Executive Summary:
In the past, vibration based energy harvesting at low frequencies (<100Hz) using miniaturized, integrated devices has proven to be difficult to achieve because of the properties of the materials that the devices are fabricated from. In particular the stiffness of conventional silicon and all piezoelectric materials makes it exceedingly difficult to make a system that can operate at these low frequencies. There are many sources of these low frequency vibrations including, human motion, vehicle engines, ship motion, winds and waves; therefore an Energy Harvester (EH) that can operate in this frequency range would have a large commercial potential and considerable opportunities for future exploitation. This multi-disciplinary project proposal provides considerable scope for innovation because it addresses the lack of durable, energy harvesting based power supply systems in this frequency range. The primary objectives of the project are the development of materials and structures for the two core components of a low frequency vibrational energy harvester:

- A low frequency, tuneable, energy harvesting device and
- A compact high energy density supercapacitor

These two primary objectives present a range of novel and substantial materials challenges in both making the components and achieving an extended and reliable power supply that has a very long, ideally infinite, unattended operational lifetime.

Self powered electronic systems using the device concepts that can be implanted into the human body is the application area that we have targeted for demonstration of this technology. We have selected this because it has a clear set of requirements for miniaturisation, energy density, efficiency and high reliability which will drive and challenge materials selection and processing, as well as providing design parameters for the design, fabrication and test of the components under consideration.

Project Context and Objectives:
In the past, vibration based energy harvesting at low frequencies (<100Hz) using miniaturized, integrated devices has proven to be
difficult to achieve because of the properties of the materials that the devices are fabricated from. In particular the stiffness of conventional silicon and all piezoelectric materials makes it exceedingly difficult to make a system that can operate at these low frequencies. There are many sources of these low frequency vibrations including, human motion, vehicle engines, ship motion, winds and waves; therefore an Energy Harvester (EH) that can operate in this frequency range would have a large commercial potential and considerable opportunities for future exploitation. This multi-disciplinary project proposal provides considerable scope for innovation because it addresses the lack of durable, energy harvesting based power supply systems in this frequency range. The primary objectives of the project are the development of materials and structures for the two core components of a low frequency vibrational energy harvester:

- A low frequency, tuneable, energy harvesting device and
- A compact high energy density supercapacitor

These two primary objectives present a range of novel and substantial materials challenges in both making the components and achieving an extended and reliable power supply that has a very long, ideally infinite, unattended operational lifetime. The secondary objectives are:

- The necessary power management electronics to allow performance assessment and control of the core components
- Packaging technologies to integrate the components and electronics into a demonstrator that can undergo realistic reliability and biocompatibility assessment
- A study of component reliability and models that can project their lifetime
- An end of life study and an environmental impact assessment

Self powered electronic systems using the device concepts that can be implanted into the human body is the application area that we have targeted for demonstration of this technology. We have selected this because it has a clear set of requirements for miniaturisation, energy density, efficiency and high reliability which will drive and challenge materials selection and processing, as well as providing design parameters for the design, fabrication and test of the components under consideration.

Energy Harvesting - two energy harvesting systems were studied and fabricated:

- Piezoelectric MEMS: AlN on silicon and AlN on polymer cantilevers whose stiffness can be tailored to bring their resonant frequency into the desired frequency range of operation.
- Electrostatic MEMS: Multiple stacked layers of free standing metal electrodes which are connected to a proof mass and held in place by polymer springs that exhibit tuneable mechanical properties.

Charge Storage - one charge storage solutions was studied and fabricated.

- A super capacitor made from nanowires embedded in a polymer electrolyte. Coaxial metal oxide/metal (e.g. NiO/Ni, MnO2/Mn) nano-wire (NW) arrays will be developed to act as high performance electrodes for large value pseudo-capacitors.

This project targets electronic systems for implanting into the human body, where the most significant vibrational energy comes from either motion or heartbeat. Both of these vibrational sources lie off in the range 1-30 Hz and it is critical to tailor the design of the energy harvesting device to extract the maximum power from it, at these frequencies and accelerations. There are two distinct peaks in the energy spectrum of the heart from which energy could be extracted. One peak is at 1-5 Hz, which exhibits very high acceleration and a second higher frequency region with a lower but much wider plateau over the range 22-28 Hz.

This characteristic spectrum is very interesting for the energy harvesting concept because it provides two regions where the devices can be targeted towards. Both of these have merit because most MEMS based EH devices have a very narrow Q (~1Hz) which in many cases is difficult to tune to a specific application by design and layout, due to process and materials variability across a device wafer. In most applications the frequency of the vibrational source varies, but in an implanted device the frequency is consistently the same within 1-3 Hz, which takes advantage of the narrow Q (1Hz) of an EH cantilever device. This application shows two places where energy could be harvested, both of which will be fabricated in the project. In addition to the more conventional piezoelectric cantilever structures, a novel electrostatic transducer device will also be evaluated. Electrostatic transducers are effectively capacitors whose capacitances change due to external mechanical forces such as the acceleration on a surrounding proof mass. This change of capacitance can be converted into electrical energy by adapted charge-discharge electronic circuits.

- Target 1: A frequency range centred around 25 Hz which is considerably lower than many currently published structures but achievable using the approaches to be adopted in this project.
• Target 2: an even lower frequency, higher acceleration regime centred around 3Hz.

Project Results:
1 Description of the main S&T results/foregrounds),

1.1 Result 1: Development of organic-based piezoelectric actuator

The first task of TU Eindhoven was exploring the possibility of making a piezoelectric material to use as a cantilever in the pacemaker device using an organic/inorganic hybrid to combine the flexibility of organic polymers and the piezoelectric capabilities of inorganics. We developed two different hybrid systems: the first was more conventional, and involved embedding the common piezoelectric material PZT (lead zirconium titanate) in a flexible PA (polyamide) or PDMS (polymethylsiloxane) host material. The second, more experimental approach was to attempt to grow ZnO (zinc oxide) nanosheets within a porous LC network. Composite PA and PDMS harvesters 14 mm in diameter and 280-300 µm thickness were fabricated with the goal of achieving resonant frequency for collecting energy from heartbeats < 50 Hz.

The mechanical properties of the composite films were tested on a dynamic mechanical thermal analysis (DMTA) at room temperature, as the mechanical properties will determine the resonant frequencies and give insight into the long-term potential stability of the cantilevers. We developed stress-strain curves of the PZT/PA composites including the pure polymer and with ceramic volume fractions up to 40%. From the graphs it can be observed that the resulting strain decreases strongly with increasing volume fraction of PZT leading to increasing Young’s modulus, which ranges from 850 to 4450 MPa.

We determined the electrical performance of the hybrid films by collecting impedance data at room temperature in a frequency range of 50 Hz – 5 MHz in order to calculate the AC conductivity σ, relative permittivity ε and loss tangent tan δ of the composites. The piezoelectric charge constant d33 in pC/N was measured at a fixed frequency of 110 Hz, and the piezoelectric voltage coefficient g33 was calculated as a figure of merit for the piezoelectric performance. Both the d33 and g33 values of the PZT-PDMS composites increases continuously with vol. % of PZT. The maximum value for d33 and g33 are observed for the 50 vol. % composite, 25 pC/N and 75 mV m/N, respectively.

The good combination of the PZT/PA hybrid material properties, including reasonable permittivity, piezoelectric charge and voltage constants with low electrical conductivity, and low elastic stiffness, promotes the continued development of such cantilevers. Moreover, by varying the volume fraction, a proper balance in dielectric and mechanical properties for various applications can be realized. It is highly likely that other piezoelectric oxide particles can be incorporated in PDMS or in PA without having any porosity in a similar easy way, thereby increasing the applicability range. In previous work by TU/e it was shown that nanoporous liquid crystal (LC) networks can be used as a template for patterned silver nanoparticle formation. In the present study, we extend this concept to synthesize highly oriented ZnO nanosheets having thicknesses of only few nanometers in long range ordered LC materials to yield flexible piezoelectric plastics for electromechanical energy applications. Since the ZnO sheets are encapsulated within a plastic material, the bending or stretching of the piece of plastic should lead to a piezoelectric deformation and hence generate electrical current. LC networks having layered surfaces (a smectic phase) were used as a scaffold for oriented ZnO nanosheet synthesis. The anisotropic organic-inorganic networks were obtained from a mixture of hydrogen bonded monomer (I) and cross linker (II) and ZnO precursor zinc acetate. The monomer forms the layered LC film. When exposed to high pH, the hydrogen bonds holding the two halves of the monomer together break. To prevent the two sheets from dissociating entirely, the crosslinker spans the gap between the monomer layers to hold the system together. We used x-ray scattering to investigate the structure of the composite films and showed well-ordered lamellar arrangement with interlayer distance of the ordered polymer layer and ZnO sheet around 5.8 nm, higher than pristine smectic film (2.9 nm), suggesting integration of the ZnO in the pores.

Unfortunately, the stiffness of both organic/inorganic hybrid film types were deemed too low to be used alone as the piezoelectric cantilever in the pacemaker system. However, if the films could be alternatively applied to stiffer sublayers, perhaps even to the inorganic cantilever, they could find function in the energy harvesting system, especially if the second feature, the tunable stiffness of the LCs, could be exploited.

1.2 Result 2: Development of materials with tunable stiffness

The piezoelectric is used as an energy harvesting cantilever, vibrating at a frequency dictated by internal heart rhythms: the target is on the order of 20-30 Hz. However, all hearts are different, and we desired to design a system that can be frequency tuned at the moment of implantation to match the characteristic frequency of the specific patient. Ideally, one would use a non-invasive trigger to adjust the frequency of the oscillation, such as light. We proposed using an organic material which can be stiffness-tuned by light at the moment of surgery to adjust the frequency. Flexible polymeric materials are typically better for biomedical implants because they can bend in order to fit into tight spaces and provide the desired properties. In order to tune the frequency response of the cantilever in the pacemaker, a combination of LC polymers was utilized. The LCs are anisotropic materials, with one axis appreciably longer than the
other axis. The LCs used contain three distinct components:
1. A reactive acrylate end group that takes part in the polymerization reaction
2. A spacer unit that separates the core of the mesogen from the polymer.
3. A core component usually composed of cyclic structures such as benzene, cyclohexane, or heterocyclic rings.

Acrylate mesogens were used in this project to form the nematic LC network. In the nematic phase the molecules do not have positional order but tend to point in the same direction (along the director). The polymerized monomers form densely crosslinked films via photo polymerization of the end acrylate groups: the physical properties of the LC network vary with the average alignment with the director. Normally, one would add an azobenzene compound to the nematic LC network to modify macroscopic properties of the film upon light exposure. The azobenzene undergoes a trans-cis isomerization upon illumination by UV light. This bending deforms the LC network, and we wished to show that this disruption results in an alteration of the elastic moduli (stiffness) of the films. However, most azobenzene chromophores require UV and visible light to induce trans to cis and cis to trans isomers, respectively. The use of highly energetic UV light can be harmful for surrounding molecules and biological systems. Therefore, a new visible light (blue and green light) responsive soft actuator has been developed using a combination of o-fluorozobenzenes as a photochromic molecule within a nematic LC polymer network for use in the human body. The trans-cis and cis-trans photoisomerization of the azo dye were carried out by green and blue light, respectively.

The photoisomerization of the F-azo in the LC networks with green and blue light were monitored using UV-vis spectroscopy. The spectra show that azobenzene exist mainly in more thermodynamically stable trans isomer in the rest state. When we exposed polymerized films containing the F-azo to sunlight, we were surprised to note the film started continuously oscillating, a process heretofore unknown in the literature. Analysis of video footage revealed a non-linear bending behavior of the cantilever, indicating chaotic actuation. After considerable study of the system, we determined the process is a delicate interplay between local heating of the network to around the glass transition temperature, the relative population of cis- and trans-conformers, and other features. It was determined continual actuation required constant light exposure to at least two different wavelengths, as we could recreate the oscillation seen in sunlight only after exposure to both green and blue light simultaneously. We also determined this oscillatory feature was common to probably all azobenzene systems, as use of simultaneous blue and ultraviolet light produced similar oscillations in regular azobenzene-doped LC systems.

A sample film was placed in the DMTA and measurements made under condition of blue light exposure, green light exposure, and to combine blue and green light. For the first time, we show a multi-wavelength tunable film, capable of generating four different stiffness values depending on the wavelength of light utilized. The difficulty for application of this LC network as a free standing film is that azobenzene reverts to its original conformation after exposure to visible light or temperature. However, this phenomenon may be different on the fixed cantilever supported films. It has been shown in the literature that the deformation can be changed from reversible to irreversible by changing the concentration of inhibitor from 0.1 to 2 wt % on glass supported films. The inhibitor controls the kinetic chain length of the network and allow out of plane reorientation of the azobenzene and a corresponding loss of molecular order. We have provided films to the program to examine light responsive behavior of the LC network on solid supported films and await the results.

Summary

We have explored a number of different materials to be used as cantilevers and as coatings for cantilevers in a self-powering pacemaker architecture. We conclude an organic based cantilever using the materials described in this work would only be possible on the longer term. However, application of organic-based layers to existing piezoelectric cantilevers has good potential, in that the material properties can be tuned by application of light in situ, allowing tuning of the vibrational frequency to match the particulars of the heart, and that multiple frequencies could be achieved with one fluorinated azobenzene doped LC host exposed to one or a plurality of light sources. Finally, the use of fluorinated azobenzene allows the use of visible light for tuning, moving away from ultraviolet light which is generally detrimental to human tissues.

This work resulted in the publications: Kumar, K., Schenning, A.P.H.J. Broer, D.J. & Liu, D., “Regulating the modulus of a chiral liquid crystal polymer network by light”. Soft Matter, 12, 3196-3201 (2016) and Kamlesh Kumar, Christopher Knie, David Bléger, Mark A. Peletier, Heiner Friedrich, Stefan Hecht, Dirk J. Broer, Michael G. Debije, and Albertus P. H. J. Schenning, “A chaotic self-oscillating sunlight-driven polymer actuator”, Nature Communications 7, 11975 (2016): the latter has garnered considerable national and international interest:

1.3 Result 3: A Supercapacitor

Supercapacitor is a fast charge-discharge capability energy storage device, which can deliver high power density and afford long...
lifetime beyond 10,000 cycles. On the other hand, battery has a good energy density which can store huge amount of charge, but only with limited power density and lifetime up to 1000 cycles. In order to store plenty energy from the heartbeats and deliver sufficient power during the emergency, a hybrid device called supercapattery has been designed. Supercapattery, a Faradaic electrochemical storage system, should have good electrical conductivity and capability to store large amount of charges and high power density with long term stability up to 20 years. Electrode material along with the electrolyte determines the charge storage characteristics of a supercapattery. Nanostructure morphology of the electrode material can bring drastic variation in capacitive nature of electrode material. Due to the high surface to volume ratio of the nanostructure, the specific surface area of the electrode material can be increased and consequently increasing the capacitive nature of the storage device. With the aim to assemble the cylinder type devices, we designed hybrid nano/micro structure on carbon fibre cloth (CFC) as supercapattery electrode. Different composition of nanostructure materials have been fabricated on carbon fibre cloth (CFC) via a simple hydrothermal method without any template or surfactant. Nine different types of electrode materials were fabricated in the past 33 months. Among the flexible carbon fibre cloth supported materials, NiO/CFC presents the best specific capacitance of 1522 F g-1 and a good cycle stability of 91% after 2,500 cycles. To increase the surface area, nickel foam was used as non-flexible substrate. Co3(PO4)2/ NF showed the highest specific capacitance of 1990 F g-1 and cyclability of 90.5% after 5,000 cycles. NiO-In2O3/NF showed a good voltage window of 0.7 V. Co3(PO4)2·8H2O / NF delivered the highest energy density of 99.9 Wh kg-1 as a single electrode.

Four symmetric supercapattery devices and two asymmetric devices were fabricated using six different materials, which were fabricated during the project. Overall, the nickel foam (NF) supported materials presents better electrochemical performance than the carbon fibre cloth (CFC) supported materials. Symmetric supercapattery devices were fabricated with NiO/CFC, Co3O4/CFC, CoMoO4/CFC and NiO-In2O3/NF nanoelectrodes and their capacitive performance has been evaluated. Two pieces of electrode were sandwiched by separator. Asymmetric devices were fabricated using activated carbon (AC) as the negative electrode and Co3(PO4)2·8H2O/NF and Co3(PO4)2/NF as the positive electrode. Among the six devices, Co3(PO4)2/NF//AC asymmetric device delivers the highest energy density of 43.07 Wh kg-1, and the NiO-In2O3/NF symmetric device offers the highest power density of 9624.5 W kg-1. These two devices showed a good cycle stability of 84% after 20,000 cycles and 79% after 50,000, respectively. Moreover, the CoMoO4/CFC presents a large voltage window of 2.5 V using 1 M TEABF4/PC as organic electrolyte. To use the supercapattery device for manpower project the complete supercapattery was designed. The NiO/CFC and Co3O4/CFC electrode based symmetric supercapattery was investigated both in the 3 M KOH and organic electrolyte (tetraethylammonium Tetrauoroborate (TEABF4) in propylene carbonate (PC)). Both electrodes exhibited a large voltage window of 2.4V in organic electrolyte, which is close to the requirement. The best performance (NiO/CFC in 3 M KOH) of the four different types of packed supercapattery devices shows the specific capacitance value of 29.3 μFmm-3 with the 2.6 nWhmm-3 of energy density. The observed energy density was comparatively lower than the required for the MANpower project at the moment. This is mainly due to the issues related to the CFC substrate stress during bending and corrosion of Cu leads. These problems will be overcome by the necessary actions. Both electrodes shows good cycle stability in 3 M KOH electrolyte over 10,000 cycles.

1.4 Result 4: Piezoelectric Energy Harvester

Piezoelectric Material- Tyndall National Institute was involved in developing new hybrid piezoelectric materials consisting of a polymer substrate and a piezoelectric material. A polymer substrate was necessary in order to lower the resonant frequency of a cantilever to values required for excitation from the heart. The group had previously developed a method for depositing high quality Aluminium nitride (AlN) on silicon substrates and had also demonstrated initial results on depositing high quality material on semi-crystalline polyimide substrates. However, the AlN quality on the polyimide substrate was inferior to material deposited on silicon, and had piezoelectric properties about 4x lower. The goal of this aspect of the project was to investigate other polymer materials that could be used that would result in high quality piezoelectric AlN.

It is well known that the quality of the AlN material is dependent on the crystallinity and crystal lattice mismatch of the underlying layers and substrate material. Therefore, the team investigated the use of crystalline or semi-crystalline polymers. The team identified one particular class of polymers that are widely used in MEMS fabrication and biomedical devices that could be used. First, we investigated methods of altering the materials crystallinity by annealing the polymer under specific conditions. We determined that it was possible to alter the crystallinity of the polymer quite significantly and this process was repeatable. By using a specific chemical alteration of the base polymer we were able to create a more crystalline polymer which could not only increase its crystallinity up to 90%, but it could also go through a phase transition. By going through this phase transition the polymer went from a monoclinic structure to a hexagonal structure, which is the ideal structure for promoting AlN growth.

Next we successfully demonstrated that we were able to deposit AlN on the polymer, and that we were able to get high quality film that was similar to material deposited on silicon substrates. However, the process for depositing the high quality AlN on the polymer had other disadvantages which made integrating the material into a fabrication process difficult. Therefore there is a trade-off that is required between quality of film and integration into a fabrication process. In addition the AlN deposition process was altered to allow...
We investigated different chemical composition of the electroplating baths and we optimized the electroplating current density and the deformation of the 3D microstructures when the sacrificial material was etched away and they were detached from the substrate. Another manufacturing challenge was to reduce as much as possible the internal stress of the structural material in order to minimize substrate during the Chemical Mechanical Polishing process enabling fine-tuning of the thickness, flatness and rugosity of each layer. One of the main manufacturing challenge was the polishing step. For this purpose, we developed a specific tool for holding the 3D structures were manufactured by successive electroplating of several layers of structural and sacrificial metals, respectively Nickel and Copper.

1.5 Result 5: Electrostatic Energy Harvester
Materials for the Electrostatic Energy Harvesting Device- The Institut d'Electronique Fondamentale of Université Paris-Sud developed a new process for manufacturing a 3D Electrostatic Energy Harvesting device. This process was based on electroplating and CMP steps. 3D structures were manufactured by successive electroplating of several layers of structural and sacrificial metals, respectively Nickel and Copper.

One of the main manufacturing challenge was the polishing step. For this purpose, we developed a specific tool for holding the substrate during the Chemical Mechanical Polishing process enabling fine-tuning of the thickness, flatness and rugosity of each layer of a multilayer stack.

Another manufacturing challenge was to reduce as much as possible the internal stress of the structural material in order to minimize the deformation of the 3D microstructures when the sacrificial material was etched away and they were detached from the substrate. We investigated different chemical composition of the electroplating baths and we optimized the electroplating current density and
Electroplating of nonmagnetic metal was investigated in view of replacing nickel as structural material in case of MRI compatibility issue. We successfully developed the electroplating process of phosphorus-doped nickel exhibiting almost no magnetic properties. The saturation magnetization was as low as 1.5 mT and the remanent magnetization was 0.5 mT only (compared to 600 mT and 130 mT respectively for pure nickel).

Electrostatic Energy harvesting device- The Institut d'Electronique Fondamentale of Université Paris-Sud was in charge of developing an Electrostatic Energy Harvesting device that could harvest mechanical energy resulting from acceleration of the heart wall by inertial effect. The optimization focused on four points: maximization of the power output, resonance frequencies, limitation of mechanical stress for reliability, and optimal use of available space in the implant. The Electrostatic Energy Harvesting device was designed and optimized based on analytical and FEM modelling. Exploiting efficiently the very low frequency of the heart acceleration was a major challenge. The impulse nature of the acceleration signal led to develop a mechanical resonator with resonant frequency in the range of 15 Hz to 30 Hz, enabling thus to optimally exploit abundant harmonics in this frequency range.

The studied 3D microstructure was composed of several interdigitated comb layers stacked. The optimization of the structure dimensions in terms of harvested power required to take into account the electronic interface of the electrostatic energy harvesting device. Indeed, this interface determines the exact nature of the energy conversion cycles and therefore the device performances. A behavioral model taking into account real heartbeat acceleration signals, including models of the Electrostatic Energy Harvesting device and the interface circuit was developed to optimize the system and predict its performances.

To reach the targeted power, as large as 1.8 mm peak-to-peak mechanical displacement of the moving part was required. For this purpose, we designed a specific shape of the suspension springs enabling to keep mechanical stress far below the limit of plasticity of nickel. In the same time, the design of the springs enabled to block all unwanted translations and rotations. The multilayer process previously developed was then used to fabricate the 3D Electrostatic Energy Harvesting Device. The first run of 5-layer prototypes exhibited excessive structural deformation after etching and releasing from the substrate. The design was then modified in order to counteract these deformations. A second run of 10-layers prototypes showed very satisfying improvements. At the final stage of the project, these prototypes were not entirely characterized, but mechanical characterization confirmed the possibility of obtaining 2 mm peak-to-peak displacement of the moving part of the device. Measured stiffness differed from less than 5% from the designed one. No sign of plasticity could be observed up to 4.6 mm peak-to-peak displacement of the moving part. At this stage of the Electrostatic Energy Harvesting device development, electrical performances were not experimentally tested. According to predictions given by the system behavioral model, the average output power of the energy harvesting system, including the interface circuit, should be around 10 microwatts.

1.6 Result 6: Electronic circuitry and systems for a self powered pacemaker

Electronic circuits for an efficient conversion of the harvested energy have been studied, designed, built up and evaluated with standard discrete components. These circuits will deliver the actual electrical power to the pacemaker system.

A circuit for the electro-static energy harvester device ("EEH circuit"), which contains voltage multiplier composed of diodes and capacitors, forming 1 to n cells, was patented by IEF/PSUD.

This EEH circuit was analysed, simulated and compared with circuits known from literature (Yen's circuit). It was theoretically shown that for e.g. Cmax/Cmin=2, the circuits with 2, 3 and 4 cells harvest respectively 4, 8 and 12 times more energy than circuits known from literature (Yen's circuit) for a given store voltage. At the same time, the ratio of Cmax/Cmin above which it is possible to harvest energy becomes lower.

IEF/PSUD has built up this circuit for an efficient energy harvesting on PCB by using a variable capacitor for simulating the EEH device and discrete elements. The electrical characterisation shows a very good agreement between experience, simulation and theory. A high power efficiency (> 75 %) for the harvesting circuit could be demonstrated from 100 nW to 10 μW average output power.

First studies for a miniaturization of the circuitry have been performed.

A scavenger circuitry - the so called Scavchip - provided as an ASIC die on wafer-level was bought from the French ASIC supplier EASiiIC within the project by Fraunhofer EMFT. After preparing the pads on wafer-level for soldering, this Scavchip can be combined by applying low temperature bonding processes like an ultra-sonic supported SLID (Solid-Liquid_Interdiffusion) process together with the circuits for the efficient energy conversion and the harvester devices for a system test.

3D PLUS has developed an innovative 3D stacking technology based on the stack of:

- several heterogeneous 2D high density PCB levels on which are soldered SMD components
- specific level with dies.

This stacking technology has been patented by 3D PLUS and is an alternative of WDoD (Wirefree Die on Die) 3D stacking technology.
already patented by 3D PLUS.

The module developed by 3D PLUS in the frame of this project allows to reach the objective of integration defined in this project with higher integration level than flex-folded solution for example

Fraunhofer EMFT developed an alternative approach based on silicon-interposer and wafer processing for integrating the electronic modules for sensing and pacemaker. Two silicon interposers with Through-Silicon-Vias (270 µm x 270 µm) filled by melted Sn-balls have been processed. The wiring of the circuit and the definition of the pads for assembly is performed by Cu-electroplating. After assembling of the interposer by conventional SMD technique using a fine-placer equipment the two interposer will be glued together by using an anisotropic conductive glue.

Together with the CIT a strategy for electrical measuring the reliability of the TSV-based connections has been developed and appropriate test structures have been implemented into the masks. After filling of the TSVs by the melted Sn-balls and testing the edge coverage of the Cu-plating over high topographies an adequate reliability of this silicon interposer module is expected.

For the overall package of the pacemaker system a concept was developed by Fraunhofer EMFT which is based on the cylindrical symmetry of the pacemaker capsule. Ceramic disks on which silicon dies can be mounted, which can be assembled by the different components energy harvester, super-cap, electronic scavenger circuitry and electronic module for sensing and pacemaker. A thin polyimide-foil with electroplated Cu-lines provides the electrical connection within the tube.

1.7 Result 7: Reliability

MANpower WP5 focused on reliability, durability and biocompatibility of the MANpower pacemaker and its mechanical and electronic components. To predict the reliability/durability of any component, we need to know three things: the reliability/durability vulnerabilities of the component, the reliability/durability stresses the component is exposed to, and how these vulnerabilities and stresses interact to produce failures. However, as highlighted in previous deliverables and reports, at the beginning of the project, there was little or no prior knowledge available regarding any of these three. The main MANpower electronic/mechanical components (pacemaker capsule, Tyndall and IEF harvesters, Tyndall supercapacitor) were completely novel and we had no prior reliability/durability history or information on their vulnerabilities. We further had only very little information on the reliability stresses imposed by the intracardiac environment in a living, moving person or animal. There was therefore no possibility of predicting possible failure events until both of these knowledge gaps were filled. Regarding biocompatibility, there was again no prior history of how the MANpower pacemaker capsule, anchored in the wall of the right ventricle and freely oscillating under the stimulus of heartwall movement, would affect the cardiac tissue both at the anchor site and in the wider intracardiac space. This knowledge gap also had to be filled if the MANpower pacemaker was to be shown to be a potentially viable medical device.

The work carried out in WP5 has made substantial contributions to filling these knowledge gaps and has allowed a roadmap to be set out for how research should continue on reliability, durability and biocompatibility of the electronic and mechanical components of the MANpower pacemaker.

1.7.1 Approach

Reliability, Durability and Biocompatibility (RD&B) are very challenging considerations in any project as they require ongoing interaction of skillsets and expertise from of a large number of disciplines. In MANpower there were several additional major challenges:

- Organisational: The coordination and integration of reliability tasks across a multinational, multidisciplinary consortium.
- Technological:
  - The majority of materials, structures and components were novel with little or no prior knowledge of their individual or collective RB&B;
  - The nature of the intracardiac environment as a source of both mechanical energy and of reliability stress was virtually unknown;
  - A very long unattended operational life target in a life-critical application but only a short time window for reliability testing: a three-year project where the majority of components would not be available until late in the project.

While these challenges certainly offered ample opportunity for research and generating new knowledge, use of traditional reliability engineering “build and test” was not feasible. MANpower therefore used a Design for Reliability (DfR) approach where RD&B are an integral part of material selection, of the design of structures and components, and of system integration strategies. This approach aimed to ensure that the final material set and the design of structures, components and pacemaker would be as reliable as possible, maximising the probability of a “right first time” design which can subsequently undergo full qualification testing. To identify, predict and characterize potential RD&B issues, DfR combines:

- Collaborative identification and criticality ranking of potential failure mechanisms following a formal DfR process;
- Physical characterisation of the properties of materials and structures;
• Identification of application RD&B stressors;
• Multiphysics simulation of reliability stresses and their effect on potential failure mechanisms;
• Accelerated testing of test structures and devices.

The work of WP5 was organised in four tasks:
Task 5.1 Ensure a uniform approach to Reliability, Durability and Biocompatibility across all MANpower activities
Task 5.2 Investigate and analyse the Reliability, Durability and Biocompatibility of MANpower materials and components
Task 5.3 Using accelerated testing, identify and characterise potential wear-out and failure mechanisms of MANpower materials and structures
Task 5.4 Prepare a roadmap for post-MANpower qualification of the MANpower device

This document reviews the MANpower RD&B challenges, the approaches taken to overcoming them and the main outcomes of the RD&B activities in MANpower.

1.7.2 The MANpower device and components

The MANpower device consists of a sealed titanium cylindrical pacemaker capsule with anchor screw (for embedding in the heartwall) and electrodes (for administration of pacing signals). Inside the capsule are pacing electronics, power storage (supercapacitor) and power generation (micromechanical energy harvester). RD&B investigation and analysis was required each of these mechanical and electronic components

1.7.3 Addressing the RD&B Challenges

1.7.3.1 Organisational: The coordination and integration of reliability tasks across a multinational, multidisciplinary consortium. This challenge was addressed in Task 5.1 which ran for the entire duration of the project. was to instil a consistent RD&B philosophy throughout all activities within the MANpower project. Each partner had their individual experience of the DfR process ranging from extensive experience to none. The primary objective was therefore to raise the awareness of reliability to a common level and to ensure that the approach taken was consistently applied and understood throughout the project. The methodology was developed through discussions with each of the partners and the development of a template which informed the structure of all reliability meetings. CIT prepared pre-meeting information which was both a structure to inform the preliminary brainstorming sessions but which also provided the participating partner with information on the DfR process. The structure of these meetings was based on a DFMEA (Design Failure Mode and Effect Analysis) process which was adapted to suit a multi-national, multi-institution research context. Following each meeting, detailed minutes were drawn up which were then sent to each of the contributing partners for comment. These were then disseminated to all the other partners via the MANpower Hub.

1.7.3.2 Technological challenges

• The majority of materials, structures and components were novel with little or no prior knowledge of their individual or collective RB&B;
• The nature of the intracardiac environment as a source of both mechanical energy and of reliability stress was virtually unknown;
• A very long unattended operational life target in a life-critical application but only a short time window for reliability testing: a three-year project where the majority of components would not be available until late in the project.

To address this challenge, WP5 followed a Design for Reliability (DfR) methodology:
(a) Measurement of the RD&B material properties of the novel materials, structures and components being used
(b) in the MANpower device and the changes in these properties when exposed to the RD&B stresses associated with the MANpower application; this information was key to informing design decisions, to providing quantified materials data for simulations, and to informing failure analysis.
(c) Identification of the stresses imposed on the MANpower device by the cardiac environment and by transport/storage; this information was essential to inform the DfR process and to set boundary parameters for reliability simulations. Extensive testing was carried out using implanted accelerometers in sheep to measure the 3D accelerations of the heartwall.
(d) Use of these material properties and environmental stresses in multiphysics simulations of component designs; Multiphysics simulations allowed simulation the effect of both individual and interacting stresses and more detailed exploration of the design space than was possible with testing of prototypes. These simulations supported the identification of the MANpower device designs that have greatest probability of being “right-first-time”.
(e) Use of the results of these simulations and the results from ongoing RD&B testing of test structures and prototypes to inform a Design Failure Modes and Effects Analysis (DFMEA) process; DFMEA applies FMEA at the device/product design stage and follows a systematic process to identify failure mechanisms and risks and to prioritise them for more detailed analysis.
(f) Use of DFMEA to identify potential failure mechanisms and design solutions to minimise the risk of failure due to these mechanisms. This was done and updated throughout the project as component and system designs evolved and more knowledge was gained on performance of materials, structures and components.
To evaluate this biocompatibility in a large animal model, we chose for a sheep model as this is a well-established model for ischemic heart disease, heart valve implantation and assist devices [1, 2]. A sheep model allows a sufficiently long term follow up after implantation with intermittent clinical, biochemical and echocardiographical analysis. Sheep are far less sensitive to stress than pig models and have less the disadvantage of body weight increase over time.

In addition to the delivery procedure evaluation of biocompatibility of an endovascular introduced device should focus on:
- risk of RV wall perforation and tamponade
To answer these questions we implanted dummy and pacing capsules in Swifter sheep through an endovascular approach and did a long term follow up. All animals were treated according to ethical legislation. All animals were treated in compliance with the Guide for the Care and Use of Laboratory Animals published by the US National Institutes of Health (NIH publication 85-23, revised 1996). The study was approved by the Ethics Committee of the KU Leuven. All animals were bred at the Zootechnical Center of the KU Leuven and procured for research through the Animalium KU Leuven. We studied and evaluated clinical, biochemical and histological repercussions and performed echocardiography and X ray controls.

Initial work up
In the first 16 months of the project the focus of the MANPOWER project was mainly on the construction and integration of components. Therefore the dummy and prototype capsules were not available from the start. We used the first period of this project to perform a literature search that studied acceleration in different animal models and addressed the issues concerning the external forces that might possibly interact on a moving (living) subject. These findings were presented on a meeting on traumatic chest injuries (trauma meeting september 2014 , Leuven).

As soon as dummy capsule’s became available we started to implant dummy capsules in the right ventricle of sheep (n=4) by endovascular approach using a delivery tool (26F diameter) developed by SORIN. Two sheep were kept 20 weeks in follow-up, two other for 16 weeks, with regular clinical check-up, blood sampling (LDH, ureum, creatinine, hemoglobin (in full blood and free in plasm)), X-ray, and echocardiography imaging. The delivery device was developed by Sorin and allowed an unpronounced angulation of the delivery tool in vivo to improve the delivery at the most optimal localisation and included also a safety line for efficient and rapid retrieval during the delivery procedure. A Torque limitor included in the delivery device allowed implantation without exaggerated force of screwing.

All these implantations were performed through jugular approach and went uneventfully. All animals survived the procedure. There were no intial dislodgements or embolisations. With echocardiography and chest X rays the correct positioning of the device was confirmed at the time of implantation and during follow up. There was no dislodgement or embolisation over time. In case two capsule’s were implanted (n=2, one coated, one uncoated), they did not interfere with each other, RV nor tricuspid valve function. Biochemical analysis was combined with the animals that received a pacing capsule (see below) and showed stable hemoglobin levels, low LDH and low free Hb in plasma levels and stable kidney function. In one case the fixation device was visible externally at the time of necropsy, but without signs of pericard effusion (near perforation, clinically unrelevant). No case of dislodgment, nor valve damage occured. In one sheep, a very small clot was found at the free end docking site of the capsule. None of the capsules were completely covered by a fibrotic cap, potentially allowing recapture and unscrewing of the device. All showed a self-limiting and normal (1) healing process at the screwing site, and (2) mechanically induced fibrosis on septum and right ventricular free wall. Coating of the device did not seem to provoke nor prevent fibrosis locally, but rather the position of the device and its degrees of freedom in relation to the RV wall defined its surrounding fibrosis.

Second phase
In a second phase after the first 16 months, and with the knowledge and experience of implanting dummy capsules, functional pacing capsules (n=7) were implanted by jugular approach in 5 animals and by femoral approach in 2 animals. In one of these implanted pacing devices, a retrieval was succesfully performed after 120 days of implantation. These animals were included in the biochemistry analysis above. All the implantations were performed through jugular or femoral approach and went uneventfully. All animals survived the procedure. There were no intial nor late dislodgements or embolisations. Also here, with echocardiography and chest X rays the correct positioning of the device was confirmed at the time of implantation and during follow up. There was no dislodgement or embolisation over time even at final follow up.

It was possible to communicate with the device wireless and to evaluate pacing function and status of the device over time. Impedance was acceptable and lowered over time. Pacing tresholds were low and lowered further after implantation. The wireless communication with the pacing device failed in 1 animal and this device was removed earlier to rule out anatomical or clinical explanations for this issue. After the removal of this animal from the data you will see that impedance and pacing capture thresholds further improve (lowered). All sheep (n=7) underwent a necropsy with microscopic analysis afterwards. Also in this group of subjects, in 1 case the fixation device was visible externally at the time of necropsy, but without signs of pericard effusion (near perforation, clinically unrelevant). No case of dislodgment, nor valve damage occured, although in 1animal the device was in approximation of the tricuspid valve. All showed self-limiting a normal (1) healing process at the screwing site, and (2) mechanically induced fibrosis on septum and right ventricular free wall. The jugular approach was far more easy to implant a device in sheep, than the femoral approach, due to the - clinical recovery and wound healing
- cardiac function and possible tricuspid valve interference
- end organ repercussions due to overload, hemolysis, or embolization
specific anatomical features in sheep: 1) a superficial big jugular vein, versus a small and deep-lying femoral vein; 2) hemodynamically better supported lateral decubitus, versus supine position; 3) and worse hygiene in the groin than in the neck in sheep. It is expected that in humans both femoral and jugular approach is possible due to the anatomical considerations. For the additional reliability testing we also evaluated both acute accelerometer implantation (internal and external). Swifter sheep were instrumented to study these effects different approaches. In these acute experiments the chest was opened and acceleration of the heart was studied by attachment of external accelerometers in basal, mid and apical position. Different hemodynamical situations (bradycardia, pacing, inotropics, ventilatory arrest) were evaluated during these acute experiments. These measurements will in the future allow us to understand the current correlation between acceleration and TDI measurements so that models and predictions in harvestable energy can be made, if any device should become available.

According to our findings and evaluation it should be safe and feasible to perform device implantations and retrievals under general anaesthesia. Retrieval is also possible after medium term implantation length, also when the subject was freely moving during 120 days. Multiple devices that are present in the right ventricle do not seem to interfere with each other nor with the RV or valve function. This makes it likely that second device can be safely implanted if the first device fails and cannot be retrieved. This is an extra safeguard in the concept. Further work to be performed in the future should focus on the optimal localisation for implantation and pacing that not only results in the most optimal cardiac synchronisation, but also delivers most optimal acceleration stimulation for loading an internal energy harvester. Also improving the imaging during the implantation and steering the device to the most optimal landing zone should be obtained. Minimal invasive evaluation of cardiac function through TDI (tissue Doppler imaging) combined with acceleration measurements could allow to gain insight in this correlation, even in the more diseased and fragile hearts, but will demand very high sampling rates combined with very good image resolution. We have made an initial evaluation of simultaneous TDI and acceleration measurements but would need a final harvesting device to do predictions concerning harvestable energy and efficiency (and the subsequent correlation with TDI)

Conclusions
With this biocompatibility evaluation of the package and prototype, we showed in 11 animals that a safe implantation and retrieval of a pacing capsula is possible in sheep via both transjugular and transfemoral approach. This capsula was designed with the size and geometry compatible with the desired energy harvester (which was not available at the end of the project). The implantation of this capsula resulted in normal and non-hazardous histological findings to the subject. Clinical, biochemical and echocardiographical analysis showed no signs of embolisation, tamponade or chronic decompensation and did not reveal any clinical relevant repercussions of the device. These findings are essential to proceed towards reliability testing in WP 6. We had one communication error after implantation in an animal.

Potential Impact:
A typical pacemaker consists of several wires which originate from a titanium module that have been threaded into the heart during a medical procedure and located in specific places so that when the heart rate drops below a set rate, the pacemaker generates an impulse that passes through the lead to the heart muscle. This causes the heart muscle to contract, creating a heartbeat. The leads and the associated electronics module are relatively cumbersome and the heart's continuous and vigorous beating also creates strain on the leads and can damage them over time. In the medical devices industry it is therefore desired that these leads be removed and replaced with a much smaller module that is implanted directly into the heart wall. This leadless innovation imposes new requirements onto the system electronics and the materials that are used to build them. It also requires that the system is reduced in volume by a factor of 16 from 8cc to 0.5cc. The major challenges in this system level size reduction lies in providing the power supply and replacing the large, long life battery that is currently employed. An energy harvesting unit that can address this requirement by extracting energy from the motion of the body has been identified as essential for this application and it is clear that new materials and device architectures will be required to make it. Within this project this platform has been chosen to become a target demonstration technology because it has clearly defined technical specifications that are very challenging and need to be achieved as well as a market need for suitable devices.

The area of monitoring cardiac disorders and providing treatment using electronic systems has been ongoing since the end of the second world war. The term artificial pacemaker was coined by Albert Hyman in 1932 and the functionality, obviously considerably improved over his original invention has grown over the intervening years to the present day where a 25 billion euro market exists for electronic cardiovascular devices alone and this is expected to grow to 32 billion by 2016. Heart Failure is the most common cause of hospital admission in people over 65 and in 2005 as many as to 14 million Europeans suffered from heart failure related problems. This is expected to increase to 30 Million by 2020 with 3.6 Million new cases of heart failure being reported each year. Cardiovascular mortality leads the way as the highest cause of mortality in Europe and creating devices and systems that can arrest this trend is very important for the health and wellbeing of the European community.

There are three major diseases treated using these cardiac rhythm management systems and they relate to the arrhythmias that can arise as a function of chronic heart disease and high (or low) blood pressure. These arise where the heartbeat may be:
• Too slow (bradycardia)
• Too fast (tachycardia)
• Irregular, uneven, or skipping beats

An arrhythmia may be present all of the time or it may come and go and symptoms may not even be detectable even when the arrhythmia is present, but they could ultimately lead to heart failure if untreated. In 2007 there was a 7.635 B€ market for implantable electronic systems that could control these phenomena. This grew to a size of 10.5 B€ in 2012, mainly on foot of growth in demand for tachycardia (58%) and heart failure (71%) treatments with the demand for bradycardia solutions remaining substantial at a level of 2.8B€ but quite static. Clearly, there is a very significant demand for this kind of device and building devices that could last for a patient's lifetime without having to replace them would be of great importance for the future.

The challenge for the European Union is to compete successfully in emerging global markets and to create the wealth necessary to ensure a continued high standard of living for all its citizens. The Europe2020 Strategy aims at "smart, sustainable, inclusive growth" with greater coordination of national and European policy making Europe the world's most dynamic and most competitive knowledge-based economy. The proposed activities of the MANpower project address some of the main priority areas of the Europe2020 strategy, including energy efficiency, promoting knowledge and innovation and supporting the development of a strong and sustainable industrial base able to compete globally.

Research into energy harvesting is ongoing across Europe and many different approaches and technologies have emerged over the last few years. However, no single country has the capability to construct a fully functional power supply module in which the power output is generated and made available to the application. This requires a holistic approach and one in which different materials technologies are combined together to create one integrated system in which every technology is optimised. In MANpower, new materials technologies from Holland, France and Ireland were combined and integrated with electronics systems from France and Germany to create a low frequency energy harvesting based power supply. The demonstrator for this project planned to utilise the specifications for an implantable electronics module to illustrate its capability.

In the short run (2-3 years from now), the current cost/benefit model of today is expected to have limited market penetration in single chamber market due to the fairly higher additional price of the system, despite the simplification of the procedure and clinical/economical advantages (reduced risks of infection/cardiac leads replacement) which necessitate longer clinical studies for being established and justified.

The availability of a full dual chamber system (implying possibly one capsule in each cardiac cavity) around 2020, combined with advanced clinical results on such leadless pacemakers, is likely to grow the market therefrom. Challenges as the miniaturization of the device to be implanted in the atrium, the communication scheme and technology between the implanted devices, and the overall cost model will have to be taken up in the meantime.

First, the Manpower project has successfully generated the possibility to develop a battery based leadless pacemaker capsule, as the biocompatible packaging, the fixation mechanism, the delivery tool, the drastic reduction in electronic consumption, the clinical functionalities (pacing, sensing, rate adapted sensor) and the human body communication have been demonstrated up to TRL 6 -7. The remaining development effort to reach commercialization and TRL9 is estimated around 2.5 years and 10M€.

Then, the transition from such a device to the Manpower device is mainly conditioned by the maturity of the energy harvester in terms of performance and reliability.

The Manpower project has provided an accurate picture of the roadmap “energy harvesting capacity vs. energy needs”. The reliability will probably require more R&D efforts (typically 2 to 3 years) to be further studied and established.

In terms of clinical benefit and commercial outlook, the Manpower device concept has been presented by LIVANOVA to > 30 physicians from France, UK, Italy and USA. An amazing and unprecedented 100% positive feedback has been collected, demonstrating the unanimous interest in the application to tackle the limited longevity (implying tricky/costly replacement procedures).

Aside the obvious impact on the patient comfort and life, it is believed and rather strongly stated that the overall and additional economical savings for the healthcare entities could further justify and boost the market penetration of leadless pacemakers with this technology.

IEF think that their patented interface circuits would be very interesting for polymer-based electrostatic energy harvesting devices, such as the ones developed in MatFlexEnd EU Project for instance.

Possible applications are (but not limited to) medical patches, smart textile and sport accessories. They have recently applied for a grant from the French National Research Agency to valorize the work on the EEH device and more especially on the electronic interface circuits. The objectives are to get a detailed market analysis made by a specialized company, to get in contact with potentially interested companies, and to develop prototypes for to the most promising applications. The result of the
call is expected end of June 2016.

Tyndall is still investigating the possible IP possibilities on the materials used in the energy harvesting device. Tyndall is currently trying to use the knowledge gained in MANpower to obtain future funding in order to continue the research technology and indeed a number of proposals have been written based on the AlN work developed in MANpower.

Tyndall is also evaluating the intellectual properties in terms of supercapacitor developed in MANpower project. After the evaluation, a possible patent filing might take place, which will enable Tyndall to investigate possible exploitation route for this supercapacitor technology.

Concerning the technological developments from 3DPlus (stacking of capacitors, stacking of microbatteries, technology flow 3.5) they are mainly linked with medical, defense and industrial markets. Numbers are not clearly identified as they are dependent on applications and customer. Regarding the pacemaker market, the exploitation plan is linked with that of LIVANOVA, based on the hypothesis that 3D PLUS technology will be selected by LIVANOVA. At the end of this project, market evaluation will be estimated.

The business areas and competences of the Fraunhofer Research Institution for Microsystems and Solid State Technologies (Fraunhofer EMFT) focus on sensor materials, Si technologies & devices (including sensors and actuators), flexible substrate technologies and heterogeneous 3D integration, i.e. for sensor/IC integration and smart sensor systems. First business cases have been recently established in the healthcare sector for micro dosing systems. New projects, where medical application demonstrators will be developed together with leading partners in semiconductor, healthcare and medical industry have been initiated.

The MANpower project enables EMFT to deepen the knowledge of sensor integration for medical applications. EMFT will distribute this Know-How to their industrial partners especially to small and medium enterprises by launching new projects in the medical and healthcare area.

System integration with respect to medical requirements to the quality and reliability is one of the main challenges within the MANpower project. The results, experience and scientific excellence achieved together with the highly competent MANpower partners enables EMFT to act as an international acknowledged research partner.

Besides the medical applications EMFT will use the additional knowledge, e.g. the integration by combing silicon substrates and flexible polymers, within system integration issues of other sensor applications with high reliability requirements.

With CITs focus on reliability exploitation of the results of MANpower can lead to

- some of the testing methods being developed, particularly for realistic robotic emulation of heart wall movement
- the modifications to the Tyndall harvester designs to improve their reliability in the specific operating environment of the pacemaker capsule
- reliability improvements suggested for other MANpower components
- the mathematical model for heart wall movement being extracted from the MANpower measurement data

They will continue to monitor the potential for IP and for exploitation of outputs such as the above.

Although not an outcome anticipated by Communicraft from this project, over the course of developing and working with the project hub, and consulting with the partners as to their main requirements for use, certain new functionality was created which offers the potential for further exploration with a view to possible creation of a product or service that may be commercialized.

Though the hub system itself, and the concept it is based on, would have many competitors in the space (online collaboration software is a mature technology at this point), certain features – such as the data collection tables, have been developed as innovative tools that might well be leveraged into other Communicraft projects either in terms of a commercial service or as a part of a larger product at some point in the future.

Communicraft will investigate this further through the deployment of a hub-type framework as a means of communicating with our own partners and commercial clients, also incorporating other aspects of our R&D software, to measure its effectiveness at improving lines of communication currently not being met by widely available commercial products such as Google Drive & Dropbox.

Should this initial test prove successful, we will look toward a feasibility study to investigate the possibility of commercializing certain aspects of the system by way of a Software as a Service model.

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Related documents

final1-images.pdf