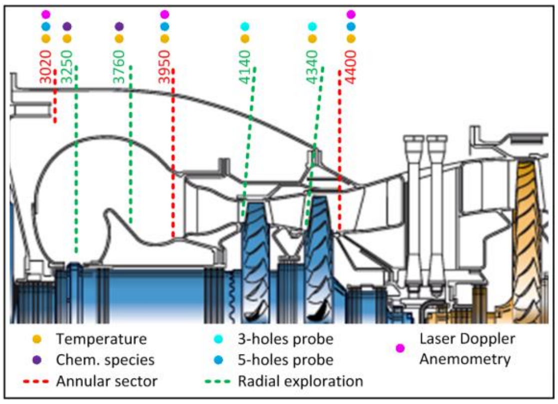

*Figure 4: BEARCAT innovative measurements*

These last kind of measurements require specific 3-hole probes capable of sustaining high Mach number flow under high thermal load for extended period of times, hence the development of ultra-high temperature multi-hole probes.

Innovative measurement techniques require traversing in order to acquire data at precise locations within annular sectors or radial traverses. A specific 3 axes 2 stages traverse system is also developed to move the probes in the r-θ plane as well as rotate them along their axis of symmetry.

## ULTRA HIGH TEMPERATURE PROBES

### Requirements

Inter-stage measurements for the BEARCAT engine require probes capable of operating in flows between Mach 0.6 and 0.8, at temperatures above 1100°C, and that can fit into small inter-stage clearance areas. Additionally, integration constraints prevent the probe from being supported close to the turbine shroud.

Traditional multi-hole probes made of Nickel base metals can withstand temperatures up to 900°C but material properties are severely degraded above that point. Preliminary calculations sizing a metal-based probe in the BEARCAT engine conditions lead to excessively large probe diameters, incompatible with integration constraints. An alternative solution involving an all ceramic probe was then considered. While ceramic material properties usually do not degrade as rapidly as those of metals, their flexural strength is typically low. Therefore, taking into account integration constraints and material properties led again to an oversized probe. An alternative solution was identified involving a ceramic-metal hybrid probe design.

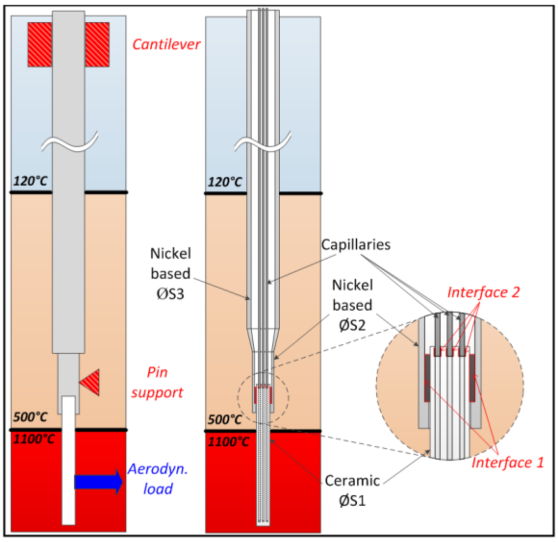

*Figure 5: UHT Probe design principles*

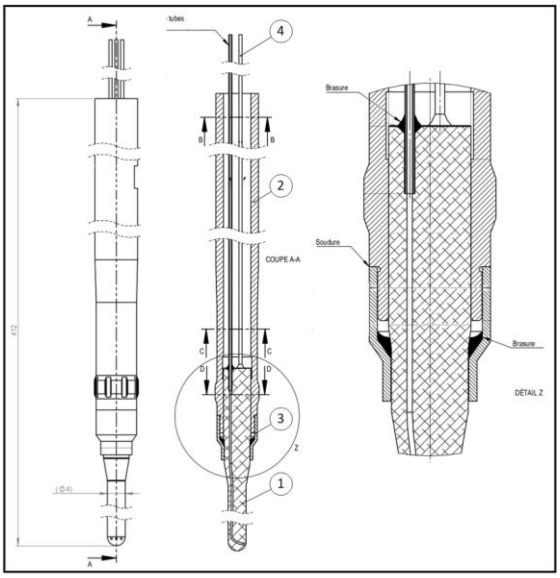

*Figure 6: UHT Probe prototype geometry*

### Concept

The hybrid probe design uses ceramic materials in the hot sections of the engine and metallic parts in sections where the temperature is more reasonable (Figure 5). Capillaries are used to transfer the pressure signal from the probe head to the pressure transducers. Two interfaces are defined, the first one (interface1) between the ceramic head and the metallic body, the second one (interface2) between the ceramic head and the capillaries. The functions and requirements for interface1 are to:

- transfer mechanical load from the ceramic head to the metallic body
- prevent the ceramic head from dropping into the engine.

The functions and requirements for interface2 are to:

- attach capillaries to the ceramic head

- ensure no loss of pressure signal between the ceramic head and the capillaries.

## Design

The retained design (Figure 6) at this stage includes 4 parts:

- Ceramic head (1) used to withstand high temperatures and communicate the pressure signal from the measuring point to the top of the part. The part is made of Alumina and produced using additive manufacturing. The wetted area has a maximum diameter of 4mm.
- Nickel based alloy body (2) used to withstand flexural load. The body has multiple sections to optimize space.
- Ferronickel alloy intermediate body (3) used to link parts (1) and (2) and accommodate the drastically different thermal expansion coefficient of both parts materials.
- Nickel capillaries (4) used to transfer the pressure signal from the top of the ceramic head to the exterior of the probe. Nickel was chosen for its greater thermo-mechanical compatibility with ceramic based materials.

The interfaces 1 and 2 between respectively the ceramic head and the intermediate body and the ceramic head and the capillaries are realized using brazing process, while the one between probe and intermediate bodies is done using welding.

## Design protocol

Probes are designed individually for each plane, taking into account specific thermodynamic conditions. The design process contains 3 steps:

- Thermal computations to establish the temperature field in the probe at the most demanding design point
- Thermo-mechanical computations to establish overall probe deflections and material stresses in each constitutive part of the probe
- Modal analysis to evaluate the probe dynamics and ensure they are compatible with engine principal frequencies.

The thermal computations are carried out using Ansys Workbench. The thermal load is evaluated in the main flow section using the thermodynamic data available. Heat exchange coefficients are computed using Churchill & Bernstein correlation for cylinders in cross-flow [13]. In the sections where the probe is traversing the secondary air system, Colburn correlations are used. The resulting temperature field (Figure 7) is used to first ensure that the brazed areas remain within acceptable temperature range, and second as thermal load for the thermo-mechanical computations.

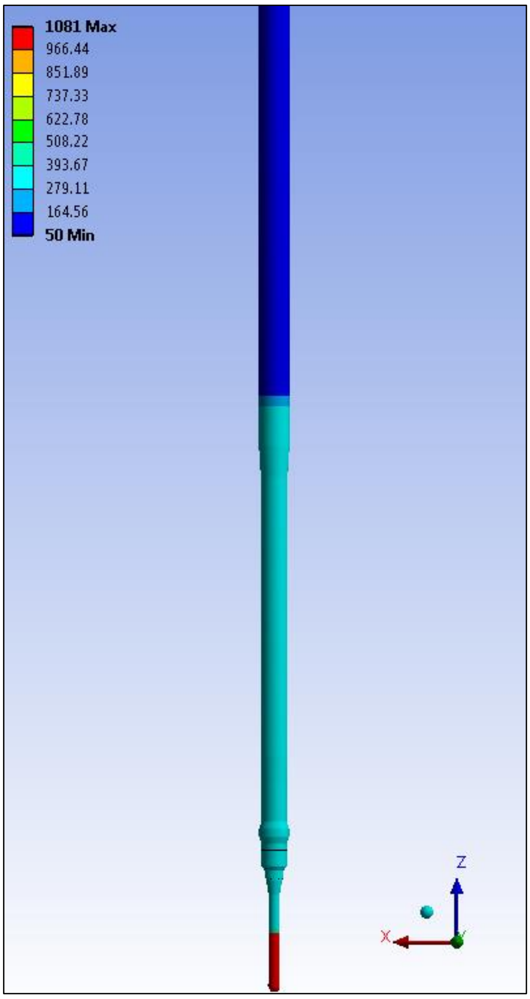

*Figure 7: Temperature field from thermal computations*

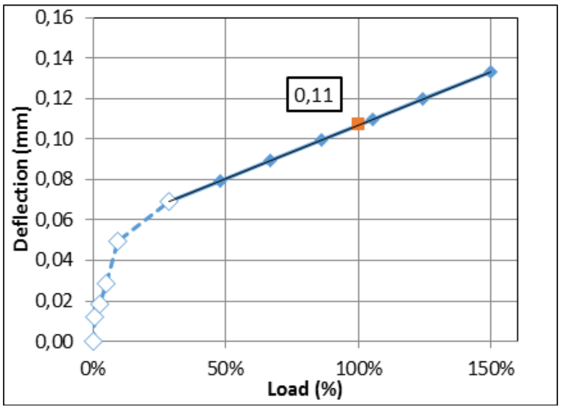

*Figure 8: Probe deflection projected on engine axis*

The thermo-mechanical computations are carried-out using Ansys Workbench. Thermal load from the thermal computations temperature field is directly imported, while aerodynamic load is computed from cylinder in cross-flow drag coefficient available in [14]. The resulting deformation and stress field are then investigated for probe clearance computations (Figure 8) and probe sizing based on stress levels (Figure 9).

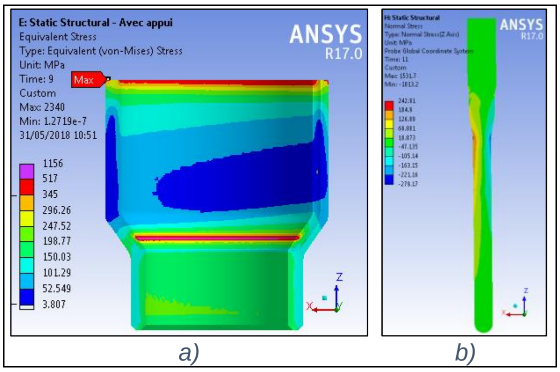

*Figure 9: Stress levels in probe parts a) intermediate body; b) ceramic head under 100% load*

Modal analysis is conducted using Ansys Workbench. The probe geometry and mechanical loading are extracted from the thermo-mechanical computations. The resulting natural frequencies are then represented onto a Campbell diagram to evaluate potentially harmful crossings with engine orders. The investigated engine orders are the 1Nx, 2Nx on both shafts, and the $N_uN_G$, $N_dN_G$ as well as the $(N_u\text{-}N_d)N_G$. The shedding frequency of vortical structures from the probe head is also monitored so as to prevent probe auto-excitation.

At this stage, probes have been successfully designed for all high temperature planes with deflections at tip compatible with engine integration and theoretical stress levels sufficiently low that probe health is not at risk. The dominant natural frequencies are found to be outside 1Nx and 2Nx engine orders and crossings are usually found between high order flexion modes and high engine orders. These crossings will be re-evaluated on the probe and traverse integrated system, which can have a significant effect on high order modes, during the prototyping stage described later on.

## Testing

Testing was conducted on several key elements of the design to demonstrate feasibility and evaluate key design parameters.

In a first stage, the strength of the metal to the 3D printed ceramic brazed bond was quantified using pseudo ASTM standard testing since due to the specificity of the printing process, the standard ASTM geometry could not be produced for the ceramic samples. Tests showed that using different metallization methods (manual deposition of vapor deposition) the 3D printed ceramic to metal bond exceeded the minimum expected strength of 43MPa (Figure 11).

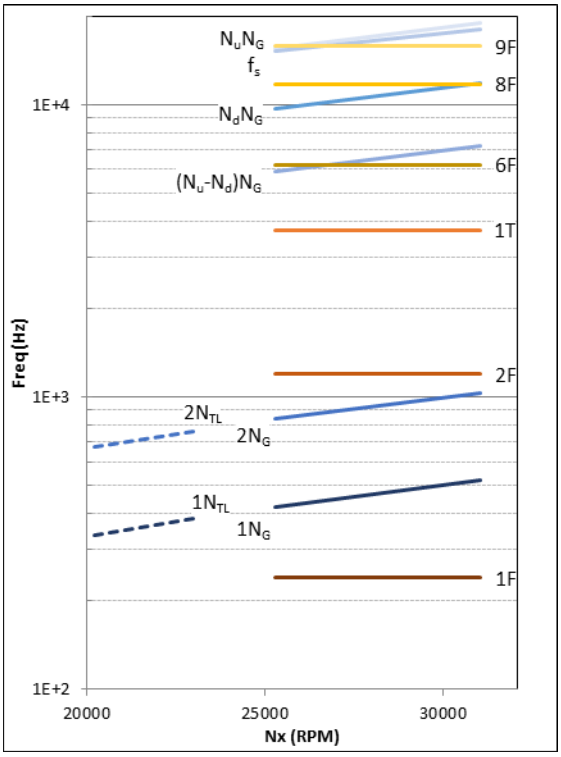

*Figure 10: Campbell diagram of UHT Probe*

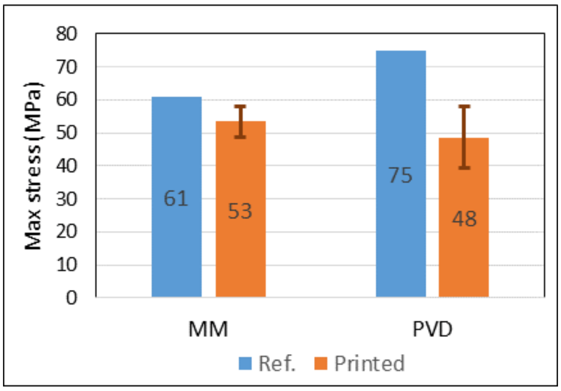

*Figure 11: 3D printed ceramic to metal brazed bond measurements*

The flexural strength of raw 3D printed ceramic rods was also evaluated using cantilevered bending testing. These tests provided average flexural strength of 350MPa.

The endurance of the 3D printed ceramics to cyclic thermal loading, high temperature gradient and rapid temperature drops were evaluated using hot air canon test rig (Figure 12), lamp furnace and halogen lamp test rigs. The hot air canon tests showed the probe head could withstand high number of thermal cycles while the lamp furnace and halogen lamp tests showed the probe head could withstand high temperature load of 960°C, severe temperature gradients of 25°C per mm and rapidly changing temperatures at a rate of 25°C per seconds when increasing, and -15°C per seconds when decreasing.

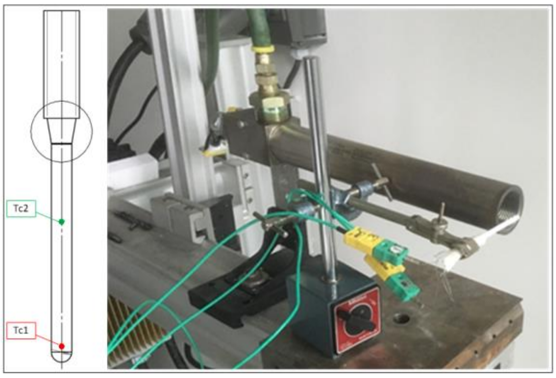

*Figure 12: Hot air canon test rig*

*Table 1 : Thermal loading tests results*

| Hot air canon | |
|---|---|
| Max. temp (Tc1) | 590°C |
| Diff. temp (Tc1-Tc2) | 400°C |
| Max gradient | 20°C/mm |
| Max rate | 18 / -8°C/s |
| #Cycles | 180 |

| Lamp furnace | |
|---|---|
| Max. temp (Tc1) | 960°C |
| Diff. temp (Tc1-Tc2) | 660°C |
| Max gradient | 25°C/mm |
| Max rate | 25 / -15°C/s |
| #Cycles | 3 |

| Halogen lamp test rig | |
|---|---|
| Max. temp (Tc1) | 900°C |
| Diff. temp (Tc1-Tc2) | 575°C |
| Max gradient | 22°C/mm |
| Max rate | 25 / -15°C/s |
| #Cycles | 20 |

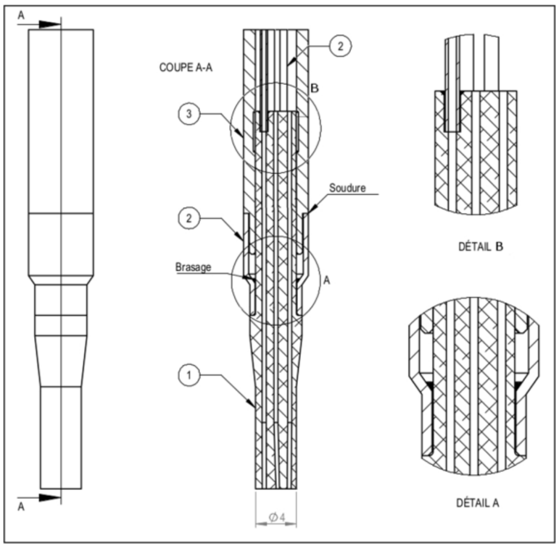

*Figure 13: UHT Probe demonstrator design*

Once the previously mentioned key physical parameters were evaluated, the integration process development was started. Development was carried out on elementary demonstrator (Figure 13) containing all constitutive elements of the full probe design yet in a reduced package for easier handling. Development steps included:

- Adjusting printing parameters to obtain ceramic head geometries within tolerances
- Adjusting rectification steps to obtain dimension tolerances compatible with brazing process
- Adjusting metallization process
- Adjusting brazing process for capillaries and inter intermediate body
- Assembly of the constitutive elements

*a)* *b)*

*Figure 14: UHT Probe demonstrator assembled*

*Figure 15: UHT Probe demonstrator mechanical testing*

The demonstrator was successfully assembled (Figure 14) and subjected to mechanical testing to evaluate the maximum strength of the pre-stressed assembly (Figure 15). The results of the test showed that brazed 3D printed ceramics could withstand flexural load up to 250MPa. The assembled demonstrator was also subjected to Rapid Change Temperature testing between -65°C and 200°C to evaluate the resilience of the ceramic head, brazed bond and its sealing capacity. After 20 cycles, the demonstrator capillaries were still airtight when subjected to helium leak test.

## CONCLUSIONS

The objective of the BEARCAT engine project is to constitute an experimental database of aerothermal quantities encountered in aero-engines HP core sections in order to provide validation data as well as realistic boundary conditions for future high fidelity computation codes. The BEARCAT test rig is heavily instrumented with standard measurement devices (thermocouples, pressure taps, capacitive clearance sensors…) as well as innovative measurement equipment such as laser Doppler anemometer, and in house developed ultra-high temperature probes.

A hybrid ceramic/metal probe design has been proposed. It uses a 3D printed ceramic head, brazed to Nickel-based alloy body via Ferronickel intermediate body. The elementary probe requirements have been verified trough mechanical and thermal testing, allowing to evaluate key design parameter such as ceramic flexural strength and thermal fatigue resistance. A demonstrator has been developed to adjust fabrication and assembly process parameters. The demonstrator was subjected to thermal and mechanical testing to validate its design. Finally, a design methodology was defined, allowing to evaluate engine integrated probe deflection and internal stress confirming the compatibility of the proposed probe design with engine integration.

Future work involves the production of full scale prototypes and engine-like condition testing including mechanical loading under room temperature as well as engine representative thermal loading, vibration testing…

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