

ANEXO DOSSIER



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TRABAJO FIN DE GRADO

2015

Sistema de procesamiento de
residuos orgánicos

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FASE 0

**INTRODUCCIÓN
PLANIFICACIÓN**

FASE 0

INTRODUCCIÓN

RAZÓN DE DISEÑO:

En la actualidad nos encontramos con numerosos problemas a la hora de procesar los residuos creados en un ámbito urbano. Algunos de ellos son:

Crecimiento de la población: implica un aumento del volumen de desecho que además se concentra en áreas urbanas debido al mayor número de personas que vive en las ciudades. (1)

Producción de desperdicios: las tasas de generación de residuos se encuentra en continuo aumento, lo que provoca problemas en las plantas de gestión y procesado al no dar abasto.

En México o Santiago de Chile este incremento ronda del 2 al 3% anual. (1)

Sitios para evacuar: los lugares urbanos donde depositar los desperdicios están muy limitados y debido a los dos primeros problemas planteados, son cada vez más escasos. Los rellenos sanitarios son emplazamientos en los cuales se entierran los residuos y posteriormente se tapan. Cuando se produce su descomposición liberan gases y sustancias tóxicas perjudiciales para los seres vivos o bacterias que eliminan el oxígeno del agua. (1)(2)

FASE 0

INTRODUCCIÓN

RAZÓN DE DISEÑO:

Residuos orgánicos: el problema que nos encontramos a la hora de eliminar este tipo de desechos, es la proliferación de bacterias que aparece si el residuo está en presencia de agua. (3)

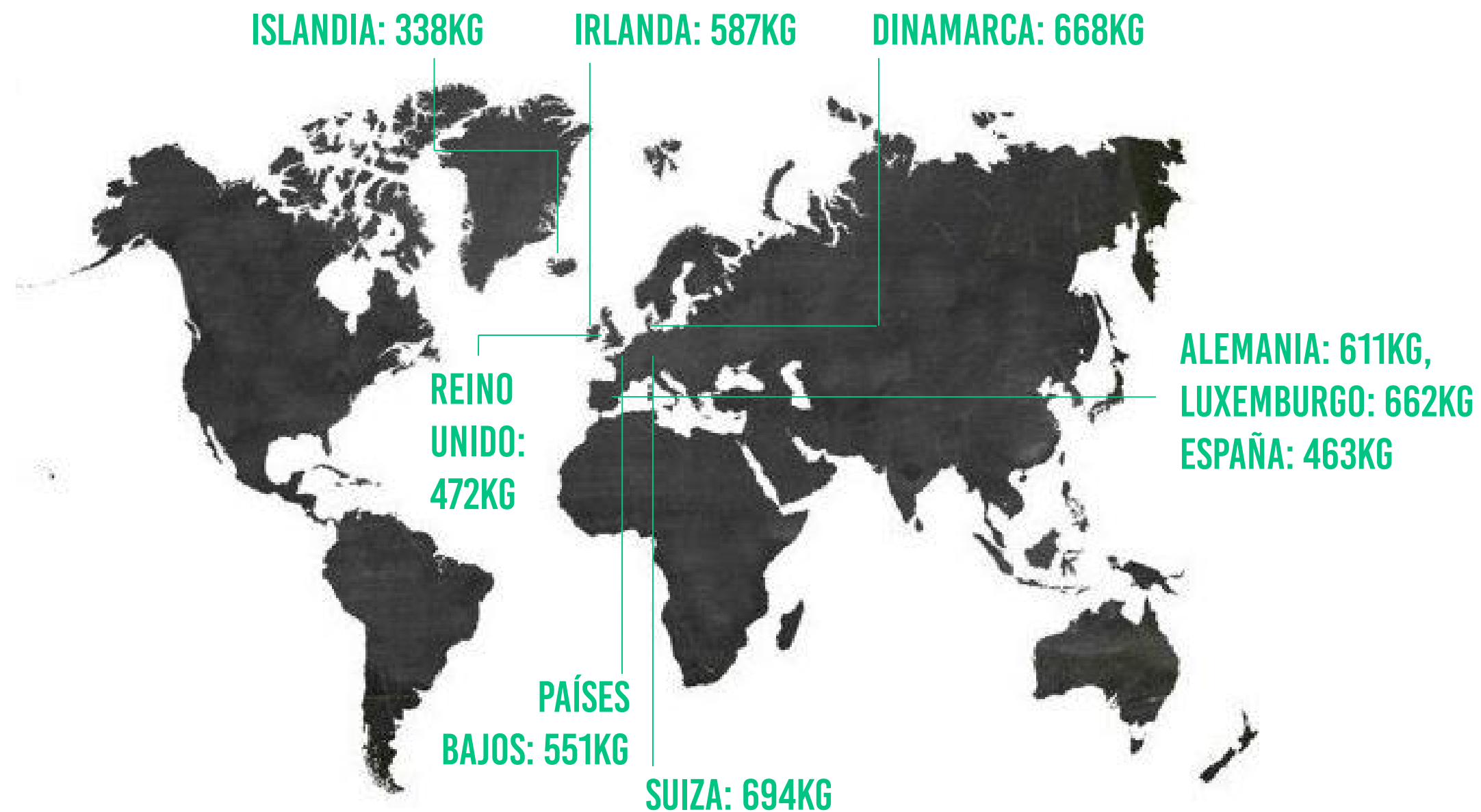
Este tipo de desechos se encuentra en forma de *aguas residuales*(4), que agota el oxígeno del medio impidiendo el desarrollo de seres vivos. El agua debe ser tratada y desinfectada en varias fases, lo que implica un alto coste económico y ambiental.

Otra forma de eliminación materia orgánica es la *incineración*(5), que posee una serie de ventajas como la valorización de cenizas, reducción de la materia en peso y volumen (hasta un 95%) y la disminución del número de vertederos. Los inconvenientes de este sistema de eliminación son los altos costes de explotación, el sistema de tratamiento de gases usados es complejo y costoso, el tiempo de preparación del proyecto largo y además el impacto medioambiental es altamente nocivo.

FASE 0

INTRODUCCIÓN

RAZÓN DE DISEÑO //CANTIDAD DE BASURA GENERADA EN 2012 POR PERSONA (6)



FASE 0

INTRODUCCIÓN

RAZÓN DE DISEÑO:

¿CÓMO EVITAR TODOS ÉSTOS PROBLEMAS?

Es evidente que la raíz del problema se encuentra en los hábitos del ser humano en el momento de lidiar con sus propios desperdicios.

Por ello, cuanto menor cantidad de basura se produzca, menor será el problema de gestionarla. Esta idea se llama “**basura cero**” que ya ha sido aplicada en ciudades como Canberra o San Francisco. En San Francisco se consiguió reducir en un 50% sus residuos a lo largo de 10 años desde su aplicación en 1995. (7)

Esta propuesta trata de **disminuir la producción de basura, reutilizar y reciclar** el resto de materiales que la componen.(7)

Al ser difícil hacer cambiar de hábitos a la sociedad, se pueden diseñar productos que ayuden a la población a adquirir la idea de reutilizar. Por ejemplo, es común la reutilización de residuos para hacer compost(8) que se necesita como fertilizante, por lo que sería interesante desarrollar un producto que ayudase a la creación de compost de forma más automatizada.

FASE 0

INTRODUCCIÓN

RAZÓN DE DISEÑO:

¿CÓMO EVITAR TODOS ÉSTOS PROBLEMAS?

Disponemos de recursos tecnológicos suficientes para ayudar al ser humano a acelerar este proceso de basura cero, el cual demuestra que es el primer paso al éxito contra la contaminación medioambiental. Zero Waste Europe(9) es una organización que insiste en implementar esta propuesta en Europa mediante campañas, conferencias, convenciones, etc desde 2011.

Este año la convención se ha realizado en Sofia, Bulgaria y una de las propuestas fue la de crear una granja que se autoabasteciese con su propio compost en este país.(10)

Como esta propuesta de basura cero trata de acabar con los rellenos sanitarios, se ha pensado que trabajar en el diseño de una compactadora de residuos orgánicos, que sería favorable para conseguir esta meta.(6)(8)

FASE 0

PLANIFICACIÓN

Para aprovechar el tiempo y dividir las tareas de manera que aporten soluciones de forma progresiva, se estableció una planificación dividida en fases.

En la fase inicial da comienzo en marzo con una duración de un par de semanas, en la cual se redacta la motivación por la que se ha elegido realizar el proyecto y el planteamiento del mismo.

Se realiza una primera estructura de trabajo que determina el tiempo invertido en cada fase.

La fase 1 de estudio de mercado y vigilancia tecnológica conlleva tres meses de dedicación al ser un campo muy amplio, en el cual hay que conocer los productos existentes y las ventajas que aportan los diferentes músculos artificiales según su aplicación.

La segunda fase de proceso creativo en la cual se aplica la metodología bioinspirada, abarca dos meses de trabajo. En ella se discuten ideas con el director del proyecto y se elige uno de los tres conceptos desarrollados.

En una tercera fase se desarrolla el concepto elegido durante el mes de agosto, y finaliza con el rediseño del producto creando la compactadora definitiva.

En septiembre se crean los modelados, planos y se comienza a sintetizar el diseño final explicando cada pieza que lo compone.

La síntesis de los materiales, forma-función, proceso de fabricación, coste y secuencia de uso se realizan en octubre.

FASE 1

ESTUDIO DE MERCADO

ANÁLISIS:

TRITURADORAS

COMPACTADORAS

INVESTIGACIÓN

FASE 1

ESTUDIO DE MERCADO

TRITURADORAS // DATOS(11)

- ❑ La trituradora fue diseñada en 1927 por el arquitecto John W. Hammes. En 1935 aprobaron su finalmente su patente.
- ❑ 1940 fue el año de lanzamiento al mercado por su empresa Insinkerator.
- ❑ Durante muchos años fueron prohibidos por la causa de obstrucciones en los sistemas de alcantarillado.
- ❑ Un estudio de 21 meses por el Departamento de Protección Ambiental anuló esta prohibición en 1997 en EE.UU.
- ❑ En 2009 el 50% de los hogares estadounidenses tenía trituradoras, el 6% en Reino Unido y el 3% en Canadá.
- ❑ En algunas localidades de Gran Bretaña se subvencionan este tipo de productos y en Suecia se fomenta su uso.

FASE 1

ESTUDIO DE MERCADO

TRITURADORAS:

Los beneficios que aporta este producto está relacionado con la secuencia de uso que se da lugar en una cocina. Posibilita la **eliminación de desechos a través del desagüe**, evitando tener que vaciarlos en un cubo y a continuación tener que aclarar la vajilla en pasos diferentes. Además al ser desechados de forma inmediata, **desaparece** una gran parte de **malos olores** en la cocina.(11)(12)

Actualmente en **España**, estos aparatos están prohibidos para uso doméstico, ya que a diferencia de EE.UU, el sistema de alcantarillado no soportaría la cantidad de residuos que fluirían por el mismo, creando problemas como **atascos**. Para permitir su aplicación, los residuos en vez de ser triturados en forma de trozos, deberían ser aplastados mediante muelas, ya que se reducirían así los trozos existiendo menos posibilidades de atasco. Las aguas residuales entonces transportarían la basura compactada y no de forma heterogénea. Pamplona es un claro ejemplo de esta prohibición al haber observado estos problemas en su sistema de alcantarillado(12)

En el resto de **Europa** también se encuentran con este problema, ya que la depuración de agua sería mucho más costosa y se opta por otros sistemas de reutilización de residuos como la creación de compost(13).

FASE 1

//DOMÉSTICAS

ESTUDIO DE MERCADO

TRITURADORA BADGER 100

Medidas: 29 x Ø16 cm
Capacidad: 0.77 L
Velocidad: 1725 rpm
Motor: 0.25 kW
Consumo: 120V
4 kWh/año
Precio: 84.96\$
Empresa: Insinkerator

(14)



(14)



(14)

TRITURADORA EVOLUTION EXCEL

Medidas: 33.65 x Ø23 cm
Capacidad: 1.18 L
Velocidad: 1725 rpm
Motor: 0.75 kW
Consumo: 120 V
4 kWh/año
Precio: 339\$
Empresa: Insinkerator

(14)



(14)

TRITURADORA SELECT PLUS

Medidas: 31 x Ø20.3 cm
Capacidad: 1.02 L
Velocidad: 1725 rpm
Motor: 0.56 kW
Consumo: 120V
4 kWh/año
Precio: 219\$
Empresa: Insinkerator

(14)

FASE 1

//DOMÉSTICAS

ESTUDIO DE MERCADO

TRITURADORA AFC 111V

Medidas: 37.85 x Ø17 cm
Capacidad: 0.78 L
Velocidad: 2500 rpm
Motor: 0.25 kW
Consumo: 120V
Precio: 59\$
Empresa: GE

(14)



(14)



(14)

TRITURADORA GFC 535V

Medidas: 34.54 x Ø19.7 cm
Capacidad: 0.92 L
Velocidad: 2800rpm
Motor: 0.37 kW
Consumo: 120 V
Precio: 139\$
Empresa: GE

(14)

TRITURADORA GFB 720V

Medidas: 42.22 x Ø21.6 cm
Capacidad: 1L
Velocidad: 3100 rpm
Motor: 0.56 kW
Consumo: 120 V
10 kWh/año

Precio: 209\$

Empresa: GE

(14)



(14)

FASE 1

//INDUSTRIALES

ESTUDIO DE MERCADO

TRITURADORA SS50-26

Medidas: 36.83 x Ø20.32 cm
Capacidad: 150 platos
Velocidad: 1725 rpm
Motor: 0.37 kW
Consumo: 115 - 230V 4 - 8.4A
Precio: 892.25\$
Empresa: Insinkerator (15)



(15)



(15)

TRITURADORA SS300-25

Medidas: 59.7 x Ø44.6 cm
Capacidad: 750 platos
Velocidad: 1725 rpm
Motor: 2.24 kW
Consumo: 208 V
Precio: 2495.65\$
Empresa: Insinkerator (15)

TRITURADORA SS1000-10

Medidas: 60 x Ø44.6 cm
Capacidad: 1500 platos
Velocidad: 1725 rpm
Motor: 7.45 kW
Consumo: 208-460 V 6.5 – 13 A
Precio: 8184 \$
Empresa: Insinkerator (15)



(15)

FASE 1

//INDUSTRIALES

ESTUDIO DE MERCADO

TRITURADORA 3/4 HP

Medidas: 40.2 x Ø44 cm
Desagüe: Ø8.9 cm
Capacidad: 75 platos
Motor trifásico: 0.56 kW
Consumo: 115 - 460V
Precio: 948.99\$
Empresa: Salvajor (15)



TRITURADORA

Medidas: 59.7 x Ø44.6 cm
Desagüe: 8.9 cm
Capacidad: 1500 – 2250 platos
Motor trifásico: 5.6 kW
Consumo: 208 - 460V
Precio: 3244.9\$
Empresa: Salvajor (15)



TRITURADORA 3 HP

Medidas: 78.11 x Ø44 cm
Desagüe: Ø8.9 cm
Capacidad: 300 - 750 platos
Motor trifásico: 2.24 kW
Consumo: 208 - 460V
Precio: 1878.99\$
Empresa: Salvajor (15)

FASE 1

PRODUCTOS
RELACIONADOS:

//INDUSTRIALES

ESTUDIO DE MERCADO

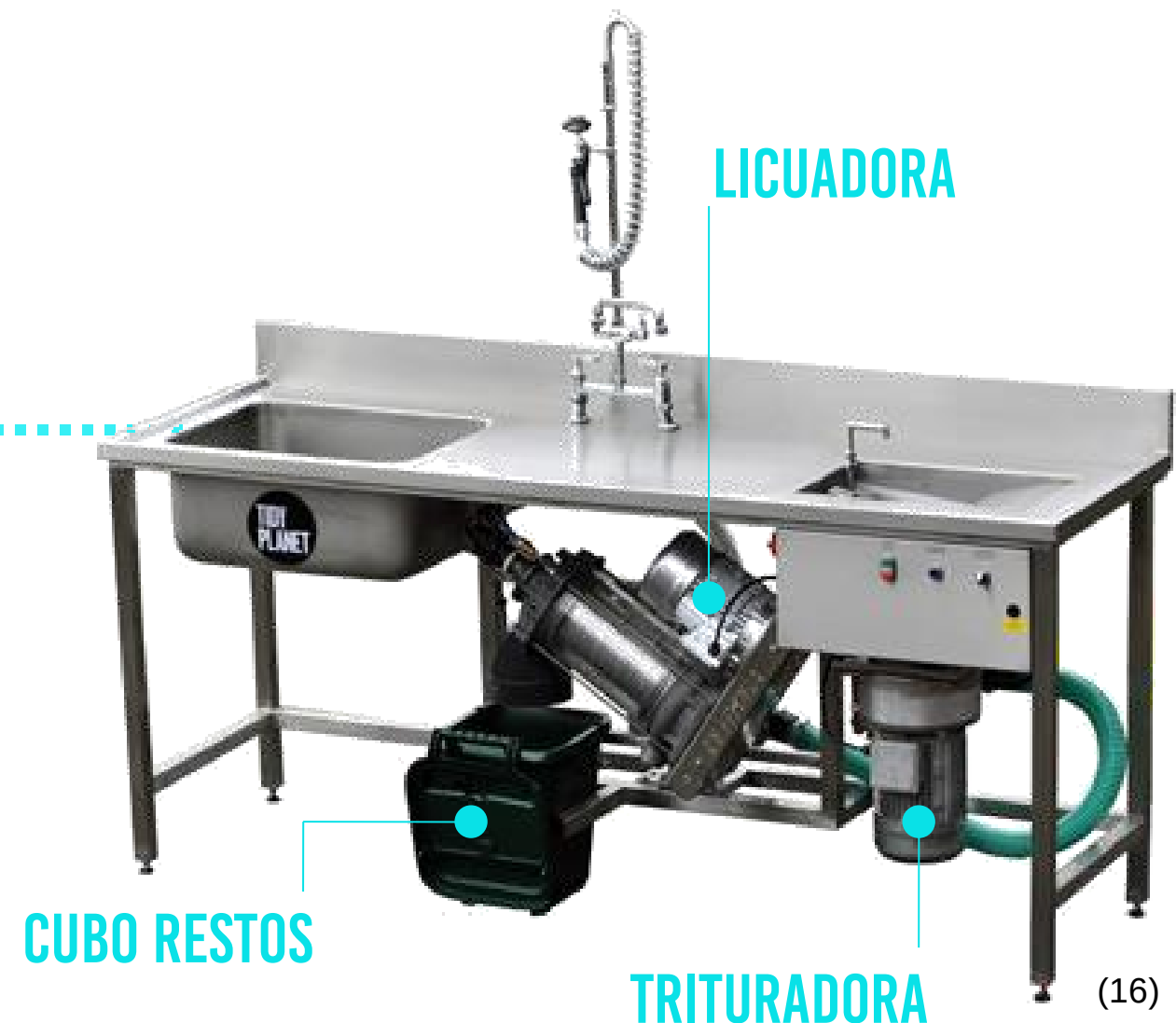
DEHYDRA FOOD WASTE DEWATERES

Compactación: 80% volumen
50% peso

Empresa: Vekkos Recycling Solutions

Se trata de un sistema de triturado y deshidratación de restos orgánicos. Los restos primero pasan por la **trituradora** y a continuación son enviados a una **licuadora** que separa el agua. Los restos sólidos deshidratados se evacúan a un contenedor, mientras que el agua es eliminada por el desagüe. **El exceso de agua puede ser reutilizado.**

(16)



FASE 1

PRODUCTOS
RELACIONADOS:

//INDUSTRIALES

ESTUDIO DE MERCADO



(17)

WASTE2EAU FOOD DIGESTOR

Procesa 180kg de restos orgánicos en 24h

Transforma la basura en agua no perjudicial para el alcantarillado.

Usa microorganismos que se encargan del tratamiento.

Al **no producir restos sólidos**, no es necesario un sistema de recogida ni su deposición en vertederos.

Reduce la huella de carbono.

Empresa: Vekkos Recycling Solutions (17)

FASE 1

PRODUCTOS
RELACIONADOS:

//DOMÉSTICOS

ESTUDIO DE MERCADO

INODORO

OCUPA $> 2.6 \text{ M}^2$

$> 0.12 \text{ KWH/DÍA}$

VOLUMEN
INSTALACIÓN: 8 M^3

BAJAS EMISIONES
DE CO_2 , H_2S Y
METANO



(18)

BIOLYTIX WASTEWATER TREATMENT

Bioinspirado en el proceso de depuración y descomposición del suelo de los bosques.

Usa **macroorganismos** que se encargan del tratamiento de residuos sólidos.

Los **microorganismos** realizan un filtrado del líquido resultante.

Una última capa de **geotextil** finaliza el proceso al filtrar el agua por completo.

El ciclo dura aproximadamente 60h.

Soporta incluso químicos.

El **agua se puede reutilizar** para regar.

Empresa: Biolytix

(18)

FASE 1

PRODUCTOS
RELACIONADOS:

//DOMÉSTICOS

ESTUDIO DE MERCADO



(19)

BOKASHI ONE

Se trata de una mezcla granulada de **microbios** que descomponen los desechos orgánicos. El cubo está sellado para evitar el acceso de otros insectos. Como no utiliza gusanos, los restos cítricos y cebollas también son descompuestos aunque **no procesa los huesos**.

Al estar sellado una vez eliminados los residuos, no desprende malos olores.

Destinado al uso doméstico.

Los restos deben ser troceados y colocados en el cubo por capas. Entre las capas se echa la mezcla de Bokashi y una vez terminado el proceso queda un **zumo** en la parte inferior que **debe ser vaciado**.

Empresa: Bokashi Composting Australia

Precio: 170\$

(19)

FASE 1

PRODUCTOS
RELACIONADOS:

//DOMÉSTICOS

ESTUDIO DE MERCADO

DESHIDRATADOR DE ALIMENTOS

Este producto se usa en cocinas domésticas y en hostelería. Consiste en la eliminación del agua que contienen ciertos alimentos, evitando que entren en estado de descomposición y así almacenarlos. También este proceso potencia el sabor de los alimentos, por lo que es muy utilizado en hostelería.

El mecanismo consiste en la aplicación de calor de forma similar a un horno, con un sistema de ventilación que elimina toda la humedad. Los alimentos se dividen en bandejas de rejillas para que el calor y el aire llegue a todos ellos.

Opera entre 54 y 70°C.

Precio: 53€

Marca: Princess

(20)

245 W



(20)

6 NIVELES
TEMPERATURA

VENTILADOR +
RESISTENCIAS



(21)

FASE 1

ESTUDIO DE MERCADO

COMPACTADORAS // DATOS (22)

- ❑ La primera patente de una compactadora industrial fue creada por M.S Wells en 1941
- ❑ Stephen Hopkins presentó una patente de compactadora para oficina en 1966.
- ❑ Primera patente de compactadora doméstica en 1968 por John A. Boyd.
- ❑ Comercialización de Whirlpool en 1970.
- ❑ En 1980 se convirtió en un electrodoméstico más en la cocina (EE.UU).
- ❑ Existen de tres tamaños para el sector doméstico 30.5 cm, 38 cm y 45.72 cm.
- ❑ Las principales empresas de comercialización son Whirlpool, Broan y Viking.
- ❑ En 1991 John Bauer modernizó la compactadora añadiendo dos compartimentos para el reciclaje de residuos.
- ❑ 1992: Ray Lackner patentó un sistema que separaba el líquido de los restos sólidos que actualizó en 1997.

FASE 1

ESTUDIO DE MERCADO

COMPACTADORAS:

Este tipo de productos ahorra a los usuarios viajes al contenedor de basura. Además benefician al medioambiente por la reducción de emisiones por parte de los camiones de transporte, al poder almacenar una mayor cantidad de basura en el mismo volumen. Así se minimiza el número de desplazamientos que deberían realizar.

Supondría a su vez un ahorro en el consumo de gasolina, por lo que el coste de estos servicios para una ciudad se vería reducido.

A continuación se realiza un estudio de mercado acerca de este producto para conocer su posicionamiento, precio y tendencias.

FASE 1

//DOMÉSTICAS

ESTUDIO DE MERCADO

COMPACTADOR 15"

Modelo: **COMPK400**

Medidas: 39.8 x 82.1(max.89.6) x 56.7cm

Índice compactación: 85%

Consumo: 220-240V

Capacidad: 204 L

Envases cartón y plástico

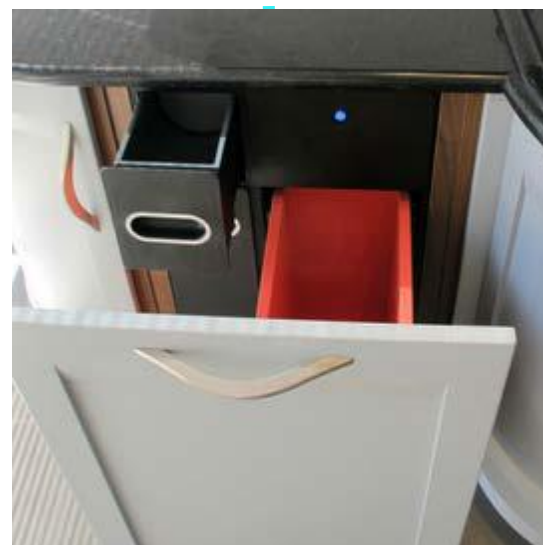
Papeles/Envoltorios

Latas,

Precio: 1801,17€

Empresa: Insinkerator

(23)



(23)

(23)



COMPACTADOR 12"

Modelo: **COMPK300**

Medidas: 29.8 x 82.1(max.89.6) x 56.7mm

Índice compactación: 85%

Consumo: 220-240V

Capacidad: 156 L

Envases cartón y plástico

Papeles/Envoltorios

Latas,

Precio: 1693€

Empresa: Insinkerator

(23)

FASE 1

//DOMÉSTICAS

ESTUDIO DE MERCADO

COMPACTADOR 15"

Modelo: **MTUC7500ADM**

Medidas: 60x87.63x38.1 cm

Índice compactación: 80%

Consumo: 120V 60Hz Motor: 0.25 kW

Capacidad: 156 L

Envases cartón y plástico

Papeles/Envoltorios

Latas

Precio: 949\$

Empresa: Maytag

(24)



(24)

(25)



COMPACTADOR 18"

Medidas: 56 x 45.46 x 31.9 cm

Capacidad: 204 L

Consumo: 120 V

Reducción: 85%

Peso: 52.2 kg

Material: Acero inoxidable

Precio: 1799\$

Empresa: KRUSHR

(25)

FASE 1

//DOMÉSTICAS

ESTUDIO DE MERCADO

COMPACTADOR 15"

Modelo: **15XESS**

Medidas: 35.56 x 86.36 x 54.6 cm

Índice compactación: 6:1

Fuerza compactación: 1361 kg

Consumo: 120V 60Hz 15A

Motor: 0.56 kW

Precio: 1511.80\$

Empresa: Broan

(26)



(26)

(27)



COMPACTADOR 15"

Modelo: **TU950QPXS**

Medidas: 35.56 x 86.36 x 54.6 cm

Índice compactación: 5:1 (80%)

Consumo: 120V 60Hz

Motor: 0.25 kW

Precio: 1149\$

Empresa: Whirlpool

(27)

FASE 1

//COMERCIALES

ESTUDIO DE MERCADO

BIG BELLY COMPACTOR

Medidas: 126.4 x 63.5 x 68.1 cm
Peso: 122kg
Índice compactación: 5:1
Fuerza de compactación: 567 kg
Placa solar: 20-30 W
Motor: 126 W
Consumo: 12 V
Capacidad: 125L
Ciclo: 40s
Empresa: Big Belly
GPRS para monotorizar online (28)



(28)

(29)



COMPACTADORA TCG-DA1000

Medidas: 129.54 x 56.56 x 53.97 cm
Índice compactación: 10:1
Capacidad: 153 L
Fuerza compactación: 6-27 kg (ajustable)
Consumo: 220V 60Hz 10A
Ciclo: 7s
Empresa: Compaction Plus (29)

FASE 1

//INDUSTRIALES

ESTUDIO DE MERCADO

ECO WEIGHING COMPACTOR

Medidas: 183 x 235 x 167.5 cm

Índice compactación: 5:1

Fuerza compactación: 25 T

Motor: 5.5 kW

Consumo: 415 V 16A

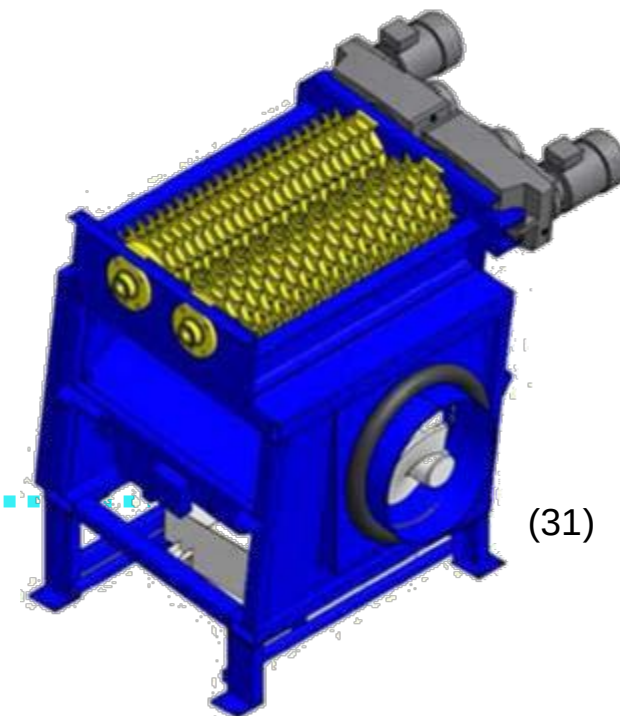
Capacidad: 600L

Empresa: Elephants Foot

Indica peso bolsa basura (30)



(30)



(31)

COMPACTADORA/DESFIBRADORA DE PET

Medidas: 150 x 142 x 170 cm

rodillos Ø47 cm

Índice compactación: 5:1 (80%)

Fuerza compactación en cubo de 32m³: 6/7 T

Consumo: 400V 50Hz 53/63A

Motor: 1.5 kW

Caudal: 200m³/h

Empresa: Elephants Foot

(31)

FASE 1

//INDUSTRIALES

ESTUDIO DE MERCADO

GTS APARTMENT TRASH COMPACTOR

Medidas: 183 x 101.6 x 106.7 cm

Índice compactación: 4:1

Fuerza compactación: 6.26-7.94 kg

Motor trifásico: 2.24 kW

Consumo: 460 VAC 60Hz

Capacidad: 42L

Ciclo: 38s

Empresa: Global Trash Solutions

(32)



(32)



(33)

COMPACTADORA X-PRESS PACK

Medidas: 96 x 81 x 68 cm

Índice compactación: 4:1 o 5:1 (80%)

Presión hidráulica: 2.250 psi (2.400psi máx.)

Caudal: 0.68 m³/h

Consumo: 406VAC 60Hz (trifase)

Motor: 2.24 kW

Capacidad: 54 L

Empresa: Global Trash Solutions

(33)

FASE 1

//INDUSTRIALES

ESTUDIO DE MERCADO

MINI-MAC APARTMENT COMPACTOR

Modelo: 3A

Medidas: 177.8 x 312.4 x 107.3 cm

Índice compactación: 4:1

Fuerza normal: 6.236 T

Fuerza expulsión: 7.448 T

Capacidad bomba hidráulica: 15L/min

Presión hidráulica: 160 kPa

Presión expulsión: 188 kPa

Motor trifásico: 2.2 kW

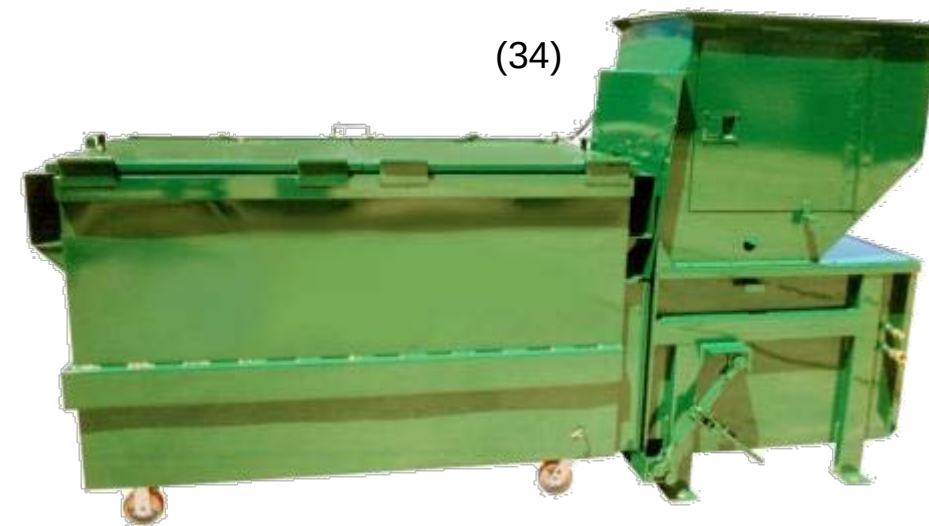
Consumo: 120 VAC

Ciclo: 21s

Caudal: 36.7 m³/h

Empresa: Marathon Equipment

(34)



FASE 1

ESTUDIO DE MERCADO

ANÁLISIS:

TRITURADORAS

COMPACTADORAS

INVESTIGACIÓN

FASE 1

ANÁLISIS TRITURADORAS

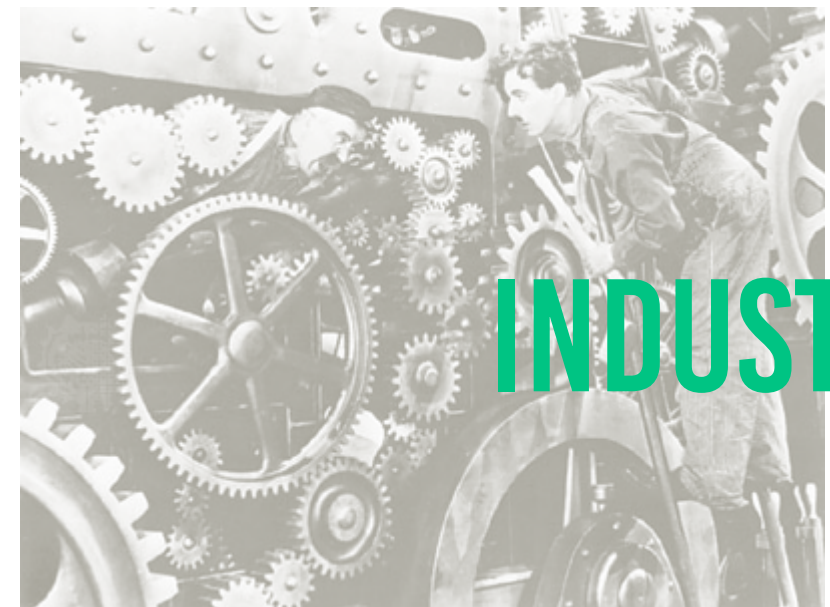
ANÁLISIS DEL ENTORNO:

Las trituradoras de restos orgánicos se comercializan desde 1940 en **EE.UU.** En 2009 el 50% de los hogares del país poseía una trituradora. Su uso también se extendió a **Reino Unido** y **Suecia** en el continente europeo.(35)

Aun en la actualidad existen problemas en Europa con el uso de estos dispositivos, ya que requieren un sistema de alcantarillado capaz de soportar residuos y el consiguiente tratamiento de las aguas residuales, que resultaría costoso. (36)

Nueva Zelanda es otro de los países con mayor tendencia al uso de trituradoras.

La perspectiva de futuro favorece la implantación de este producto, porque todos los países aspiran a ciudades sostenibles, actualizando leyes y diseñando programas de respeto medioambiental. (37)



INDUSTRIAL



DOMÉSTICO

FASE 1

ANÁLISIS DEL ENTORNO:

ANÁLISIS TRITURADORAS

Las trituradoras son capaces de agilizar la secuencia de eliminación de residuos orgánicos en la **cocina**.

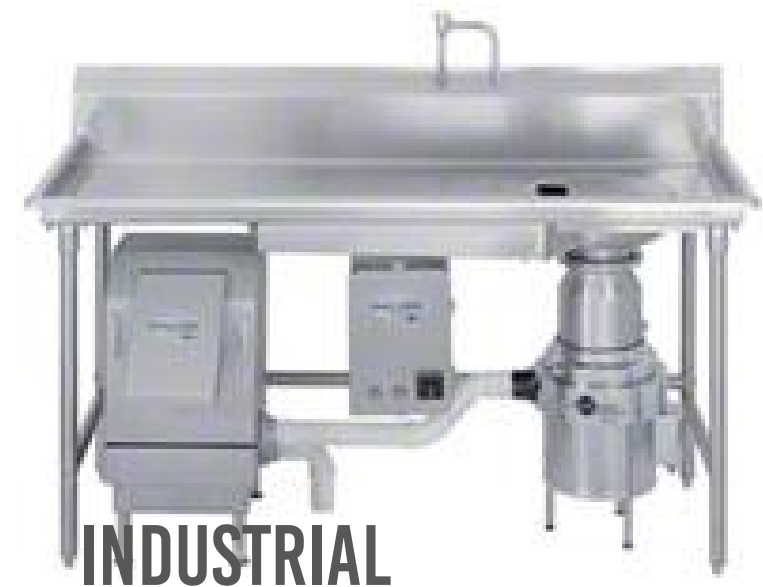
Se coloca **debajo de la fregadera**, conectando así con el desagüe. Su tamaño varía dependiendo del entorno en el cual se aplique. El volumen que ocupa el dispositivo se encuentra entre los 6 y 93 dm³, según sea destinado al ámbito doméstico o industrial. (38)

En el entorno doméstico al colocar las trituradoras bajo las fregaderas, éstas quedan ocultas tras armarios. Al ocupar un espacio reducido, permiten aprovechar el restante para almacenar otros objetos de la cocina.

Observando el entorno industrial, las trituradoras normalmente no quedan ocultas, ya que el factor estético que presenta importancia en el hogar, no lo hace en este ámbito de trabajo. Las cocinas son ante todo funcionales y el fácil acceso al triturador es esencial en caso de avería. Destinadas a cafeterías, restaurantes, hospitales, hoteles, y **espacios en los que se atiende a cientos de personas** en general. (39)



(40)

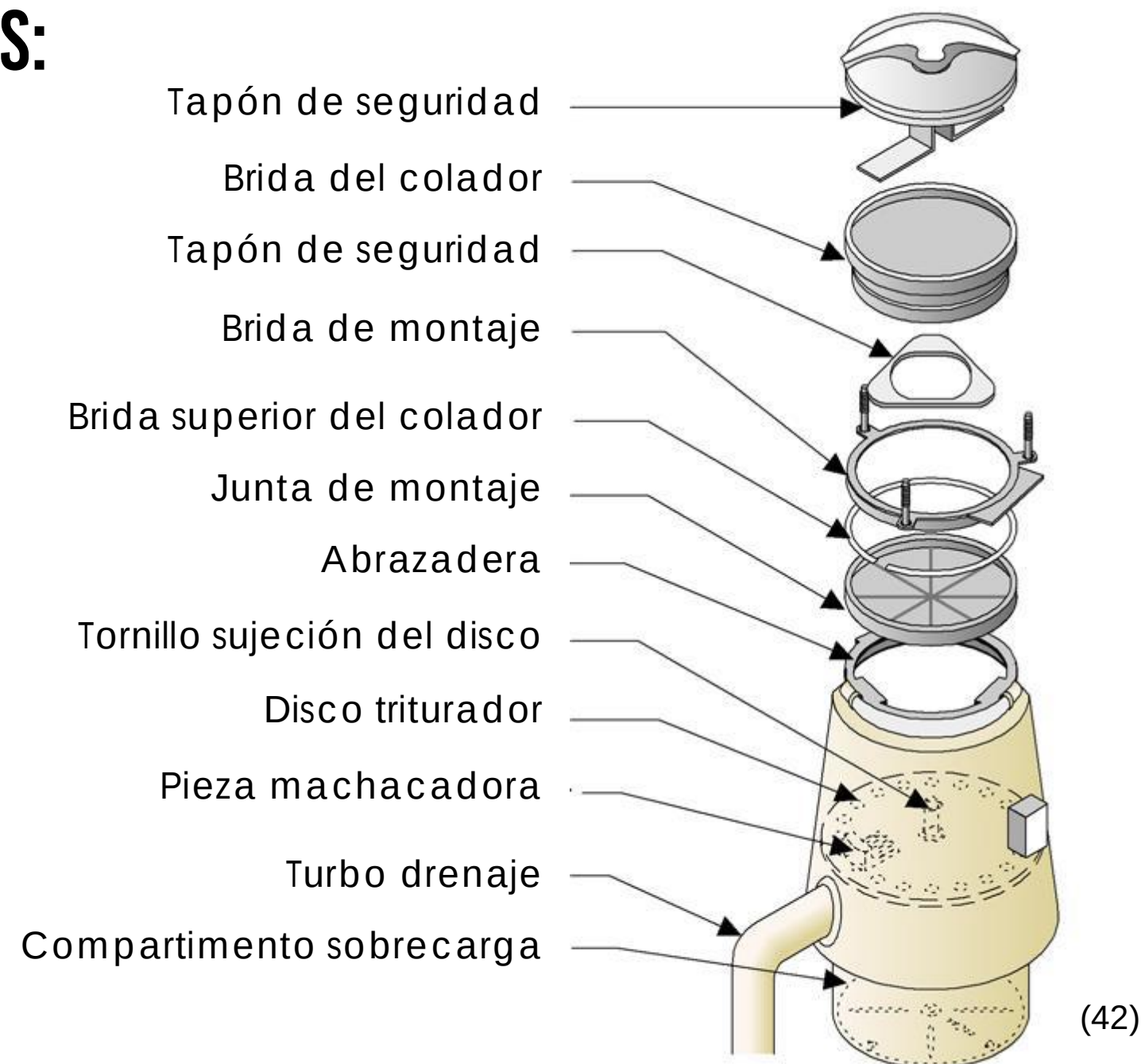


(41)

FASE 1

ANÁLISIS TRITURADORAS

ANÁLISIS DE COMPONENTES:



FASE 1

ANÁLISIS TRITURADORAS

ANÁLISIS FORMAL/FUNCIONAL:

El producto está dividido en una serie de piezas circulares que se encargan de procesar los residuos en un orden determinado.

La **forma cilíndrica** se debe a la conexión establecida con el **sumidero** de las fregaderas, también con estructura cilíndrica.

A raíz de este primer factor, se diseña su sistema de triturado. Lógicamente las paredes **curvas ayudan a dirigir los restos hacia el centro**. Con esta manera se evitan recovecos u obstáculos que atrapen los residuos y no permitan su completa eliminación.

Conforme fluyen los residuos por el aparato, son drenados a través de un **disco** encargado de triturar, desfibrar e impulsar los sólidos mezclados con agua.

Esto sucede gracias a unas **piezas con formas rectangulares** colocadas sobre este disco que arrastran los desechos a través de los orificios del disco. (44)



FASE 1

ANÁLISIS TRITURADORAS

ANÁLISIS FORMAL/FUNCIONAL:

Los desechos traspasan estos orificios gracias a la **aceleración centrípeta** que adquieren al girar en el disco en funcionamiento. Por ello los agujeros están dispuestos en el borde del disco triturador.

En este compartimento se recogen los restos sólidos de gran tamaño y conforme van chocando **contra las paredes y atravesando los agujeros**, disminuyen su tamaño.

Una vez conseguido el menor tamaño posible, el agua los arrastra por el tubo de drenaje. (44)



FASE 1

ANÁLISIS TRITURADORAS

ANÁLISIS DE USO: (45)

Separar los restos fibrosos y las peladuras de patata para evitar atascos si es requerido.



1



2

Abrir el grifo para que salga agua y así ayudar a drenar los residuos.

3

Encender el triturador y arrastrar los restos orgánicos hacia el sumidero.

4

Una vez eliminados los desechos, dejar correr el agua unos segundos más y apagar el dispositivo.

FASE 1

ESTUDIO DE MERCADO

ANÁLISIS:

TRITURADORAS

COMPACTADORAS

INVESTIGACIÓN

FASE 1

ANÁLISIS COMPACTADORAS

ANÁLISIS DEL ENTORNO/USUARIO:

Las compactadoras de residuos orgánicos son utilizadas en el ámbito industrial o doméstico, ya sea en hostelería o en el sector sanitario reduciendo el volumen de residuos y evitando molestos olores. Las mas comunes son las manejadas con vehículo, accionadas eléctricamente que se empujan por el usuario o compactadoras de prensa para interior.(46)



URBANO

(47)



INDUSTRIAL

(48)



DOMÉSTICO

(49)

FASE 1

ANÁLISIS COMPACTADORAS

Productos como este ayudan a motivar a la población a través de la innovación en este ámbito para facilitar la gestión, reciclaje y eliminación de residuos.

En **EE.UU** el entorno urbano de varias ciudades se acondiciona con compactadoras de basura para diferentes restos, ya sean envases, orgánicos o de papel y cartón.

La primera ciudad estadounidense en instalar este producto fue Needham, Massachusetts en 2003. Su funcionamiento se realiza a base de energía solar, y su uso se ha extendido a numerosas ciudades por todo el país (Nueva York, Boston, San Diego, Texas, etc). También se han implantado estas compactadoras en **Escocia** e **Inglaterra**. (50)

Actualmente en *Nueva Orleans* se ha determinado un sector de la ciudad para instalar este producto, concretamente en las calles más comerciales en las cuales la afluencia de gente es mayor. (51)

Philadelphia es otra de las ciudades que hacen uso de este tipo de productos, ya que ayudan a evitar malos olores en las calles, además de reducir el tránsito de camiones de recogida de basura. (52)



ANÁLISIS DEL
ENTORNO
/USUARIO:

URBANO

(47)

ANÁLISIS DEL ENTORNO /USUARIO:



(53)

FASE 1

ANÁLISIS COMPACTADORAS

Este servicio es muy beneficioso para el mantenimiento de las ciudades:

- ☐ Incrementa la limpieza
- ☐ Se ahorra en servicios de recogida
- ☐ Elimina olores
- ☐ Evita la aparición de plagas de roedores o insectos
- ☐ Promueve la conciencia social
- ☐ Aumenta la eficacia en la gestión de basura
- ☐ Invierte en un modelo de ciudad sostenible
- ☐ Mejora la calidad de vida de sus ciudadanos
- ☐ Instalación sencilla

(28)

URBANO

FASE 1

ANÁLISIS DEL ENTORNO /USUARIO:

ANÁLISIS COMPACTADORAS

El perfil de usuario en el entorno urbano coincide con una persona que se preocupa por la limpieza y el buen mantenimiento de su ciudad.

Posee una **visión de futuro** que apuesta por **ciudades más ecológicas**, en las cuales el impacto negativo de la sociedad sea mínimo. Defiende valores como el **reciclaje** y la reutilización para dar una segunda vida a los residuos que se generan diariamente.

Este modo de pensamiento hacia el medioambiente es el más adecuado para llegar a un futuro con recursos, ya que si se explotan sin limitaciones, las siguientes generaciones no podrán hacer frente a sus necesidades.

URBANO

A grayscale photograph of an industrial facility, likely a refinery or chemical plant, featuring tall distillation columns, complex piping, and storage tanks. The image is semi-transparent, serving as a background for the text on the left side of the slide.

ANÁLISIS DEL
ENTORNO
/USUARIO:

INDUSTRIAL (48)

FASE 1

ANÁLISIS COMPACTADORAS

En el sector industrial las compactadoras de basura orgánica se aplican en diferentes ámbitos, al ser responsables del manejo de un gran volumen de desechos. Algunos de los sectores que requieren este tipo de productos son la **hostelería, sanidad, fábricas, cárceles, universidades, grandes medios de transporte, aeropuertos, centros comerciales, edificios de viviendas, etc.**

En estos entornos comparados con el urbano, se requieren compactadoras de mayor tamaño para residuos orgánicos, ya que en el primer entorno se contemplan también otro tipo de residuos (papel, cartón, envases). (46)

Se trata de compactadoras de características similares, aunque sean aplicadas en ámbitos diferentes, ya que cubren necesidades comunes. Aun así existe una gran variedad, dependiendo de la cantidad de residuos de deban procesar. Es entonces cuando encontramos compactadoras industriales capaces de hacerse cargo de la basura de un edificio o plantas de reciclaje.

A continuación se van a desarrollar un par de ejemplos para la mejor comprensión de la manera en que el producto satisface a los usuarios y el papel que realiza en dichos entornos.

FASE 1

ANÁLISIS DEL ENTORNO /USUARIO:

ANÁLISIS COMPACTADORAS

Hostelería: en este sector el uso de compactadoras es habitual por la serie de ventajas que presentan para el control de una gran cantidad de residuos. El espacio en el cual se sitúan depende de las necesidades de los usuarios, ya sea en hoteles, restaurantes, colegios, cafeterías, comedores sociales, etc. (29)

En los **restaurantes de comida rápida** colocan este producto en la zona del comedor, ideados para vaciar la bandeja con todo tipo de residuos directamente en la basura. (29)

En cambio, los restaurantes que se dedican a otro tipo de cocina, colocan las compactadoras en el interior de las mismas. Al servir a usuarios que no desechan sus restos de comida de forma directa, el entorno del producto también cambia. Se contempla a si mismo, la necesidad de los **cocineros**, que trabajan los alimentos y eliminan restos o envoltorios de forma continua. (29)

INDUSTRIAL

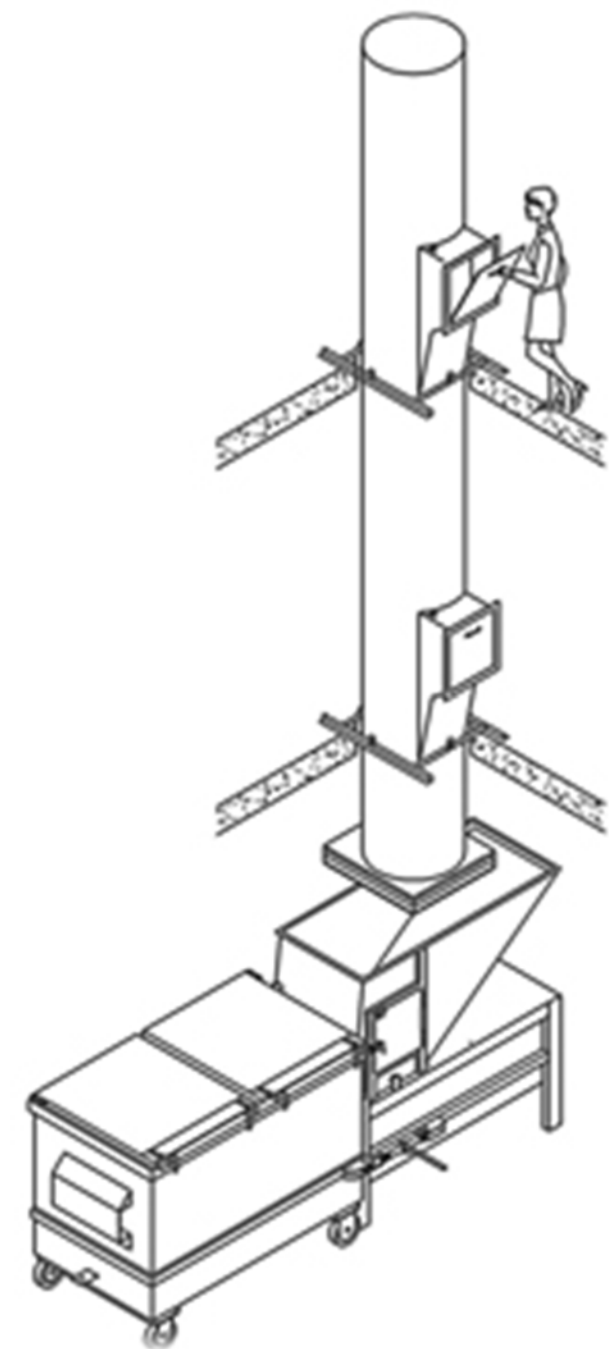
FASE 1

ANÁLISIS DEL ENTORNO /USUARIO:

ANÁLISIS COMPACTADORAS

Edificios: en una **comunidad** se genera un volumen de residuos que debe ser recolectado diariamente por los camiones de basura.

Debemos tener en cuenta que conforme el nivel adquisitivo es mayor, también lo es la cantidad de desperdicios que se generan. Una persona en EE.UU genera una media de 2kg(54) de residuos al día y en España esta cifra ronda los 1.3kg. (55) Si en un edificio suponiendo que viven una media de **200 personas** y producen al día 2kg de basura cada una, al final de la jornada sólo esta comunidad habría concentrado una cantidad de 400kg de desechos. Por ello la presencia de sistemas de compactación en estos entornos es fundamental para la gestión de residuos.



(56)

INDUSTRIAL

FASE 1

ANÁLISIS COMPACTADORAS

ANÁLISIS DEL
ENTORNO
/USUARIO:

En el entorno doméstico las compactadoras se sitúan bajo la encimera tal y como se realiza con otros electrodomésticos como lavadoras o lavavajillas. Su volumen es reducido y está destinado a usuarios concienciados con el medioambiente. (26)
Al ocupar menor espacio que las anteriores no obstaculizan el trabajo realizado en la cocina y están destinadas a facilitar la gestión de residuos en el hogar.



(57)

DOMÉSTICO (49)

ANÁLISIS FORMAL /FUNCIONAL:



AUTOMÁTICA

(58)

FASE 1

ANÁLISIS COMPACTADORAS

Compactadoras domésticas: esta clase de compactadoras, al estar destinadas a espacios más reducidos, son de menor tamaño.

Sus formas suelen ser **prismáticas**, ya que se colocan debajo de las encimeras como el resto de los electrodomésticos en la cocina.

Aquellas empotradas a la pared, poseen un sistema de extracción lateral de la basura ya compactada, mientras que las de figuras cilíndricas tienen la apertura en la zona superior. En estas últimas al no ser eléctricas, es el usuario el que debe ejercer presión de forma manual, en sentido vertical hacia abajo. Por ello su estructura ayuda a comprimir la basura de manera mas equitativa, ya que la fuerza se reparte por el área circular de la tapa aunque se focalice en la zona central.(59)

FASE 1

ANÁLISIS FORMAL /FUNCIONAL:

ANÁLISIS COMPACTADORAS

Compactadoras domésticas: La prensa rectangular propia de las compactadoras automáticas puede repartir la presión por todo el área al no concentrarse la tensión en un solo punto.

Las formas prismáticas tienen más capacidad y optimizan el espacio evitando molestias a los usuarios.

Las formas cilíndricas transmiten más cercanía y sus curvas se adaptan bien al movimiento del usuario respecto en el entorno, aunque no son muy prácticas en espacios reducidos.

En la zona superior de las compactadoras eléctricas se encuentra la interfaz mediante la cual el usuario programa el producto de forma personalizada. Llegan a reducir los restos alrededor de un 75% lo que implica ahorrar hasta 6 bolsas de basura. (59)

(59)



MANUAL

FASE 1

ANÁLISIS FORMAL
/FUNCIONAL:

ANÁLISIS COMPACTADORAS



Imágenes de compactadoras de la marca Broan

Los acabados que presentan son variados, En **acero inoxidable**, aporta sensación de limpieza, calidad técnica y seguridad. El acabado en **negro brillante** da sensación de elegancia, sofisticación y sobriedad. Además, como en el resto de electrodomésticos actuales, el usuario puede personalizar la parte delantera de su compactadora para que ésta quede totalmente **integrada** en su cocina.

FASE 1

ANÁLISIS FORMAL /FUNCIONAL:

ANÁLISIS COMPACTADORAS

Encontramos compactadoras de diferentes tipos según la necesidad específica que cubren. El entorno limita su volumen máximo y la función que desempeñan el mínimo.

Compactadoras comerciales: la cantidad de residuos que procesan es bastante alta y por ello su capacidad es mayor que las destinadas a uso doméstico. **Reducen de 8 a 12** el número de **veces** que debe ser vaciado el cubo de basura.(60)

Suelen ser estructuradas con formas prismáticas, racionalizando así el espacio. Están compuestas por un cajón que ocupa la mitad inferior del producto (en el cual se deposita la basura) y la prensa que se sitúa en la mitad superior junto con los componentes electrónicos.

Al estar destinadas a espacios públicos, su aspecto suele ser sobrio e impersonal. Suelen tener acabados en gris, negro o madera.

La zona por la cual el usuario debe introducir la basura queda muy bien delimitada, haciendo de él un producto intuitivo.

Funcionan de manera automatizada una vez programada y se basa en la afluencia de gente en el lugar de uso. La basura es compactada por la acción de la prensa, que desciende según haya sido programada. La mayoría también poseen un sensor que indica cuando el cajón se ha llenado, entonces comienza a compactar.(61)



(61)



FASE 1

ANÁLISIS FORMAL /FUNCIONAL:

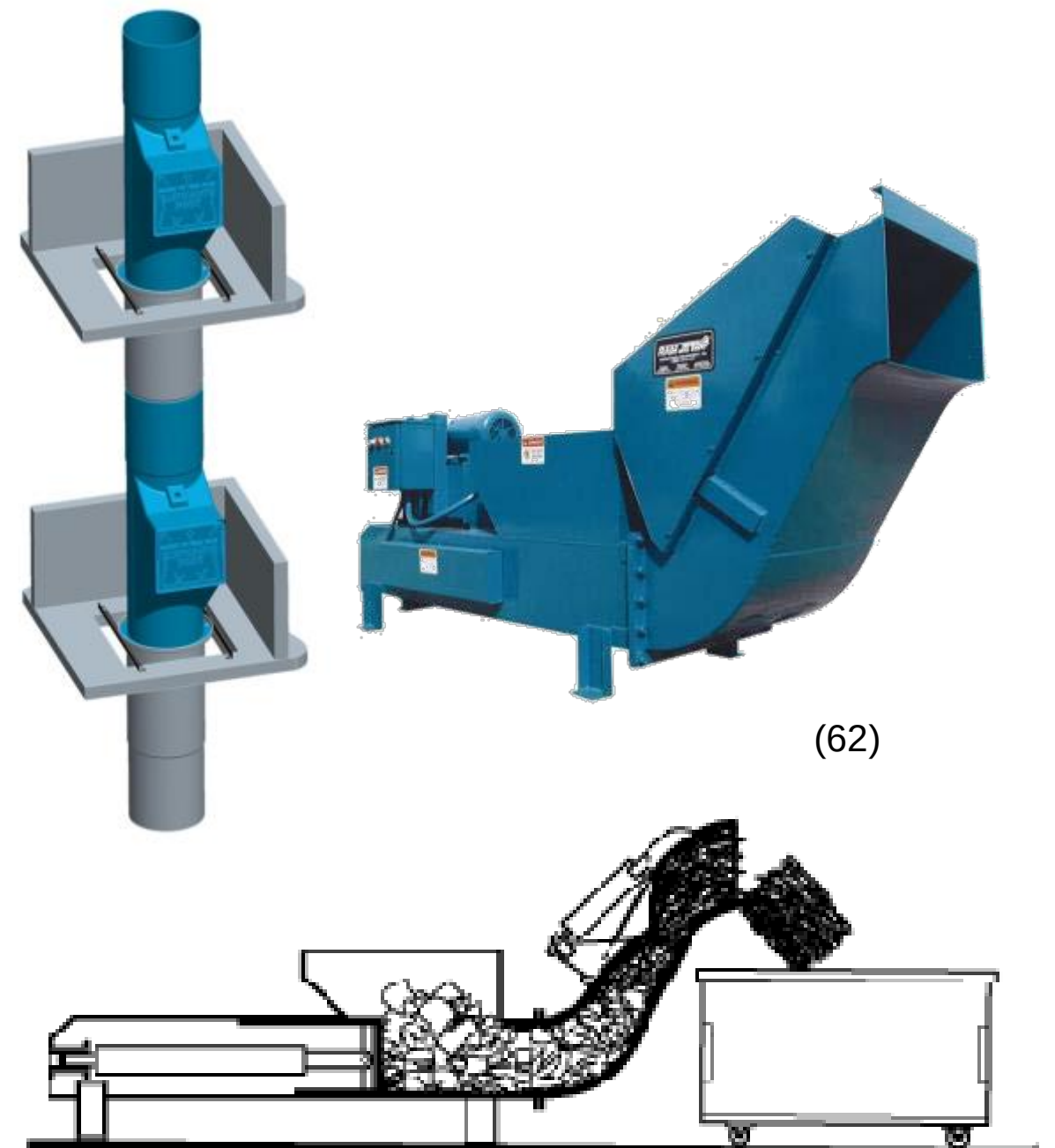
ANÁLISIS COMPACTADORAS

Compactadoras industriales: a diferencia de las estudiadas anteriormente, esta clase de compactadoras son encargadas de reducir toneladas de basura y están destinadas a edificios, plantas de reciclaje o fábricas. Su instalación requiere la realización de obras para colocar los tubos por los cuales descenden las bolsas de basura, que finalmente van a parar a las compactadoras. El área de la base es mayor que las domésticas o comerciales, teniendo así suficiente capacidad para realizar su función.

En los edificios, por ejemplo, reciben la basura a través de conductos de un diámetro de 76cm aproximadamente. Entonces las bolsas pasan a un compartimento con forma de **embudo** que las añade a la compactadora de forma regulada.

Las compactadoras destinadas a este uso rondan una **capacidad de 0.21m³**. Tienen una estructura similar a los grandes **contenedores** (prismas rectangulares) ya que así es posible optimizar el espacio de almacenamiento. (62)

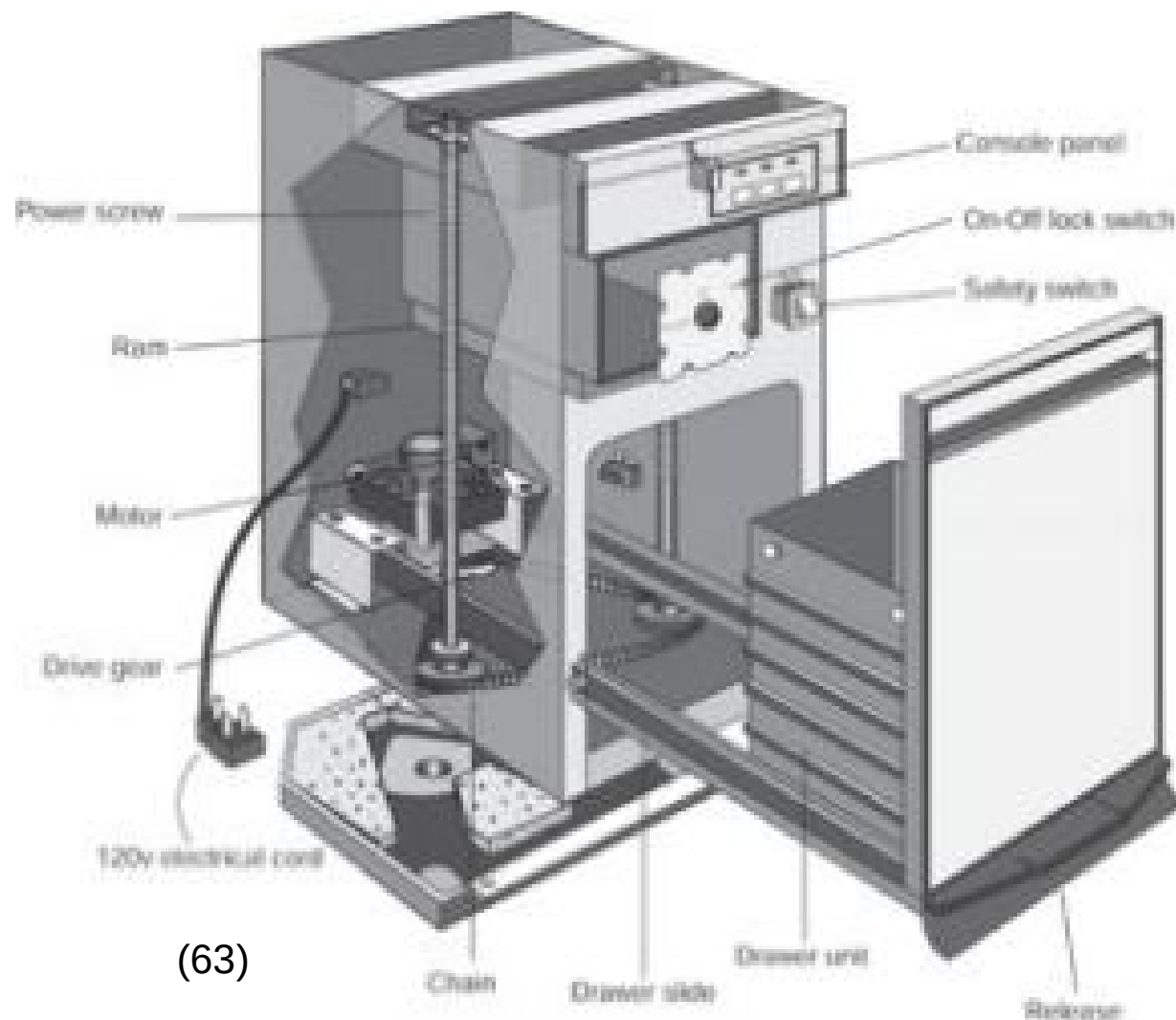
En este ejemplo de compactadora, uno de los extremos finaliza con **forma de "s"** coincidiendo por el hueco de salida del residuo compactado. Este factor es debido a que así se eleva el hueco de salida para facilitar la caída de lo compactado a los contenedores de recogida. Además esta curva en la estructura facilita el proceso de compactado.(62)



ANÁLISIS MECÁNICO /ELECTRÓNICO:

FASE 1

ANÁLISIS COMPACTADORAS



Las **compactadoras domésticas** poseen un mecanismo de prensa que utiliza alrededor de **1050kg** de fuerza, utilizando 220-230V de voltaje y una intensidad de corriente que ronda los **15A**.

El índice de compactación varía entre 5:1 a 6:1, compactando hasta un 85% de residuos.

El motor eléctrico requerido es de **0.25 KW**. Es el encargado de mover el sistema de engranajes y cadenas que hacen posible descender la prensa.

La prensa tarda en actuar una media de 30 segundos.

Poseen sistemas de ventilación para airear el interior de la compactadora, además de ayudarse de unos discos intercambiables ideados para absorber los malos olores.

(Información en anexo: Compactadora doméstica)

FASE 1

ANÁLISIS FORMAL /FUNCIONAL:

Las **compactadoras urbanas** se alimentan gracias a la energía solar, para poner en funcionamiento un motor que realiza alrededor de **5,3 KN** de fuerza.

Su mecanismo se basa en un **sistema de cadenas y engranajes**, necesitando una **batería de 12V** para poder compactar. Esta batería se cambia cada 3 semanas.

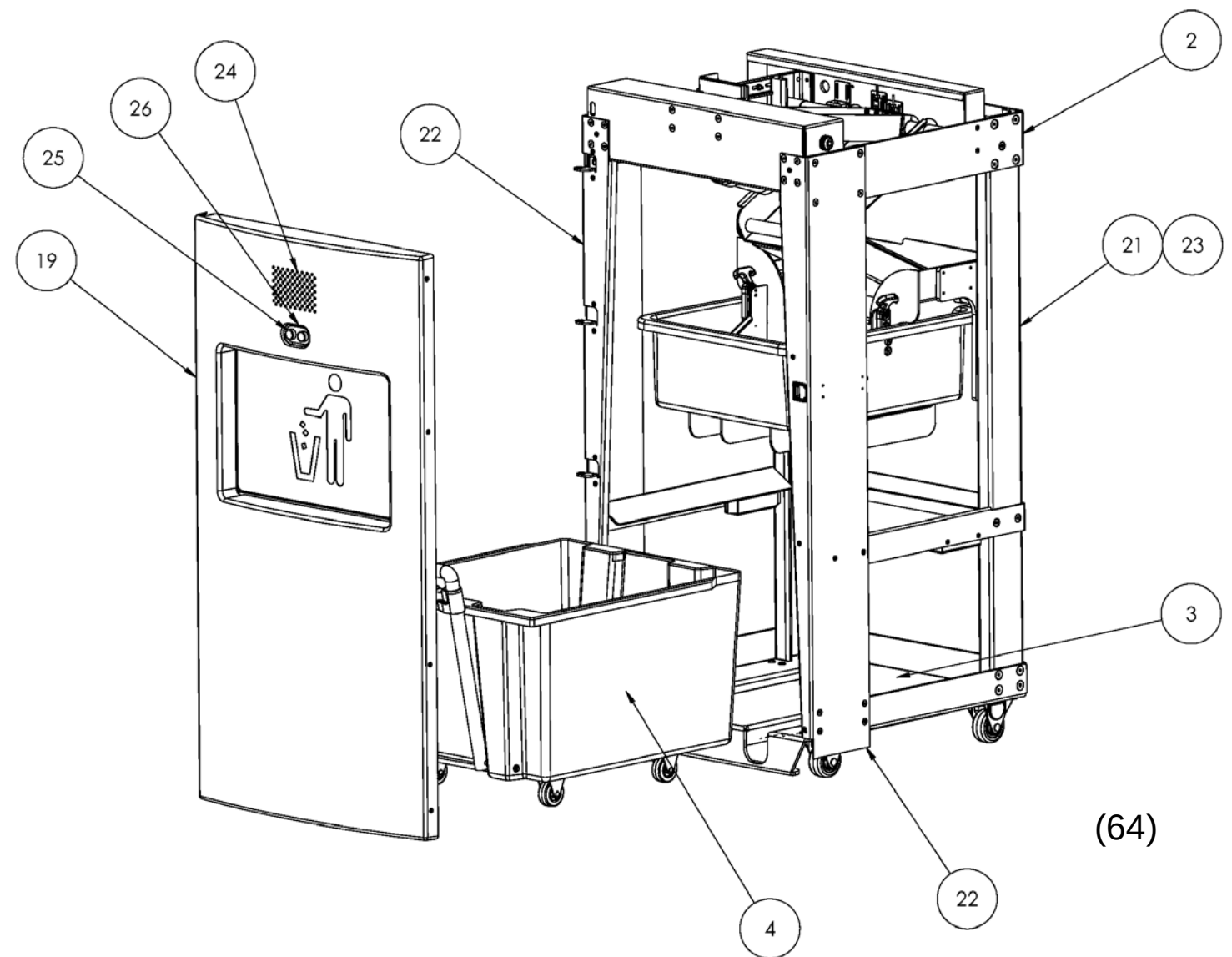
(Información en anexo: Compactadora urbana)

Las **compactadoras comerciales**, destinadas a centros comerciales, universidades y otros espacios públicos, se conectan a la corriente para permitir el funcionamiento de su **motor de 0.38 KW**. Consumen una intensidad de aproximadamente **15 A** y **115V**. Su mecanismo también se basa en la acción de **cadenas y engranajes**.

El proceso de compresión dura unos 7 segundos, pudiendo ser ajustable.

(Información en anexo: Compactadora comercial)

ANÁLISIS COMPACTADORAS



ANÁLISIS FORMAL /FUNCIONAL:

FASE 1

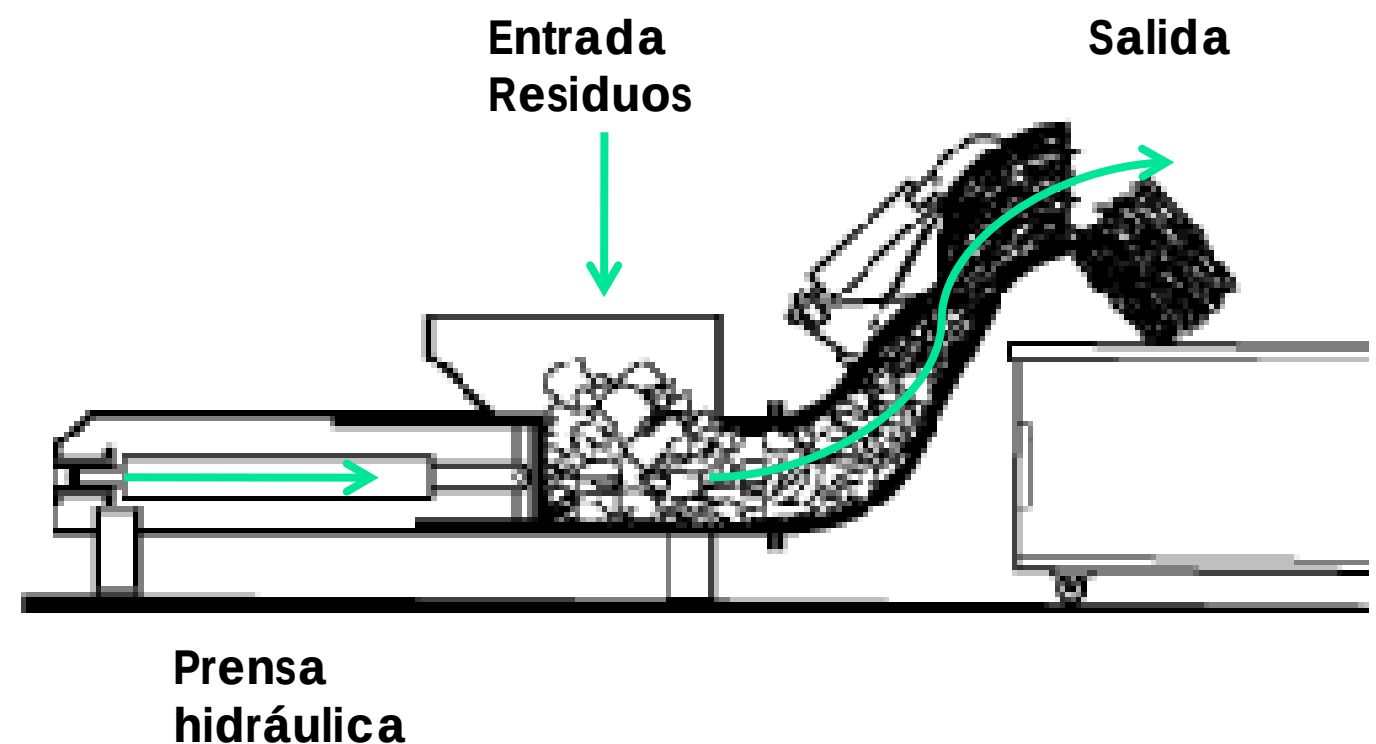
ANÁLISIS COMPACTADORAS

Compactadoras industriales:

ASPECTOS MECÁNICOS

Capacidad caja de carga	0.21m ³
Dimensiones tapa de entrada	775x711 mm
Capacidad/hora	25m ³
Ciclo	32s
Fuerza normal	206 kN
Fuerza máxima	257 kN
Presión compactación	885 kPa
Presión máxima	1105 kPa
Recorrido prensa	114 mm

(Información en anexo: Compactadora industrial)



FASE 1

ANÁLISIS FORMAL /FUNCIONAL:

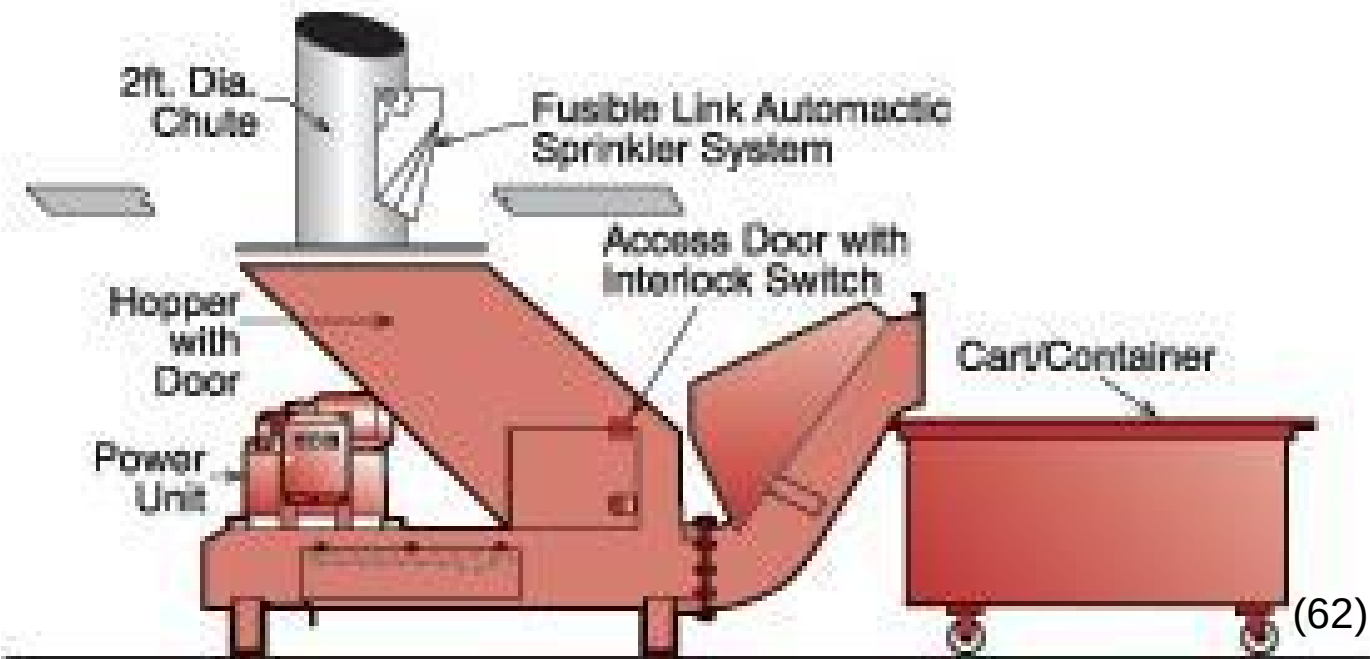
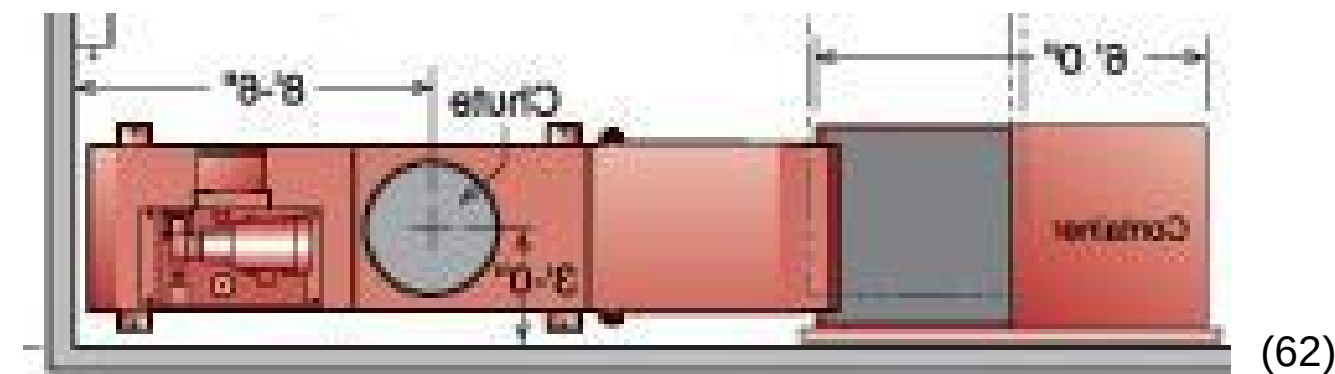
ANÁLISIS COMPACTADORAS

Compactadoras industriales:

ASPECTOS ELÉCTRICOS	
Motor	11.2 kW
Voltaje	120 VAC
Panel Control	NEMA tipo 3

ASPECTOS HIDRÁULICOS	
Capacidad bomba	70 L/min
Presión	83 bar
Presión máxima	103 bar
Cilindro	Ø102mm
Peso	1497 kg

(Información en anexo: Compactadora industrial)



FASE 1

ESTUDIO DE MERCADO
ANÁLISIS
INVESTIGACIÓN

FASE 1

EAP'S ELECTRÓNICOS // ESTUDIO GENERAL

INVESTIGACIÓN PEA

POLÍMEROS FERROELÉCTRICOS	Cristal no conductor polarizado. Reversible por otro campo E. Funcionan en agua, aire y vacío.
POLÍMEROS DIELECTRICOS	Baja rigidez elástica y alta constante dieléctrica. Muy deformables. Gran similitud músculos.
PAPEL ELECTROELECTRICO	Adhesivo de papel con propiedades electroactivas.
ELASTÓMEROS ELECTROELECTRICO DE INJERTO	Elastómero de grafito con propiedades electroactivas. Macromoléculas
ELASTÓMEROS ELECTRO-VISCOELÁSTICOS	Silicona + fase polar que se polariza con campo E. Módulo de corte depende del campo E.
ELASTÓMEROS DE LÍQUIDO CRISTALINO	Características piezoeléctricas. Estructura alineada según tensión mecánica y se queda fija.

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

¿CÓMO FUNCIONAN?

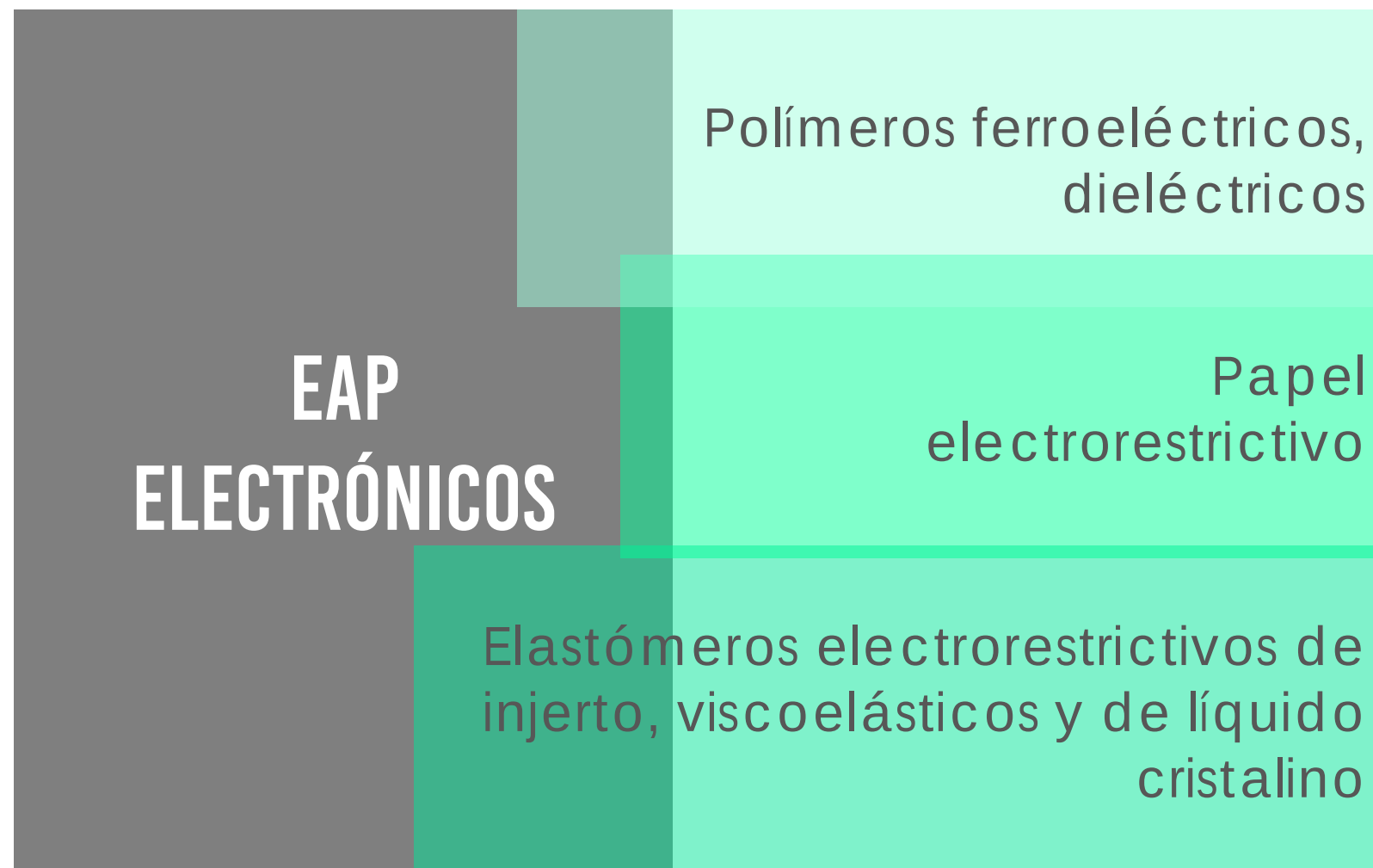
Gracias a campos o altas fuerzas eléctricas.

Corriente continua.

Desplazamientos producidos por voltaje

FASE 1

INVESTIGACIÓN PEA



VENTAJAS

Funcionan a temp. ambiente durante mucho rato.

Respuesta rápida (ms)

Inducen grandes fuerzas de actuación

Mantienen tensión por debajo de la de activación

INCONVENIENTES

Altos campos eléctricos necesarios.

Temp. de transición vítrea inadecuada para tareas en temp. bajas.

(Información en anexos: «EAP's ventajas – inconvenientes», tabla 1y «Aplicaciones polímeros electroactivos», pág.15)

FASE 1

EAP'S ELECTRÓNICOS // APLICACIONES

DIELÉCTRICOS

// APLICACIONES

Retroalimentación háptica
Músculos artificiales
Posicionadores ópticos para enfoque automático, zoom, estabilizador de imagen (c)
Muestras de braille activas (d)
Bombas
Válvulas
Prótesis
Control activo de vibraciones de estructuras
Altavoces
Ventanas con anulación de ruido
Motores

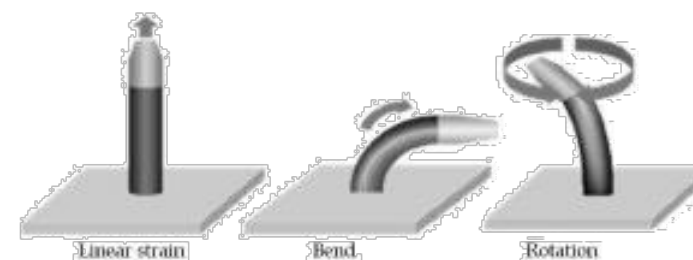
❑ Propiedades: elongación, alta densidad de energía elástica, eficiencia y velocidad de respuesta. Son ligeros, económicos y han exhibido un buen desempeño en demostraciones de laboratorio.

❑ Alto potencial en reemplazar a actuadores piezoeléctricos, neumáticos y electromagnéticos.

(Información en anexo: «Aplicaciones polímeros electroactivos»)

INVESTIGACIÓN PEA

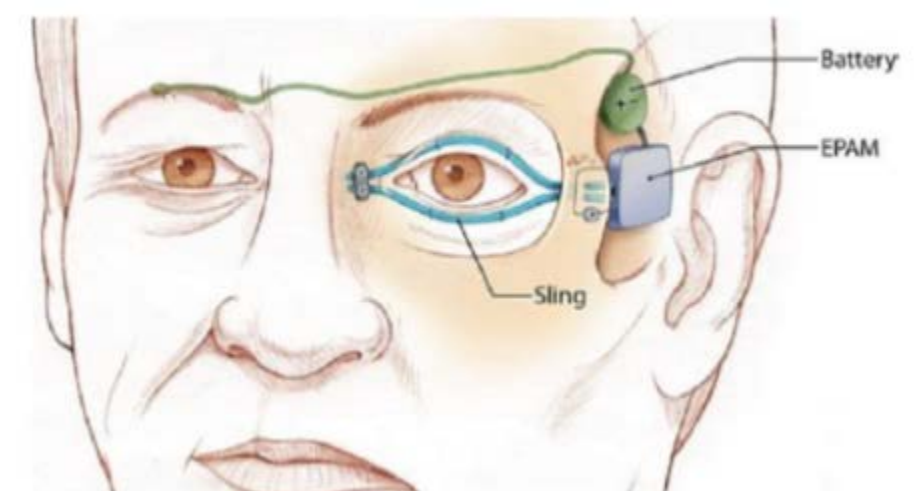
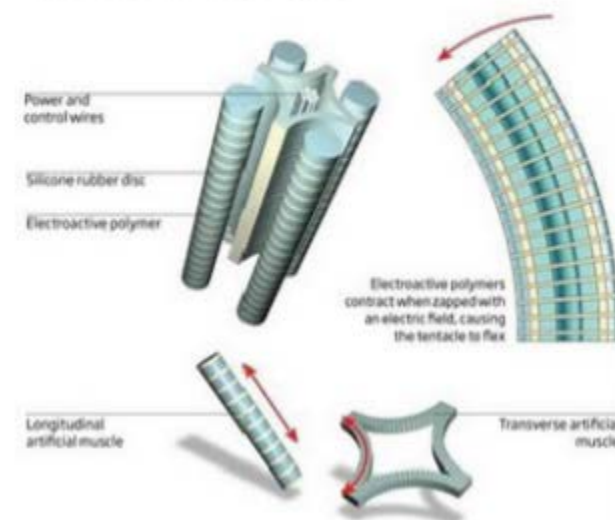
3 grados de libertad



b)

Artificial tentacles

The structure of octopus arms can be reproduced using artificial muscles made of silicone rubber interspersed with electroactive polymers.



FASE 1

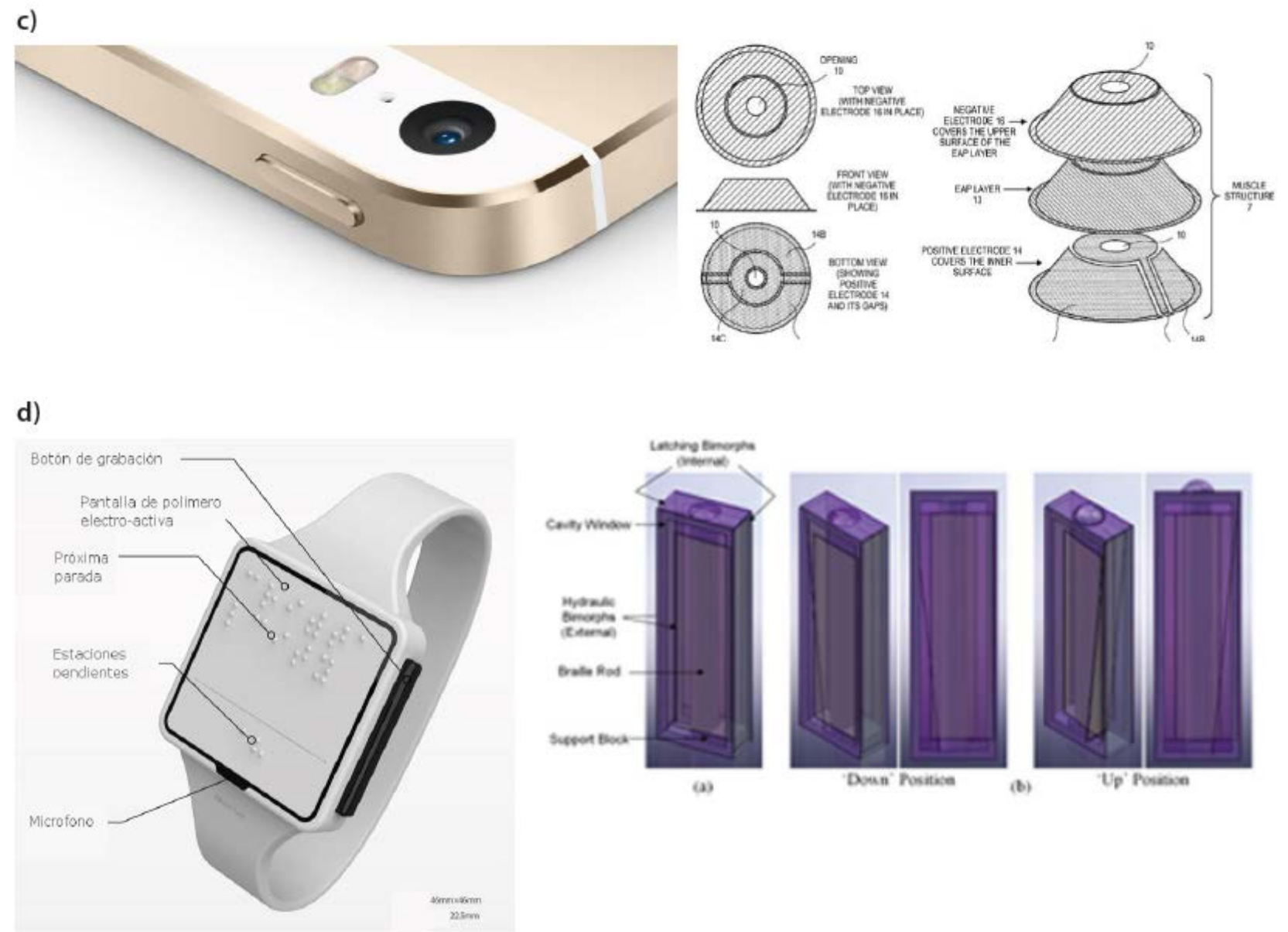
EAP'S ELECTRÓNICOS // APLICACIONES

DIELÉCTRICOS

// APLICACIONES

Retroalimentación háptica
Músculos artificiales
Posicionadores ópticos para enfoque automático, zoom, estabilizador de imagen (c)
Muestras de braille activas (d)
Bombas
Válvulas
Prótesis
Control activo de vibraciones de estructuras
Altavoces
Ventanas con anulación de ruido
Motores

INVESTIGACIÓN PEA



(Información en anexo: «Aplicaciones polímeros electroactivos»)

FASE 1

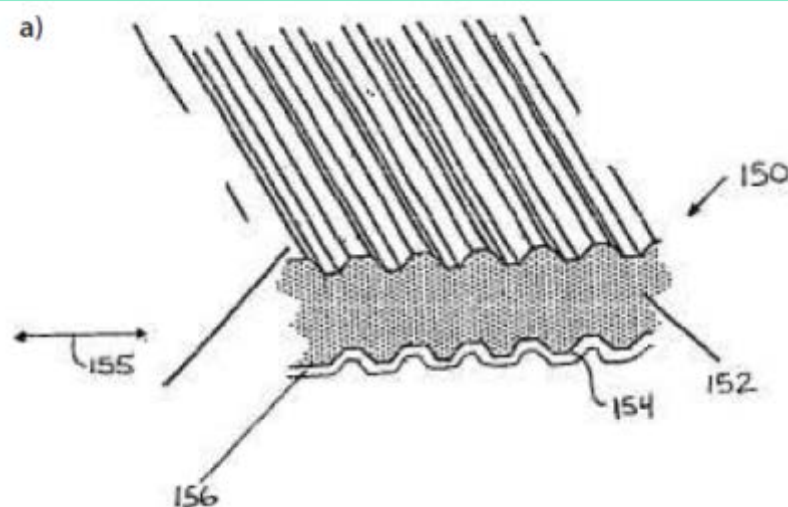
EAP'S ELECTRÓNICOS // APLICACIONES

FERROELÉCTRICOS

- ❑ Propiedades: piezoelectricidad y piroelectricidad.
- ❑ PVDF: alta resistencia eléctrica, buena resistencia a la llama y baja impedancia acústica, permisividades y conductividad térmica.

// APLICACIONES

Transductores electroacústicos (a)
Altavoces
Dispositivos ultrasónicos
Actuadores electromecánicos



(Información en anexo: «Aplicaciones polímeros electroactivos»)

INVESTIGACIÓN PEA

ELASTÓMERO DE CRISTAL LÍQUIDO

- ❑ Alargan en presencia de orden nemático y se contraen cuando éste se pierde (calentamiento, iluminación o disolvente)
- ❑ Actúan como músculo = fase nemático a isotrópica hace que se contraiga uniaxialmente.
- ❑ Alta capacidad de reacción y de deformación mecánica-
- ❑ MATRIZ ELASTOMÉRICA: vencen limitaciones de voltaje por presentar % de actuación mejorados.

// APLICACIONES

Dispositivos Industriales
Microválvulas
Brazos articulados
Dispositivos electrónicos
Altavoces ultraplano
Posicionadores de lente
Componentes biomédicos
Prótesis
Vendajes activos



FASE 1

EAP'S ELECTRÓNICOS // APLICACIONES

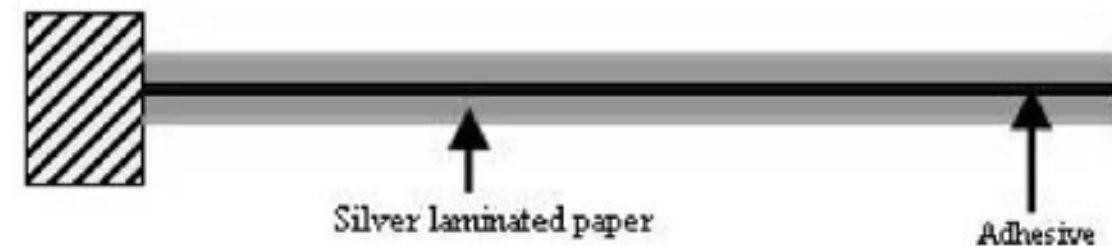
INVESTIGACIÓN PEA

PAPEL ELECTROESTRICTIVO

- ❑ Material electrostrictivo sólo puede alargarse mientras que el piezoeléctrico puede también contraerse.
- ❑ Producen grandes desplazamientos con una pequeña fuerza bajo una excitación eléctrica. La hoja se compone de una red de partículas de naturaleza fibrosa.
- ❑ Fabricado mediante la unión de dos papeles laminados de plata con electrodos de plata colocados en la superficie exterior. Cuando se aplica una tensión eléctrica a los electrodos del actuador se produce el desplazamiento.
- ❑ Peso ligero y de fácil aplicación.

// APLICACIONES

Amortiguadores de sonido
Altavoces activos flexibles
Dispositivos inteligentes de control de forma

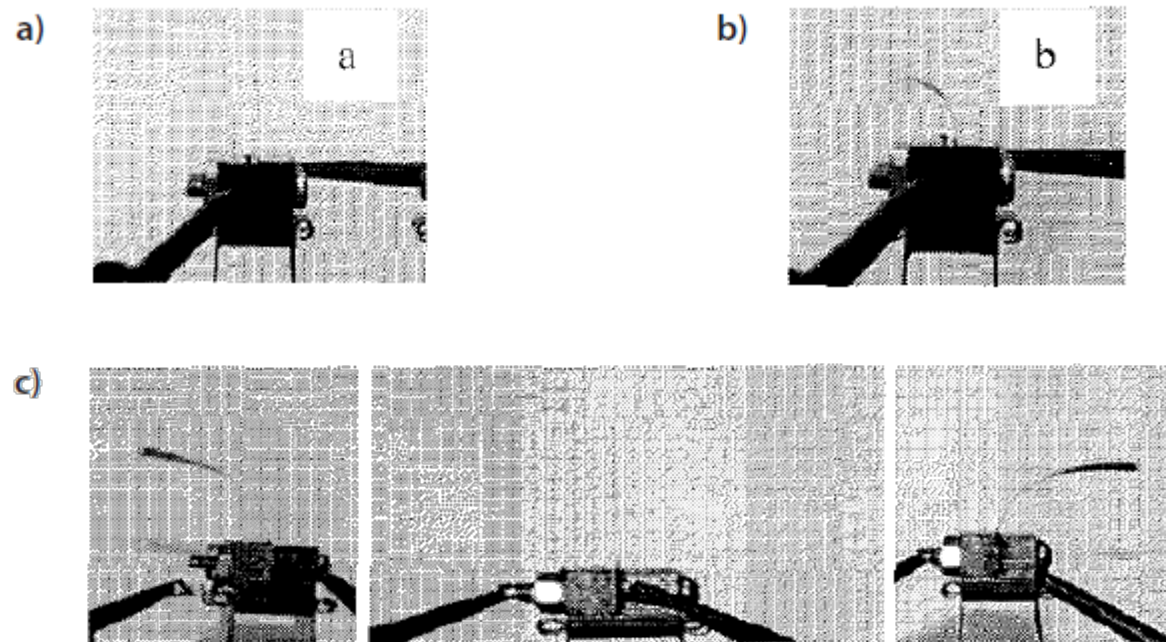


FASE 1

EAP'S ELECTRÓNICOS // APLICACIONES

ELASTÓMEROS ELECTROELECTRIVOS DE INJERTO

Polímero piezoeléctrico + elastómero electrorestritivo de injerto = **Actuadores electrorestritivos**



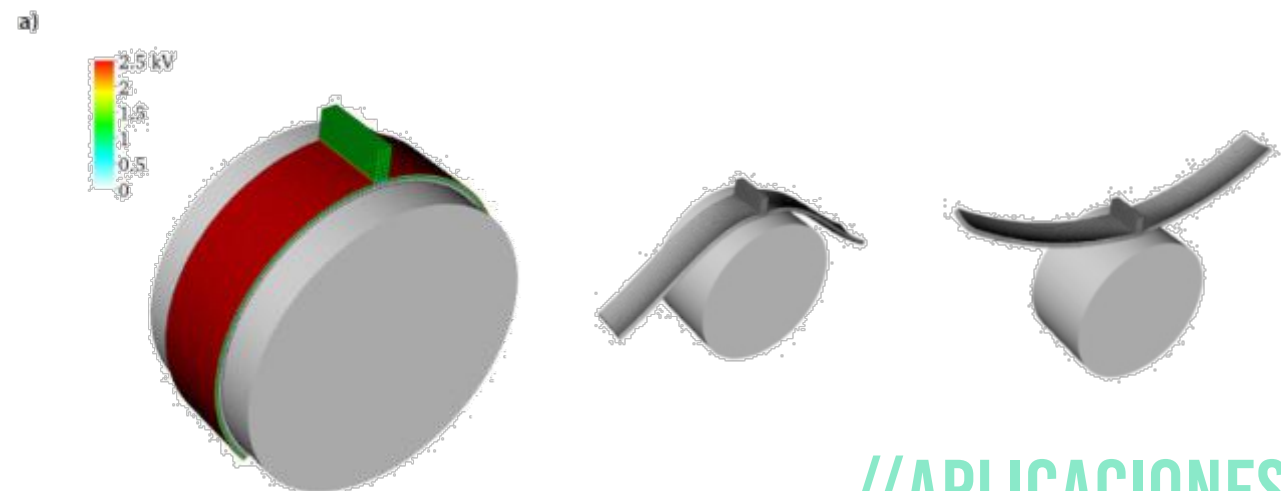
// APLICACIONES

Músculos artificiales

INVESTIGACIÓN PEA

ELASTÓMEROS ELECTRO-VISCOELÁSTICOS

- Rigidez y amortiguación dependiendo de temperatura, frecuencia y tensión aplicadas.
- Silicona elastómero + fase polar.
- Módulo de corte varía con campo E ($<6V/m$)



// APLICACIONES

Aplicaciones adaptativas (pinza) (a)
Músculos artificiales
Válvulas
Frenos
Embragues
Amortiguadores
Microfluidos

(Información en anexo: «Aplicaciones polímeros electroactivos»)

FASE 1

EAP'S IÓNICOS //ESTUDIO GENERAL

INVESTIGACIÓN PEA

GELES DE POLÍMERO IÓNICO	Fuertes actuadores. Ácido-alcálido.
COMPUESTOS PORLÍMERO-METÁLICOS IONOMÉRICOS	Movilidad de cationes por red permiten su deformación. Bajos voltajes.
POLÍMEROS CONDUCTORES	La movilidad de los iones hincha el polímero. Bajos voltajes.
NANOTUBOS DE CARBONO	La variación de la distancia entre los enlaces hace que se estire o contraiga la red de nanotubos.
FLUIDOS ELECTRO-REOLÓGICOS	Suspensión de polímeros en un líquido con constante dieléctrica. Variación de viscosidad, consistencia, fluencia debido al campo E transformándose en gel (incluso en sólido).

¿CÓMO FUNCIONAN?

Gracias a voltajes entre 1 y 2 V + humedad.

Así se produce la difusión y el movimiento de los iones.

Es difícil mantener una corriente continua

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

FASE 1

INVESTIGACIÓN PEA

EAP IÓNICOS

Geles iónicos

Compuestos
polímero-metal
ionoméricos

Polímeros
conuctores

Nanotubos de carbono

VENTAJAS

Funcionan a
bajos voltajes

Permiten
doblado

Grandes
desplazamientos
en doblado

INCONVENIENTES

Respuesta lenta
(fracción de
segundo)

El material se
dobla con menos
fuerza

Bajo rendimiento

Hidrólisis en agua
si $V > 1.23V$

No mantienen
tensión por
debajo de I
continua

(Información en anexos: «EAP's ventajas – inconvenientes»,
tabla 1y «Aplicaciones polímeros electroactivos», pág.15)

FASE 1

EAP'S IÓNICOS // APLICACIONES

GELES DE POLÍMERO IÓNICO

- ❑ Gel biomimético que puede andar como un gusano por la energía química disipada de una reacción oscilante.
- ❑ Compresión del gel por aplicación de voltaje, al desconectar la corriente éste se estira.
- ❑ Prototipo de mano robótica capaz de coger pequeños objetos.

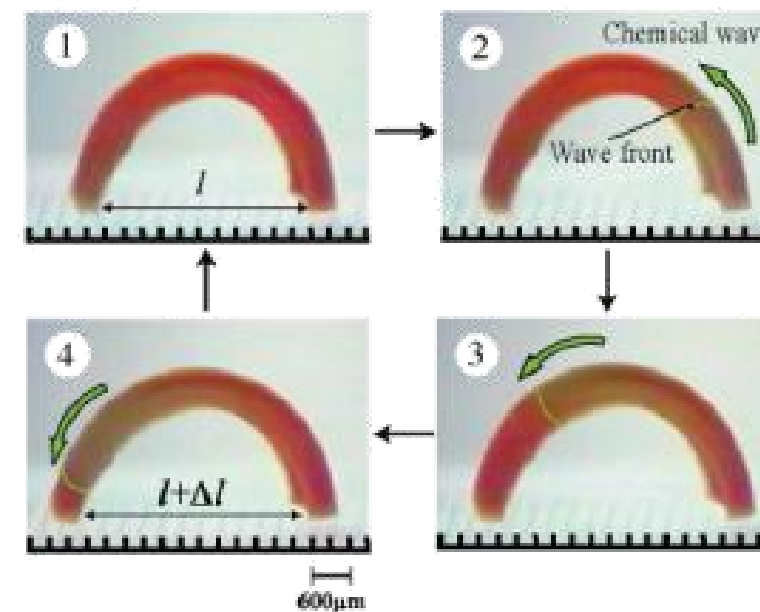
// APLICACIONES

Movimiento autónomo (a)
Transporte (b)
Músculos artificiales (c)
Interruptores
Altavoces

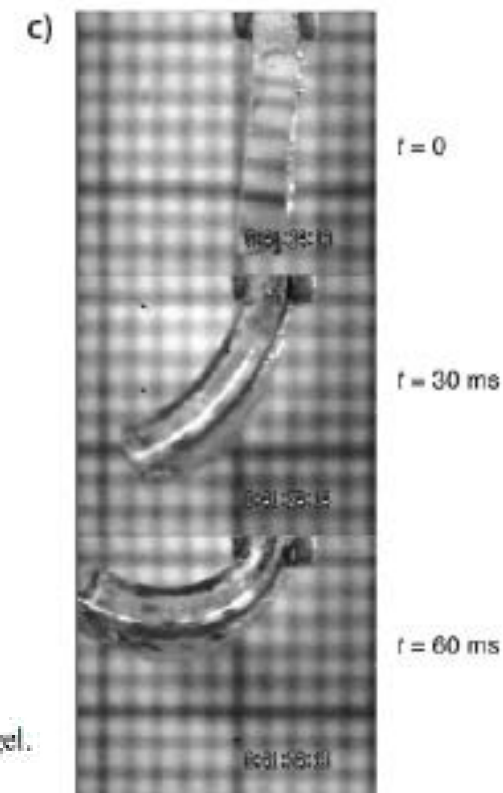
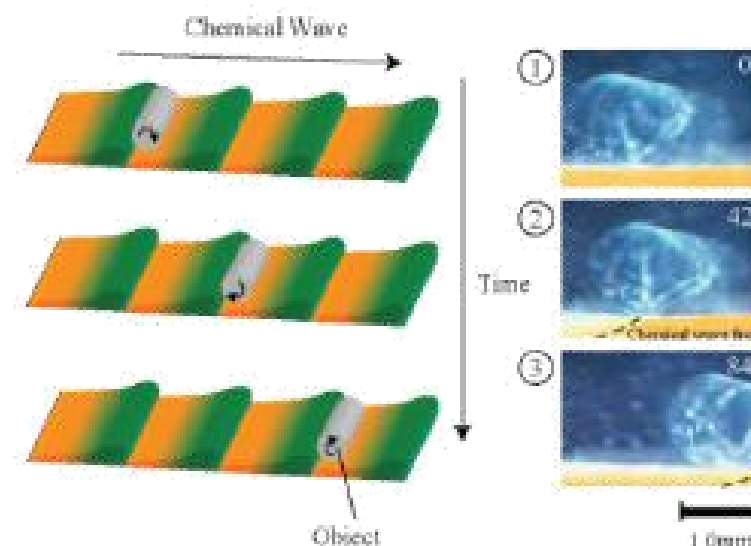
(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

INVESTIGACIÓN PEA

a) Cyclic process



b) Figure 11. Schematic illustration of the matter transport using peristaltic motion of the gel. Reproduced from [29].



EAP'S IÓNICOS // APLICACIONES

COMPUESTOS POLÍMERO-METÁLICOS IONOMÉRICOS

❑ Su respuesta es ligeramente superior a las aleaciones de memoria-forma y pueden utilizarse para **emular las operaciones de los músculos biológicos**.

❑ Propiedades únicas de baja densidad al igual que una alta resistencia mecánica y un gran rango de tensión para actuar.

❑ Existen actuadores **multidireccionales** gracias a un transductor de 4 electrodos. Se plantea para realizar cirugía láser ocular.

❑ Prototipos de **pinzas** que simulan apertura y cierre de dedos al agarrar objetos.

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

FASE 1

INVESTIGACIÓN PEA

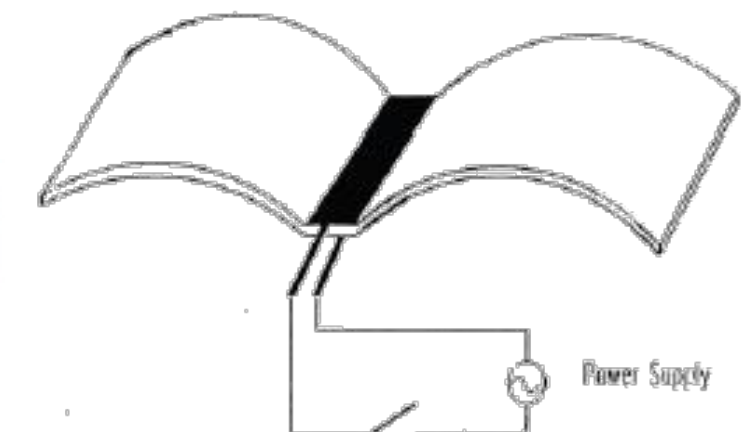


Figure 16. Wing-flapping flying machine design depicted schematically.

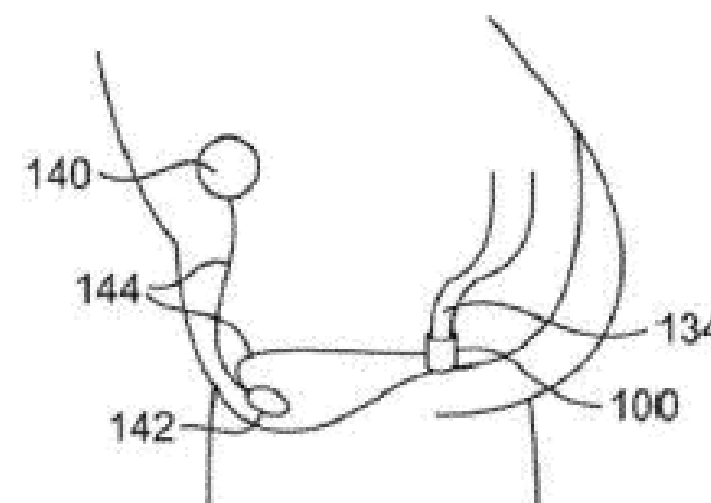


Fig. (2). Cuff sphincter (100) for regulation of the urinary incontinence in a woman patient [5].

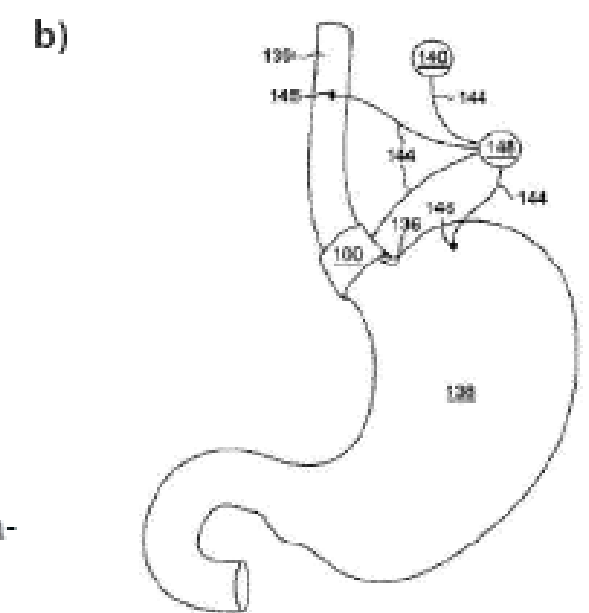
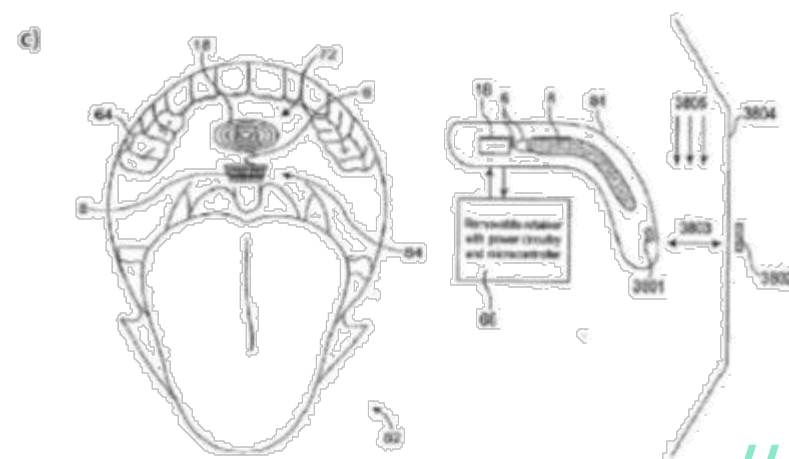


Fig. (1). Esophageal sphincter (100) made by IPMC material [5].

FASE 1

EAP'S IÓNICOS // APLICACIONES

COMPUESTOS POLÍMERO-METÁLICOS IONOMÉRICOS



// APLICACIONES

- Músculo artificial (a)
- Esfínter para incontinencia urinaria/estomacal (b)
- Tratamiento contra la apnea (c)
- Marcapasos en forma de parche (d)
- Control microfluídos (e)
- Actuadores lineales (f)

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

INVESTIGACIÓN PEA

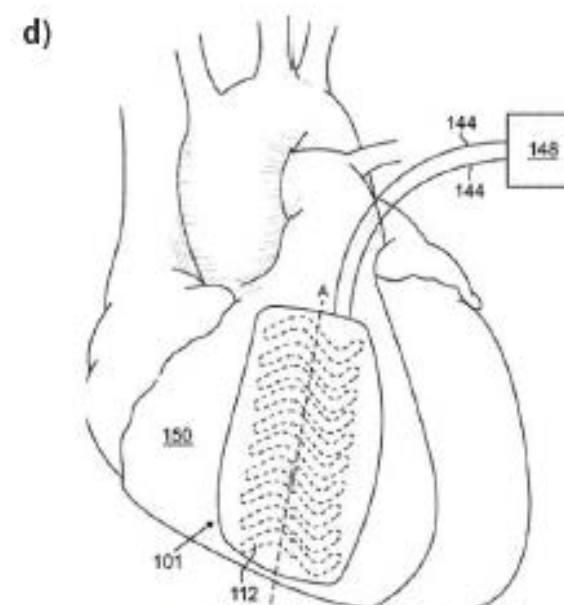


Fig. (3). Artificial muscle patch (101) attached to a heart [5].

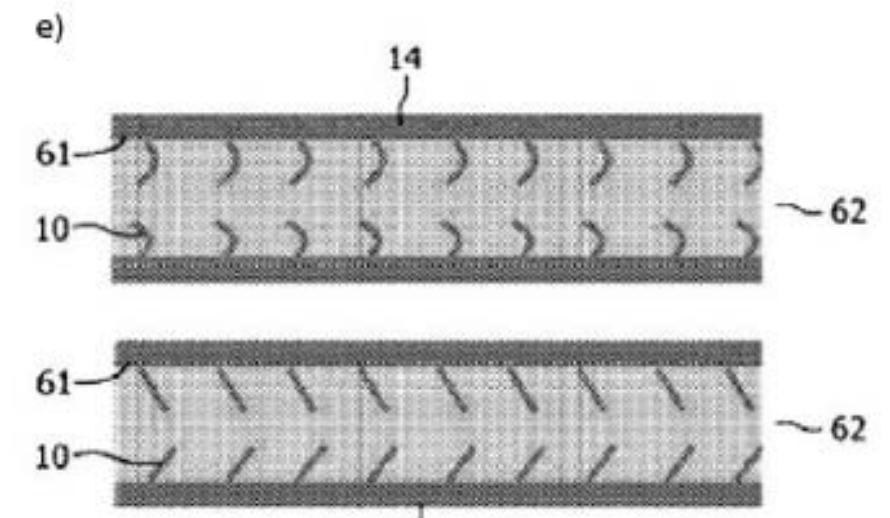


Fig. (10). Control of the fluid flux by IPMC actuators [8].

f)

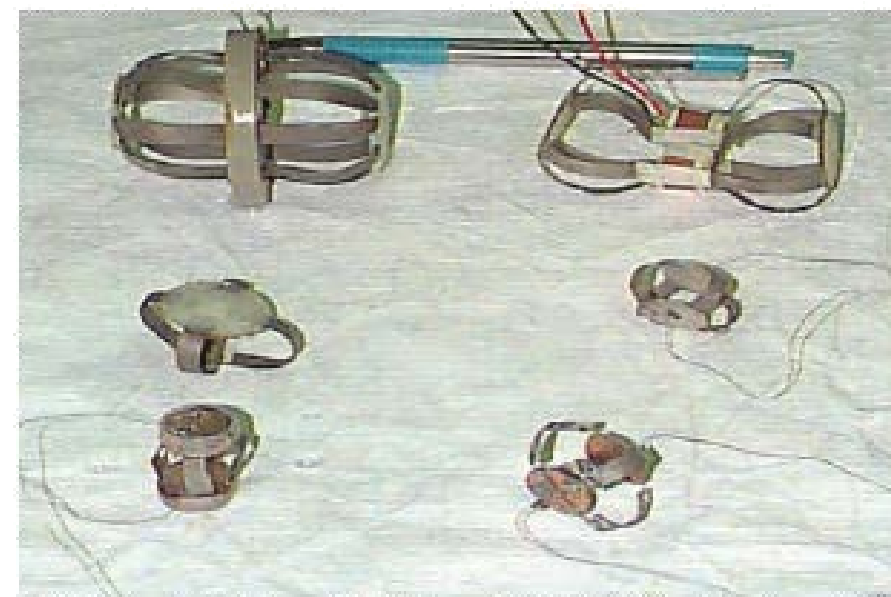


Figure 12. An assortment of linear and platform type actuators based on the design depicted in figure 11.

EAP'S IÓNICOS // APLICACIONES

POLÍMEROS CONDUCTORES

- ❑ Trabajan a **contracción y extensión**, basándose en un proceso electroquímico reversible controlable.
- ❑ Capaces de levantar 1000 veces su propio peso.
- ❑ Bajo voltaje

// APLICACIONES

Músculos artificiales (a)
Dispositivos para braille
Válvulas
Catéteres

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

FASE 1

INVESTIGACIÓN PEA

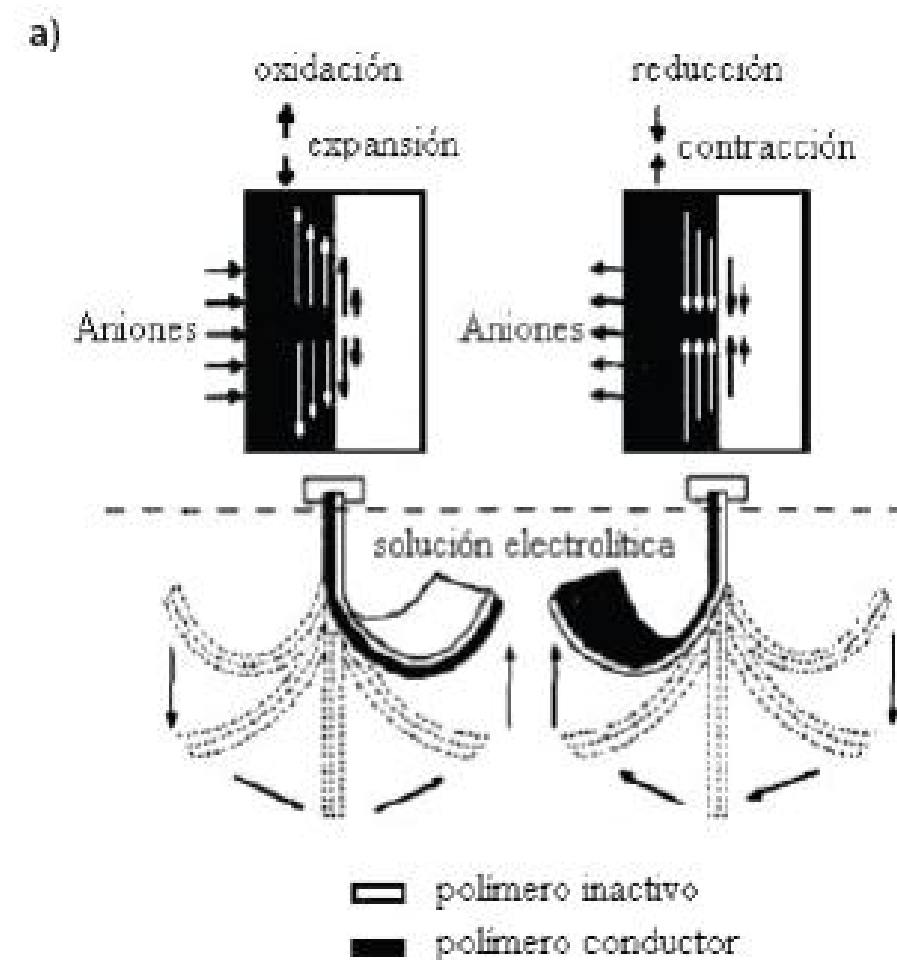


Fig. 3.12. Movimiento de una bicapa polímero conductor/cinta adhesiva, con la distribución de tensiones entre el polímero y la cinta y con los movimientos de aniones [20].

FASE 1

EAP'S IÓNICOS // APLICACIONES

NANOTUBOS DE CARBONO

❑ Una fibra de nanotubos hilados **pueden elevar 200 veces el peso que podría elevar un musculo** de ese tamaño o lo que sería 50.000 el peso del nanotubo

❑ Prototipo de láminas de aerogel de nanotubos de carbono que **puede operar entre -196 °C y 1538 °C**. Puede llegar a estirarse 10 veces más que un musculo natural y 1000 veces más rápido. Además **genera 30 veces la fuerza de un musculo con la misma sección**. Mientras que los músculos naturales puedes contraerse al 20% por segundo, estos nuevos músculos artificiales pueden contraerse a 30.000% por segundo.

❑ Son candidatos perfectos para situaciones donde el peso y la temperatura son importantes (aplicaciones aeroespaciales).

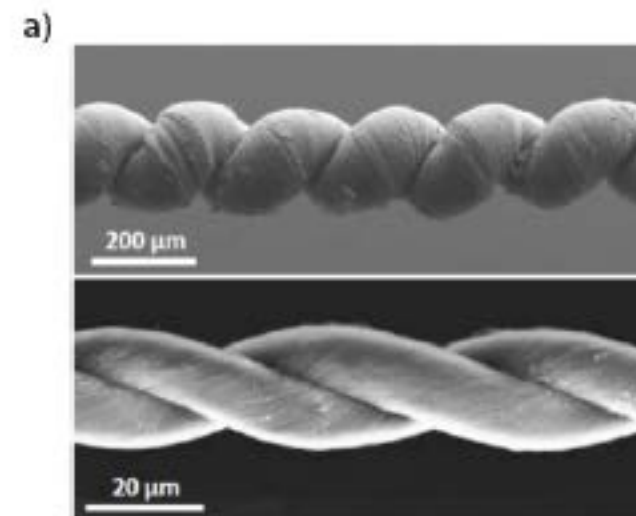
❑ Lámina para generar válvulas o bombas dada su **alta capacidad de trabajo por ciclo**.

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

INVESTIGACIÓN PEA

// APLICACIONES

Músculos artificiales (a)
Microbombas (b)
Microfluidos
Dispositivos ópticos



FASE 1

EAP'S IÓNICOS // APLICACIONES

INVESTIGACIÓN PEA

FLUIDOS ELECTRO-REOLÓGICOS

❑ Prototipos de pequeños actuadores mecánicos con una capacidad de **respuesta en menos de 100 ms**. Capacidad de **soportar 1,2 gramos**.

❑ Capacidad de endurecimiento en una fracción de segundo gracias a un determinado potencial que abre o cierra válvulas.

❑ Su cambio en la viscosidad puede aplicarse en amortiguadores o en pantallas flexibles que interesen que sean rígidas en determinados momentos y flexibles en otros (Motorola).

❑ **Producen más energía mecánica que la eléctrica que usan**, por ello se pueden aplicar como amplificadores.

❑ Dispositivos de recuperación permiten generar movimientos más suaves, ayudando a seguir y medir el progreso del paciente de forma más cómoda y precisa.

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)

// APLICACIONES

Músculos artificiales

Válvulas (a)

Frenos (b)

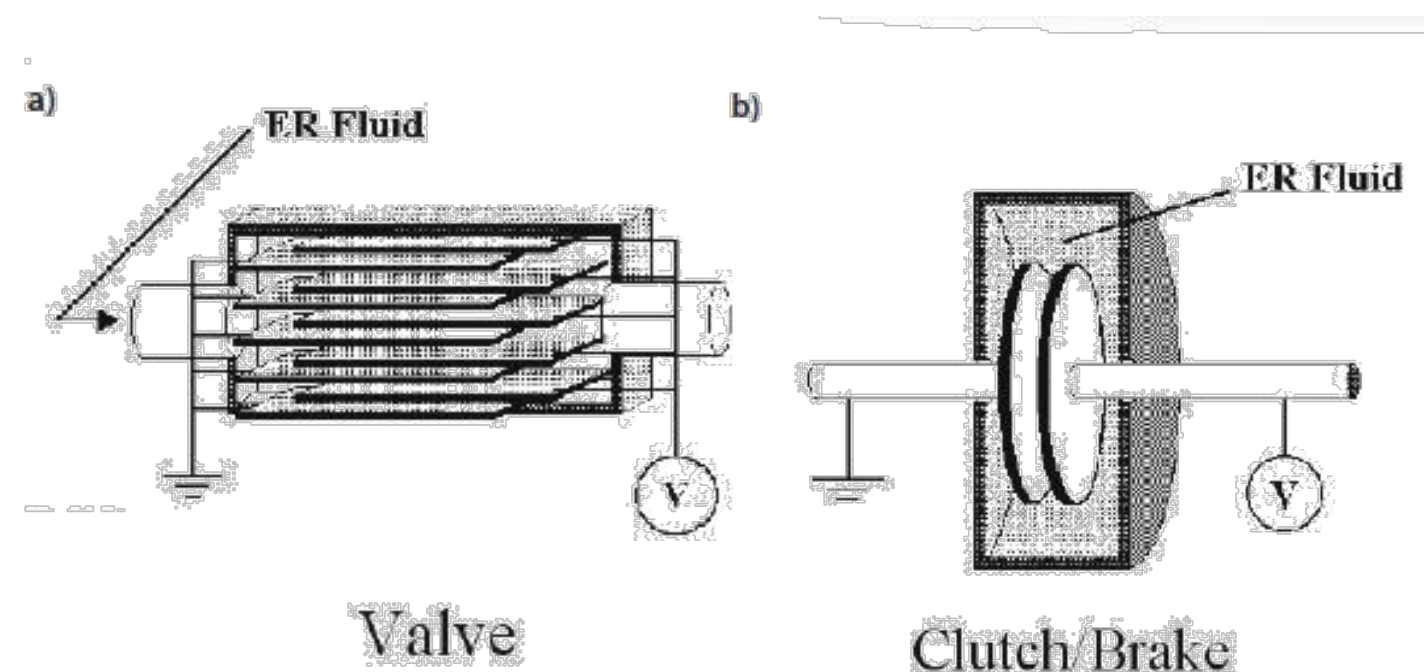
Embragues

Amortiguadores (c)

Dispositivos braille/hápticos (d)

Microfluidos (e)

Dispositivos de rehabilitación (f)

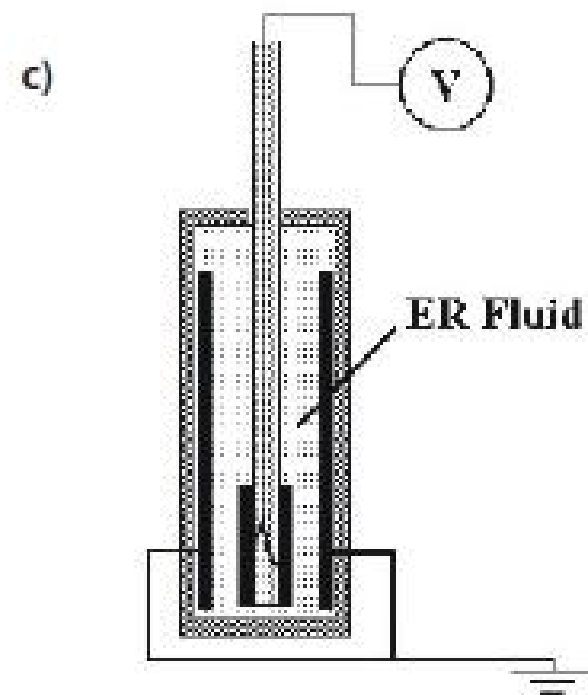


FASE 1

EAP'S IÓNICOS // APLICACIONES

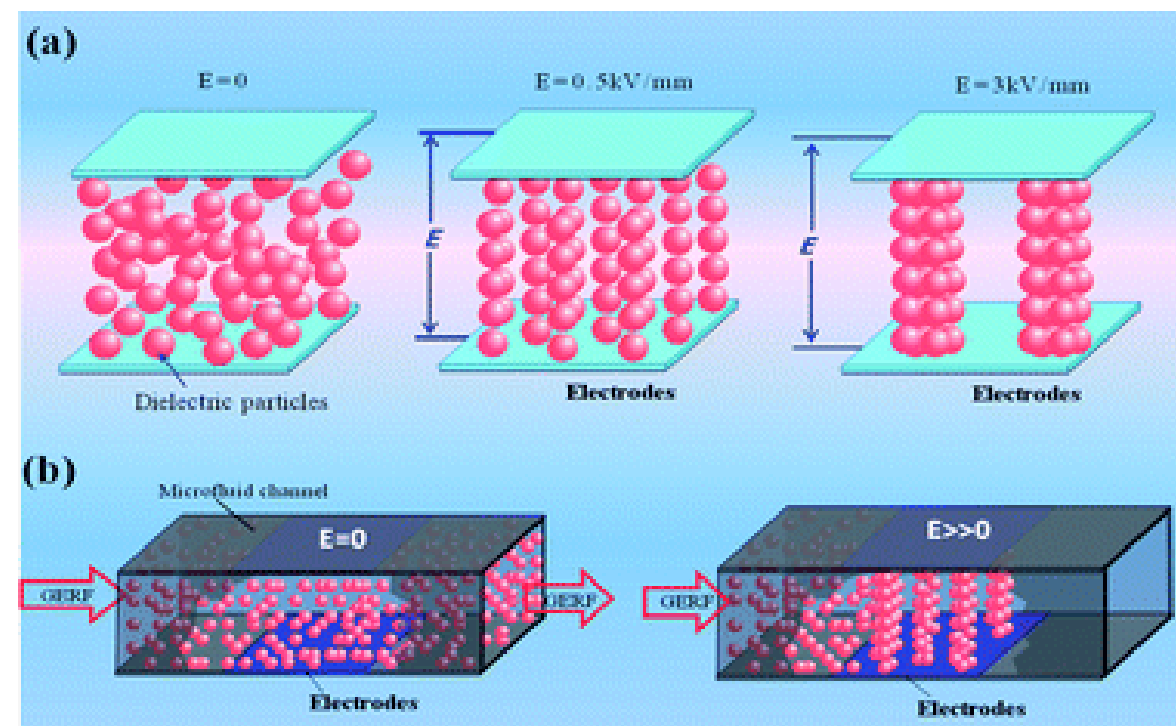
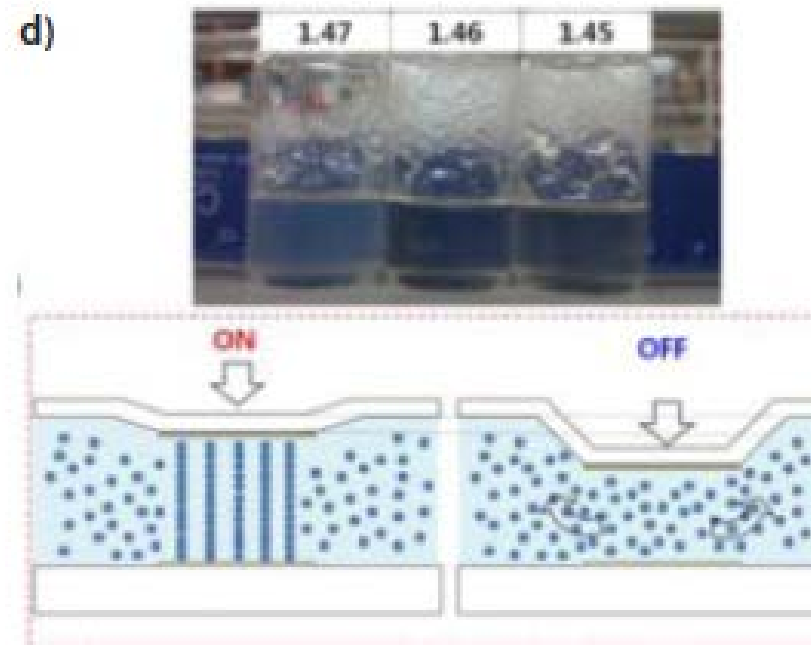
INVESTIGACIÓN PEA

FLUIDOS ELECTRO-REOLÓGICOS



Shock Absorber

(Información en anexo: «Músculos artificiales usando polímeros electroactivos»)



FASE 1

EAP'S ELECTRÓNICOS //CONCLUSIONES

INVESTIGACIÓN PEA

GENERALES:

Todas las aplicaciones han sido llevadas a cabo en laboratorios o centros de investigación y a pequeña escala. Por ello se siguen estudiando sus capacidades y se descubren aplicaciones pero sin llegar a determinar de forma sólida el grado de beneficio en su uso.

Se obtienen **buenos resultados tanto mecánicos como eléctricos**, ampliando el campo de aplicación conforme se avanza en su investigación.

Al ser el propio material el que genera el movimiento, se **reduce el número de piezas** implicadas.

(Información en anexo: «Músculos artificiales usando polímeros electroactivos», pág.30)

EAP'S ELECTRÓNICOS //CONCLUSIONES

ESPECÍFICAS:

Polímeros dieléctricos: Presentan grandes ventajas competitivas y un mayor número de campos de aplicación. Tienen potencial para reemplazar a muchos **actuadores**.

Polímeros ferroeléctricos: Debido a su efecto piezoeléctrico se aplican en **transductores acústicos**.

Elastómeros de cristal líquido: A través de la transición de dos de sus fases se logra la **contracción reversible** de este. Son idóneos para su aplicación en dispositivos industriales, electrónicos y médicos.

Elastómeros electrostrictivos de injerto: Mejoran muchas propiedades gracias al polímero injertado en el compuesto que responde al campo eléctrico. No se especifican las aplicaciones concretas.

(Información en anexo: «Músculos artificiales usando polímeros electroactivos», pág.30)

FASE 1

INVESTIGACIÓN PEA

Elastómeros electro-viscoelásticos: Antes de aplicar el campo eléctrico se comportan como fluidos electrorreológicos por lo que se utilizan como alternativas a estos en aplicaciones de **amortiguación activa**.

Papel electrostrictivo: Sus aplicaciones están menos extendidas ya que todavía se encuentran en fases de desarrollo pero son susceptibles de ser utilizadas en **amortiguadores de sonido o altavoces flexibles**.

EAP'S IÓNICOS //CONCLUSIONES

ESPECÍFICAS:

Geles de polímeros iónicos: Altos índices de compresión y expansión, y además pueden generarse geles orgánicos biocompatibles, lo que los hace ideales **para aplicaciones biomédicas**.

Compuestos polímero-metálicos iónicos: Dado su bajo voltaje y alta resistencia mecánica son los más utilizados para nuevas aplicaciones.

Polímeros conductores: Buena aplicación como músculos artificiales o **válvulas**, con un bajo voltaje operativo. También se están investigando sus aplicaciones en **dispositivos hápticos**.

(Información en anexo: «Músculos artificiales usando polímeros electroactivos», pág.30)

FASE 1

INVESTIGACIÓN PEA

Nanotubos de carbono: Excelentes características mecánicas. Su densidad los hace unos candidatos perfectos para sus uso como **músculos o válvulas**.

Fluidos electroreológicos: Aplicaciones variadas como **frenos, válvulas, embragues, amortiguadores o dispositivos hápticos**. Se están empezando a usar como dispositivos de **recuperación médica**.

FASE 2

EDP'S
PROCESO DE DISEÑO
METODOLOGÍA
CONCEPTOS Y ELECCIÓN

FASE 2

// GENERALES

EDP'S

Entorno: tras observar los análisis se concluyó que para el diseño de un nuevo producto con una tecnología tan innovadora, el entorno más adecuado para su aplicación era el **industrial**. Esto es debido a la **mejor aceptación** que se realizaría por parte de empresas de sector. Las beneficiaría en aspectos tanto competitivos como económicos.

El uso de un músculo artificial para sustituir el mecanismo de las compactadoras industriales reduciría en gran medida el número de piezas utilizadas. Además el consumo también disminuiría, al utilizar voltajes menores a los actuales para realizar la misma fuerza.

Versátil: ésta nueva tecnología debe ofrecer una variedad de aplicaciones, ya que cualquier movimiento podría realizarse con ella sin necesidad de motores, válvulas o bombas, simplificando el mecanismo totalmente.

Eficiente: debe realizar la función principal ahorrando energía en comparación al resto de productos en el mercado. Además en el proceso de fabricación y montaje, se eliminarían muchas secuencias y componentes. Actualmente su consumo parte de los **1.5kW hasta 6 kW en las compactadoras industriales**.

Funcional: su correcto funcionamiento es necesario para la satisfacción del usuario. Se necesita realizar una fuerza a partir de 600 kg para una compactación del 80% dependiendo del volumen.

Seguro: no debe perjudicar al usuario en el momento de interacción del producto, ya sea durante el uso o limpieza del mismo.

Innovador: al aplicar una nueva tecnología debe mejorar algo ya existente en los productos actuales, como los relacionados con el consumo eléctrico, la funcionalidad, el coste de fabricación, etc.

FASE 2

ELECCIÓN DE UN GRUPO Y TIPO

EDP'S

ELECTRÓNICOS

VENTAJAS

INCONVENIENTES

IÓNICOS

Conclusiones:

Al comparar las ventajas y desventajas de cada grupo, se ha llegado a la conclusión de que el grupo con **mejores propiedades** en relación al nuevo diseño es el de **PEA's electrónicos**. Presentan características favorables como:

Operan a **temperatura ambiente** durante largos periodos, a diferencia de los iónicos que necesitan un medio electrolítico para funcionar.

Poseen una **respuesta** de actuación más **rápida** que los del otro grupo.

A diferencia de los iónicos pueden **mantenerse estirados** tras la corriente de activación.

Lo determinante para la elección de este grupo fue la **alta fuerza de actuación** que poseen frente a los PEA's iónicos.

(Información en anexo: «EAP's ventajas – inconvenientes»)

ELECCIÓN DE UN GRUPO Y TIPO

//ESQUELETO MAMÍFEROS

	Mínimo	Máximo
Estiramiento	20%	>40%
Ratio estiramiento		>50%/s
Densidad trabajo	8 KJ/m³	40 KJ/m³
Densidad	1037 Kg/m³	
Tensión	0.1 Mpa	0.35 Mpa
Potencia	50 W/kg	284 W/kg
Eficiencia		40%
Ciclo vida		10^9
Módulo elástico	10 - 60 MPa	83 GPa

Para poder **averiguar si el futuro producto puede compactar incluso los restos sólidos más duros** (huesos) se ha estudiado esta tabla de valores en comparación con el Nitinol, y polímeros ferroeléctricos.

Ratio estiramiento: cambio de longitud por unidad de tiempo en un golpe de actuación.

Tensión: Newtons que puede soportar la sección.

Potencia: se trata de la tensión por el estiramiento dividido por la densidad del material.

Eficiencia: trabajo generado para introducir energía gastada.

Módulo elástico: capacidad del actuador para ignorar cambios de carga o perturbaciones. Es la rigidez por longitud dividido por la sección.

(Información en anexo: «Principios físicos y perspectivas navales. Tablas propiedades»)

ELECCIÓN DE UN GRUPO Y TIPO

//ALEACIONES DE MEMORIA-FORMA (NITI)

	Mínimo	Medio	Máximo
Estiramiento		5%	8%
Ratio estiramiento		300%/s	
Densidad trabajo		1000 KJ/m³	10000 KJ/m³
Densidad		6450 Kg/m³	
Tensión			200 MPa
Potencia		1000 W/kg	>50000 W/kg
Eficiencia			<5%
Ciclo vida	300 (~5%)		10^7 (~0.5%)
Módulo elástico	20 GPa		83 GPa
Fuerza tensil		1000 MPa	
Voltaje aplicación		4 V	
Conductividad		12500 S/cm	14250 S/cm

La **velocidad de contracción** del Nitinol queda determinada por la **velocidad de transición de fase** (austenita → martensita).

Por tanto, depende también de la potencia eléctrica cuando sucede un efecto de calentamiento eléctrico de Joule. Es decir, **a mayores pulsaciones de corriente, menor tiempo de contracción.**

También se tendrá en cuenta el calor latente y la capacidad calorífica durante el cambio de fase. El agua fría reduce el tiempo de refrigeración, por lo que aumenta el tiempo de respuesta en milisegundos.

(Información en anexo: «Principios físicos y perspectivas navales. Tablas propiedades»)

ELECCIÓN DE UN GRUPO Y TIPO

//POLÍMEROS FERROELÉCTRICOS

	Medio	Máximo
Estiramiento	3.5%	7%
Ratio estiramiento		>2000%/s (10kHz, ~0.1%)
Densidad trabajo	320kJ/m³	>1000kJ/m³
Densidad	1870 kg/m³	2000 kg/m³
Tensión	20 Mpa	45 Mpa
Ancho banda	<100 Hz	>10000 Hz (~0.1%)
Acoplamiento S3	0.1-0.2	
Acoplamiento S1	0.4	
Módulo elást.	400 Mpa	1200 Mpa
Voltaje		>1000
Campo máx.	13 MV/m	150 MV/m
Cte. Dieléctrica (entre ~4 y 60)	55	Depende temp.
Rango temp.	ΔT~60°C	

Producen estiramientos moderados (7%), soportan tensiones altas (45MPa) y poseen una muy buena frecuencia de respuesta (~100 kHz).

Su alta rigidez (>0.4 Gpa) y largo ciclo de vida hacen de estos polímeros una buena opción para aplicaciones de músculos artificiales.

Los problemas que presentan son la histéresis, los altos campos requeridos y los voltajes que necesitan para su funcionamiento.

Actúan bien en dispositivos pequeños o con bajos estiramientos, pero al no poder soportar frecuencias >100Hz resulta imposible realizar aplicaciones a mayor escala.

(Información en anexo: «Principios físicos y perspectivas navales. Tablas propiedades»)

FASE 2

ELECCIÓN DE UN GRUPO Y TIPO

EDP'S

CONCLUSIONES ACERCA DEL TIPO DE MATERIAL:

La principal desventaja de los **polímeros ferroeléctricos** es que presentan **histéresis**. Para controlarla son necesarios altos campos magnéticos que se opongan para cambiar la polarización. Este proceso provoca una gran disipación de energía. Pueden llegar a requerir campos de hasta 152 MV y voltajes de **>1 kV frente** a los **4V** necesarios para el Nitinol.

Además resulta **imposible aplicar frecuencias >100Hz** para estos actuadores debido a la disipación y calentamiento que comportan.

El **estiramiento** que es capaz de realizar el **Nitinol** es ligeramente **mayor** que el de los polímeros ferroelectricos como se puede ver en las tablas anteriores. También es mayor la **densidad de trabajo** del Nitinol, es decir, produce más

La **tensión** que soporta por sección el Nitinol es mucho más alta (200Mpa) factor importante para el producto..

El **módulo elástico** también es necesario tenerlo en consideración, ya que representa la rigidez por longitud en una determinada sección. En el Nitinol es mayor, por lo que es más rígido a mayor longitud.

	POLÍMEROS FERROELÉCTRICOS	NITINOL
CONSUMO	****	*
ESTIRAM.	*	**
DENSIDAD T.	***	*****
TENSIÓN	**	*****
MÓD.ELÁST.	****	*****

CONCLUSIONES DE ELECCIÓN DEL NITINOL:

Gracias a la tabla anterior se puede deducir el material más apropiado para la realización de un mecanismo actual que sustituya al de las compactadoras industriales.

Después de este estudio generalizado, se ha decidido estudiar el nitinol en profundidad, para averiguar las características específicas que posee en relación a limitaciones eléctricas, magnéticas, mecánicas o de transformación.

Así se obtendrá una conclusión más fiable acerca de su aplicación en el ámbito de las compactadoras industriales.

FASE 2

EDP'S
PROCESO DE DISEÑO
METODOLOGÍA
CONCEPTOS Y ELECCIÓN

FASE 2

ESTUDIO DE APLICACIÓN

PROBLEMAS TÉCNICOS COMPACTADORAS:

Consumo eléctrico: uso de motores que llegan a consumir hasta 6kW .

Alto número de piezas: producto con mecanismo complejo de gran número de piezas.

Costes proceso fabricación: elevado debido a los diferentes componentes tanto estructurales y formales como internos. Diferentes materiales y procesos de montaje.

Volumen compactación reducible: el 80% de reducción es favorable en relación al volumen de residuos inicial, aunque en el ámbito industrial siguen siendo cantidades demasiado elevadas.

No reutilización de residuos orgánicos: si el diseño ayuda a automatizar su reutilización, el 100% de los residuos tendría una segunda vida.

Transporte y gestión: reducción del volumen implica reducción de recogida de basura. Reutilización de los residuos facilita su gestión.

Discos inodoros extra: no todas las compactadoras los poseen, necesarios debido a la descomposición de residuos por presencia de humedad.

Sistema ventilación necesario: la humedad puede dañar el diseño, perjudicando su durabilidad y correcto funcionamiento. Presencia de olores desagradables para el usuario.

(Datos extraídos de la Fase 1: «Estudio de mercado» y «Análisis», en este documento)

REQUISITOS DEL NUEVO DISEÑO:

↓ CONSUMO

↓ NUMERO DE PIEZAS

AHORRO EN MATERIALES Y PROCESOS

↑ COMPACTACIÓN

REUTILIZACIÓN DE RESIDUOS

↓ FRECUENCIA RECOGIDA Y MEJORA EN GESTIÓN

↓ PESO AL ELIMINAR HUMEDAD

FASE 2

ESTUDIO DE APLICACIÓN

REQUISITOS DEL NUEVO DISEÑO:

REQUISITOS:

↓ CONSUMO

↓ NUMERO DE PIEZAS

AHORRO EN MATERIALES Y PROCESOS

↑ COMPACTACIÓN

REUTILIZACIÓN DE RESIDUOS

↓ FRECUENCIA RECOGIDA Y MEJORA EN GESTIÓN

↓ PESO AL ELIMINAR HUMEDAD

Disminuir el consumo igualando o **mejorando la eficiencia** de las compactadoras actuales sería un factor idóneo para el desarrollo de este nuevo producto.

El hecho de que existan prototipos que se programan para realizar movimientos tan sólo con el hilo de nitinol creando una malla, revoluciona el ámbito de los **motores** que realizan determinados movimientos pero con una **gran cantidad de piezas**.

Además para la producción de los motores actuales se utilizan diferentes materiales y procesos de fabricación así como secuencias de montaje. El **mecanismo** es mucho más **complicado** y por tanto necesita de un mantenimiento, seguridad, funcionalidad muy elevados. Resultaría **más fiable** un motor con menores probabilidades de error, **simplificando su mecanismo al propio movimiento**.

El progreso de las compactadoras reside en realizar una **reducción** en el **volumen cada vez mayor**. Por ello, la eliminación de la humedad ayudaría no solo a la disminución de volumen y peso, si no a la eliminación de malos olores.

Al crear **residuos compactos** de menor tamaño, la frecuencia de recogida sería menor, los vertederos no se explotarían y se podrían evitar aguas residuales si se les diese un **segundo uso**.

Una forma de facilitar al usuario esta acción de reusar sus desechos, sería mediante una **compensación económica**.

FASE 2

ESTUDIO DE APLICACIÓN

REQUISITOS DEL NUEVO DISEÑO:

REQUISITOS:

↓ CONSUMO

↓ NUMERO DE PIEZAS

AHORRO EN MATERIALES Y PROCESOS

↑ COMPACTACIÓN

REUTILIZACIÓN DE RESIDUOS

↓ FRECUENCIA RECOGIDA Y MEJORA EN GESTIÓN

↓ PESO AL ELIMINAR HUMEDAD

Para **eliminar la humedad**, es necesario seguir una serie de normas de deshidratación de residuos para eliminar las bacterias de los residuos orgánicos.

Una de las especificaciones es la aplicación de calor a **80°C**, temperatura a la cual se **destruyen virus y otros organismos** perjudiciales para la salud y el medio ambiente. La Salmonella puede desarrollarse hasta los 65°C.

Además a esta temperatura se consigue reducir la humedad de residuos diarios quedando ésta en un 10% (cada 24h), pudiendo diseñar un producto más competente frente a las compactadoras actuales.

Los sistemas actuales de compactación tal y como se ha estudiado en la primera fase, realizan un **movimiento descendente a lo largo de un eje vertical**.

En las compactadoras industriales también se ejerce presión en los ejes **horizontales** ya que es necesario para el posterior manejo de los residuos comprimidos. Deben ser trasladados en camiones o contenedores, que recogen una gran cantidad de desperdicios.

Sería interesante ejercer una **fuerza en todo el volumen** de residuos, y no a través de ejes verticales u horizontales como se realiza actualmente. Este factor desarrollaría una presión completa en toda la superficie de desechos.

El **resultado** sería un aglomerado libre de aristas o vértices, en **forma de esfera o sólido orgánico**.

FASE 2

ESTUDIO DE APLICACIÓN

REQUISITOS DEL NUEVO DISEÑO:

Así como las **formas racionalizadas**, de líneas rectas crean volúmenes que ayudan a **aprovechar el espacio**, las formas **orgánicas** podrían realizar el **efecto contrario** si se requiere en el diseño.

Los prototipos estudiados con mallas de nitinol recrean movimientos de cualquier tipo, de forma orgánica y no lineal como los mecanismos actuales.

No se trata de transformar un movimiento circular en lineal o al revés, a base de numerosos elementos, si no de **crear cualquier movimiento deseado con un solo elemento**.

Los músculos artificiales basados en nitinol permiten la realización de movimientos orgánicos requeridos en este nuevo diseño, como se muestra en las imágenes de la derecha. Por ello se van a estudiar diferentes seres vivos que realicen movimientos orgánicos de compresión repartida además de otras características a considerar.

(información de la fuente: <http://news.mit.edu/2012/autonomous-earthworm-robot-0810>)



FASE 2

METODOLOGÍA BIÓNICA

ESTUDIO DE CARACTERÍSTICAS EN LA NATURALEZA:

FUNCIÓN COMPACTADORA		
Básica	Detallada	Específica
Compactar	Compactar y contraer	Reducir Forzar Dividir Aplastar
	Eliminar restos orgánicos	Evacuar Trasladar Arrastrar Reutilizar Embutir

A continuación se realizará una búsqueda de seres vivos que realicen los principios biológicos de compactar y eliminar agua o residuos. La naturaleza ya ha diseñado mecanismos, tejidos, organismos, etc que realizan esta función de diferentes maneras.

Las funciones específicas derivan de las diferentes formas en las que se podrían compactar o eliminar los residuos.

Una vez estudiadas las maneras de llevar a cabo estas funciones por parte de individuos en la naturaleza, se podrá extraer su **principio biológico e ingenieril** que será aplicado posteriormente al producto.

(Información en anexo: «Metodología biónica 2», pág 13 hasta 23. Asignatura Biónica. Autor: Ignacio López Forniés.)

FASE 2

METODOLOGÍA BIÓNICA

ESTUDIO DE CARACTERÍSTICAS EN LA NATURALEZA:

SER VIVO:

Vorticella convallaria: se trata de un protozoo existente en los lagos que se adhiere al plancton de rocas, plantas y otros organismos a través de su tallo llamado spasmoneme. Cuando es alterado, el tallo se contrae rápidamente. Puede crear una fuerza de 300 nanonewtons, que comparado con su ínfimo tamaño resulta ser más potente que el motor de un coche.

Útero de mamíferos: de las 3 capas del útero, la central llamada miometrial se encarga de la expansión y contracción del útero. Está compuesta de un tejido cuyas fibras de la cara externa están dispuestas longitudinalmente y las internas en forma de espiral.

PRINCIPIO BIOLÓGICO:

Compactar al verse alterada.

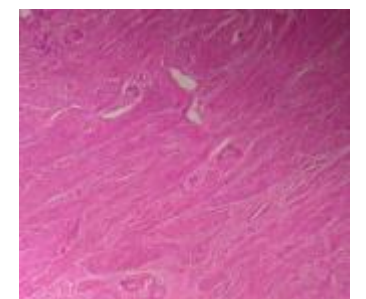
Compactar y calentar para mantener a un ser vivo. Contraer para liberarlo.

PRINCIPIO INGENIERIL:

Enrolla su tallo en forma de espiral al segregar iones de calcio de una proteína.

Acción mecánica por señales del cerebro enviadas por sistema nervioso.

IMAGEN:



FASE 2

METODOLOGÍA BIÓNICA

ESTUDIO DE CARACTERÍSTICAS EN LA NATURALEZA:

SER VIVO:

Medusa *Polyorchis penicillatus*: los músculos en la campana de la medusa aumentan su amplitud de movimiento un 40%, reduciendo la energía requerida para realizar un ciclo entre el 24-37%. Esto lo consigue gracias a la sincronización de la frecuencia de movimiento del cuerpo a la de resonancia.

Seda de araña y gusano: contracción cíclica según grado de humedad, capaz de generar un trabajo 50 veces mayor a su equivalente en la masa muscular de un ser humano. Las fibras de seda operan con un diámetro de 5µm de tamaño, pudiendo ser escalable. Las fibras de seda de gusano ya son comerciales y funcionan por aire húmedo o seco.

PRINCIPIO BIOLÓGICO:

Contraer para nadar.
Ahorrar energía en movimiento.

Contraer para aumentar resistencia ante humedad.

PRINCIPIO INGENIERIL:

Contracción radial de campana.
Sincronización frecuencias.

Acción mecánica por aire seco o húmedo.

IMAGEN:



FASE 2

METODOLOGÍA BIÓNICA

ESTUDIO DE CARACTERÍSTICAS EN LA NATURALEZA:

SER VIVO:

Canguro: tendones de colágeno que son capaces de almacenar el trabajo realizado en las patas al aterrizar. Traspasan la fuerza de los músculos a los huesos. Pueden almacenar hasta un 40-50% en el momento de volver a tocar el suelo.

Gusanos (piel): el movimiento y cambio en la forma de los gusanos se realiza gracias a las fibras que contiene su piel. Estas fibras se distribuyen de forma helicoidal alrededor y en toda la longitud de su cuerpo.

PRINCIPIO BIOLÓGICO:

Reutilizar el trabajo para ahorrar energía en el salto.

Contraer para trasladarse y disminuir su sección.

PRINCIPIO INGENIERIL:

Tendones de colágeno recogen trabajo de los músculos y lo envían a los huesos.

Acción mecánica de fibras en disposición helicoidal.

IMAGEN:



FASE 2

METODOLOGÍA BIÓNICA

ESTUDIO DE CARACTERÍSTICAS EN LA NATURALEZA:

SER VIVO:

Elefante: trompa capaz de moverse en 3 dimensiones gracias a un hidrostato muscular (estructuras compuestas de un fluido no comprimible) que les aporta consistencia en volumen y fuerza de torsión reversible. Estas estructuras se distribuyen a lo largo, de forma helicoidal, oblicua, transversal, etc del eje longitudinal de la trompa. Además almacenan energía.

Lombriz: los segmentos independientes de las lombrices les permiten moverse y contraerse para introducirse en la tierra. Su interior se compone de una sola cavidad, pero el exterior se divide en segmentos elásticos y cilíndricos que contienen un cierto volumen de fluido. Bajo los segmentos existen músculos circulares que cambian el diámetro y longitudinales que cambian la extensión del gusano.

PRINCIPIO BIOLÓGICO:

Movimiento y fuerza para coger alimentos y agua.

Contraerse para introducirse en la tierra y moverse por ella.

PRINCIPIO INGENIERIL:

Músculos contraen y opuestos estiran. Estructuras en superficie cilíndrica.

Acción hidráulica de músculos circulares y longitudinales. Tejido fibroso.

IMAGEN:



FASE 2

//CONCLUSIONES

ESTUDIO DE CARACTERÍSTICAS EN LA NATURALEZA:

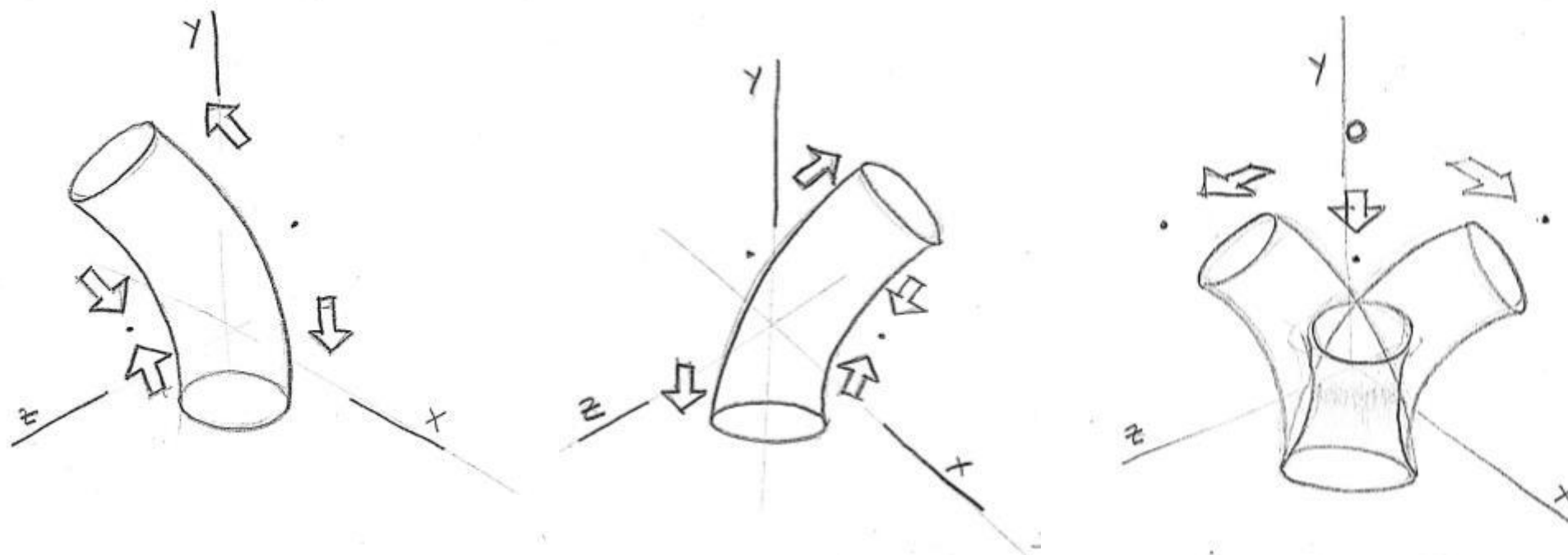
METODOLOGÍA BIÓNICA

	Ser vivo	P. Biológico	P. Ingenieril
	Protozoo	Compactar al alterarse	Enrolla su tallo en forma de espiral al expulsar iones de calcio
	Útero	Compactar para sostener	Acción mecánica por señales enviadas desde el cerebro
	Gusano	Contraer para trasladarse y disminuir sección	Acción mecánica de fibras en sentido helicoidal
	Trompa	Movimiento 3D y fuerza para alimentarse	Músculos contraen y opuestos se estiran.
	Lombriz	Contracción para moverse	Acción hidráulica de músculos circulares y longitudinales

FASE 2

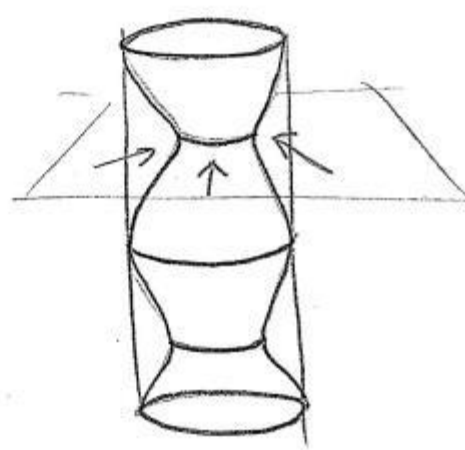
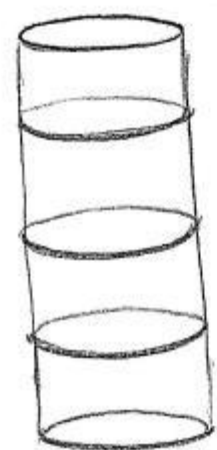
//CONCLUSIONES APLICACIÓN DE LAS CARACTERÍSTICAS ESTUDIADAS:

METODOLOGÍA BIÓNICA

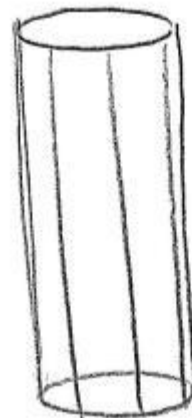


Los principios ingenieriles escogidos fueron:

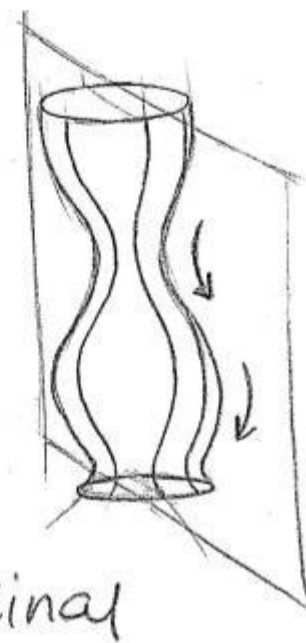
Movimiento 3D de la trompa de los elefantes gracias a la ontracción de un lateral y estiramiento del opuesto.



Sección transversal



Traslado longitudinal



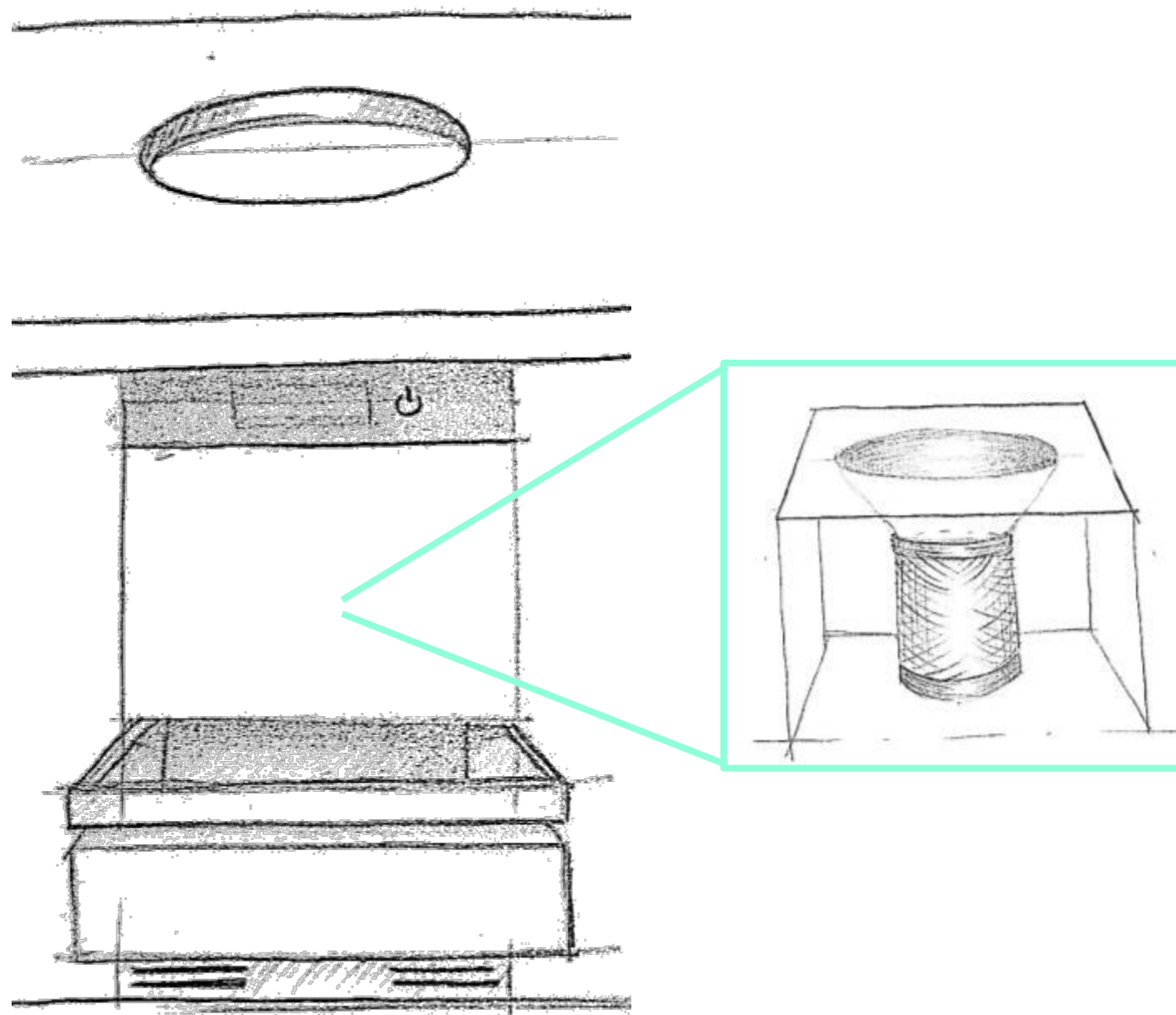
Sección transversal de los gusanos y lombrices que aplicado al producto permiten la compactación de los residuos. Este efecto de produce por la creación de **circunferencias** a lo largo del músculo.

Además el traslado de los restos se ayuda de los **cables** colocados **longitudinalmente**.

FASE 2

**EDP'S
PROCESO DE DISEÑO
METODOLOGÍA
CONCEPTOS Y ELECCIÓN**

1º CONCEPTO //ELEMENTOS



FASE 2

CONCEPTUALIZACIÓN

Este primer concepto se divide en tres partes principales para poder realizar las funciones de **compactar y deshidratar** los residuos orgánicos.

El **orificio** superior realizado en la **encimera** de la cocina (o del lugar de trabajo) permite arrojar los restos directamente a la zona de compactación. En esta **parte central** se encuentra el **músculo** de compactación.

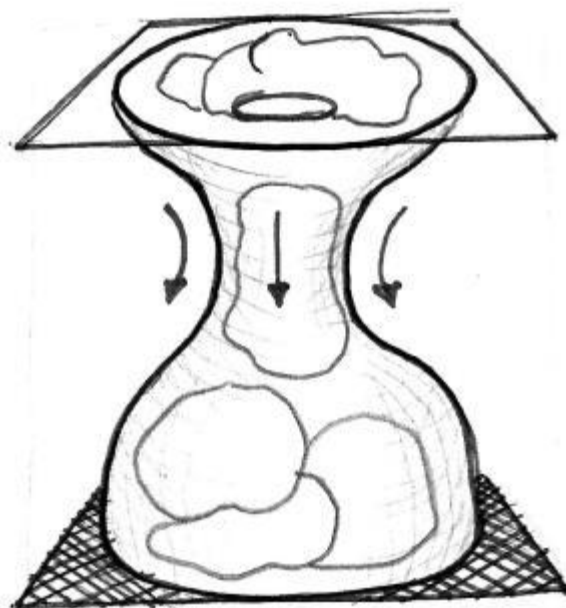
Una vez ha terminado de compactar, los residuos pasan a un cajón con **bandeja** de rejillas en la **parte inferior**. En esta zona se alcanzan temperaturas de hasta **70°C*** y posee **ventilación** continua.

Al haber acabado el proceso de deshidratación, se extraen los residuos y se envían a procesar.

* Temperatura deshidratación

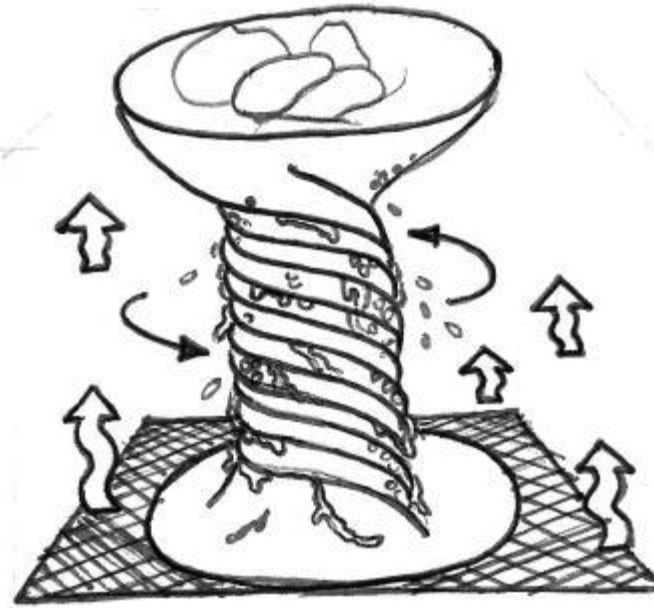
1º CONCEPTO // FUNCIONAMIENTO

1º Absorber los restos orgánicos hasta llenar el volumen disponible para compactar.

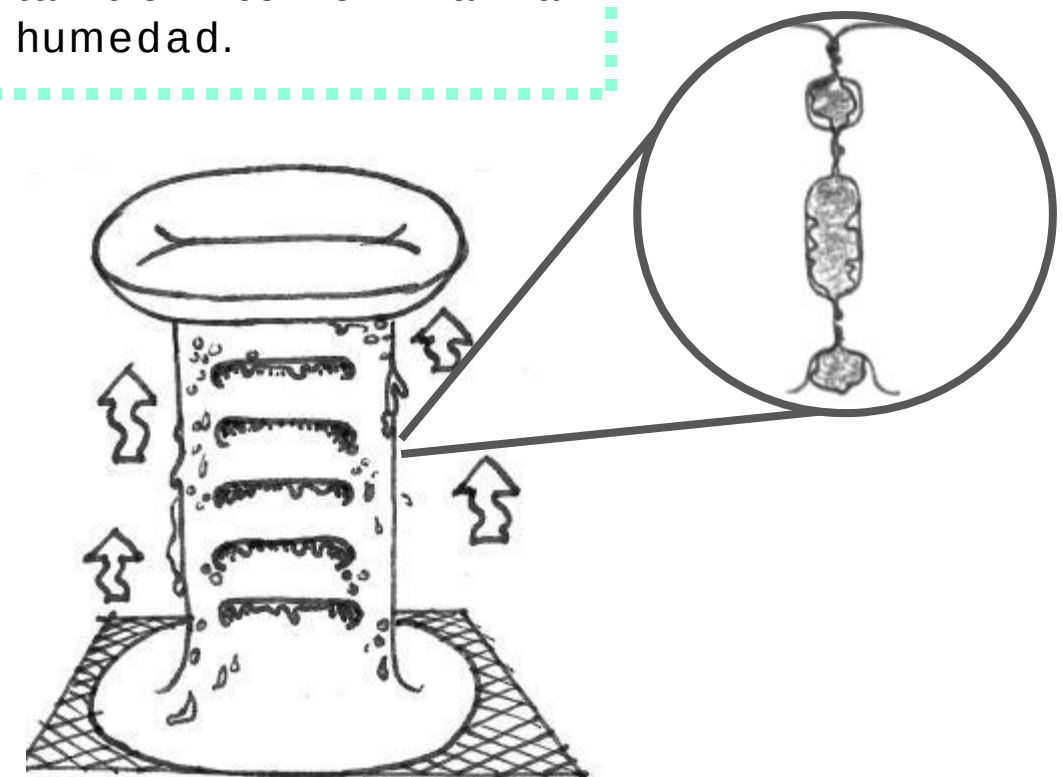


2º Retorcer los residuos para deshacerlos en una masa maleable. En este paso los huesos y sólidos duros se machacan. El líquido presente en los residuos sale a través de la malla de nitinol.

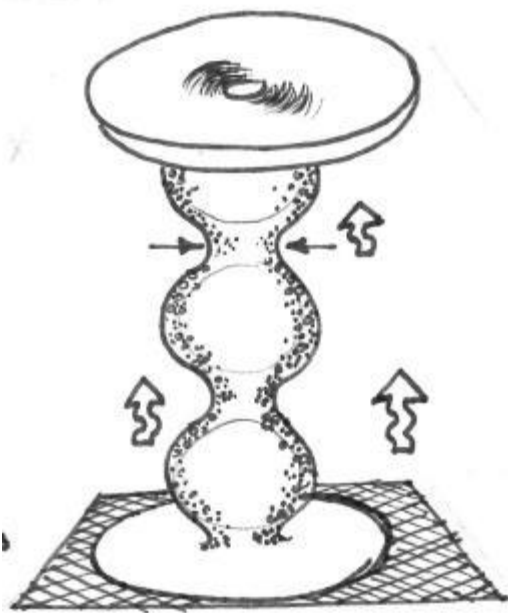
En la parte inferior se encuentra una rejilla que permite el paso de aire muy caliente, que elimina la humedad.



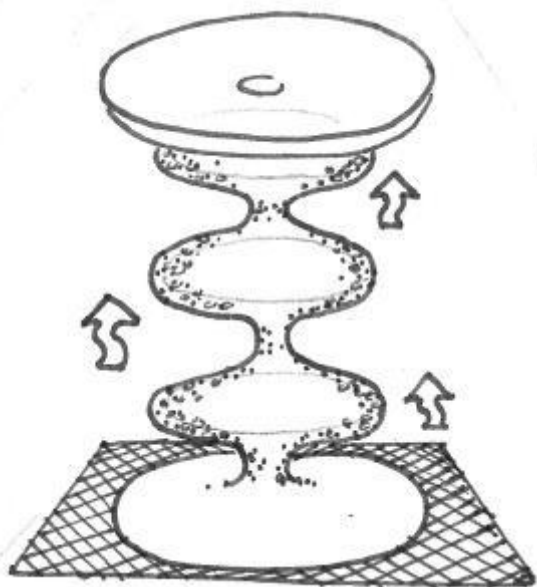
3º La malla adopta forma plana, con dos superficies enfrentadas. De estas dos caras aparecen salientes que actúan como muelas. La malla procesa los residuos y destroza los elementos sólidos. Además las muelas se separan unas de otras en dirección vertical, desgarrando los desechos. Durante esta fase también se elimina la humedad.



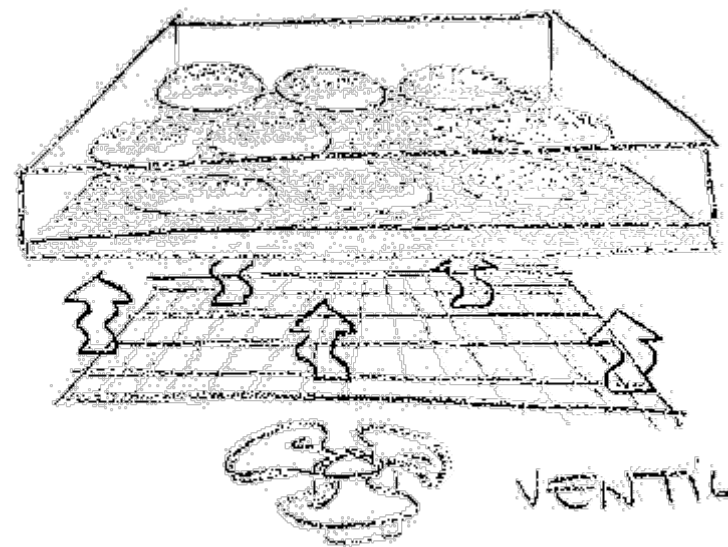
1º CONCEPTO // FUNCIONAMIENTO



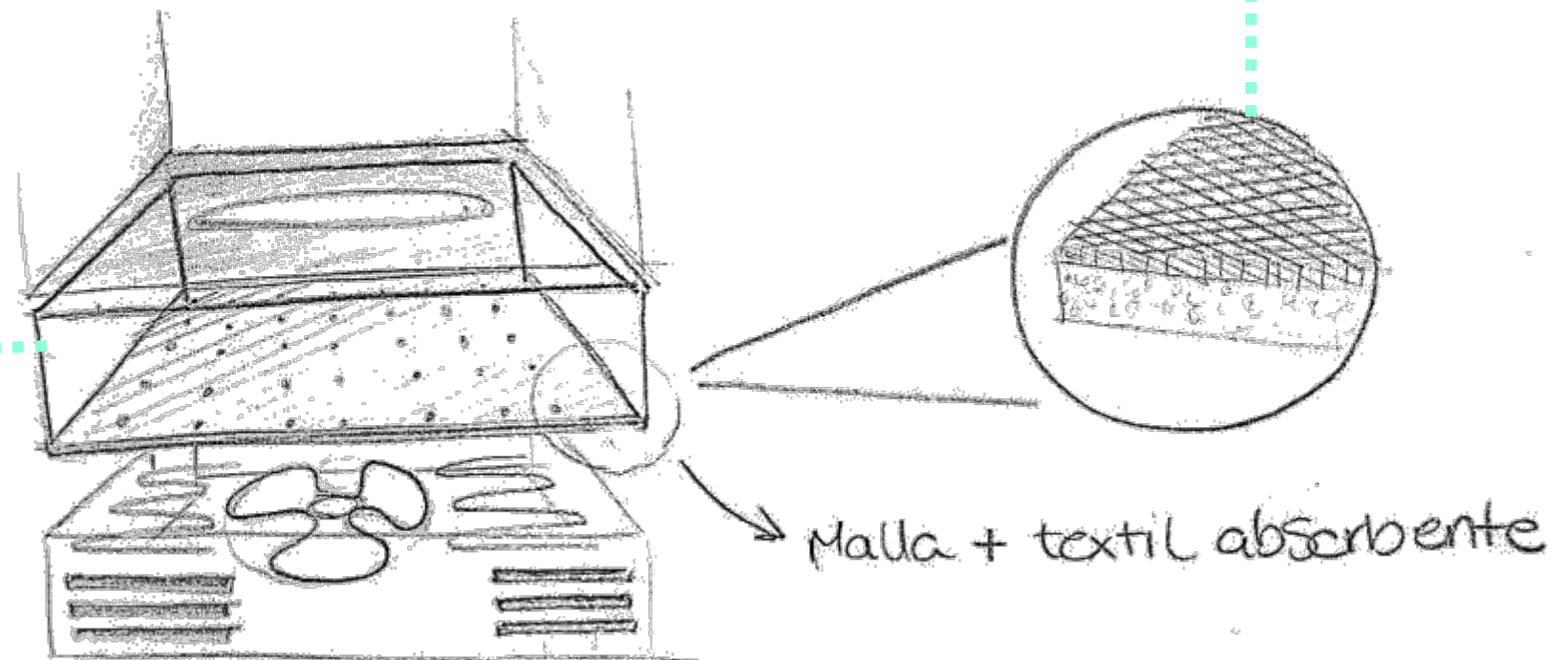
4º En este paso la malla crea unas bolas de menor tamaño, y continúa compactándolas hasta alcanzar un máximo. La humedad queda en la superficie de la malla pero se evapora gracias a la acción del aire caliente.



5º Por último las bolas se aplastan para ayudar a su deshidratación en el proceso siguiente, al haber menos grosor que deshidratar.



6º Deshidratación: los residuos aplastados se disponen sobre la rejilla del cajón, debajo de la cual se coloca un material absorbente para que el goteo no entre en contacto con los elementos electrónicos.. Entonces se someten a una temperatura de 70°C y a la acción del ventilador. Así se evapora toda la humedad contenida en los restos orgánicos y puedes pasar a ser gestionados.



1º CONCEPTO //CONCLUSIONES

Después de repasar todas las acciones desarrolladas en el procesado de residuos, se detectaron varios puntos fuertes y débiles en este primer concepto:

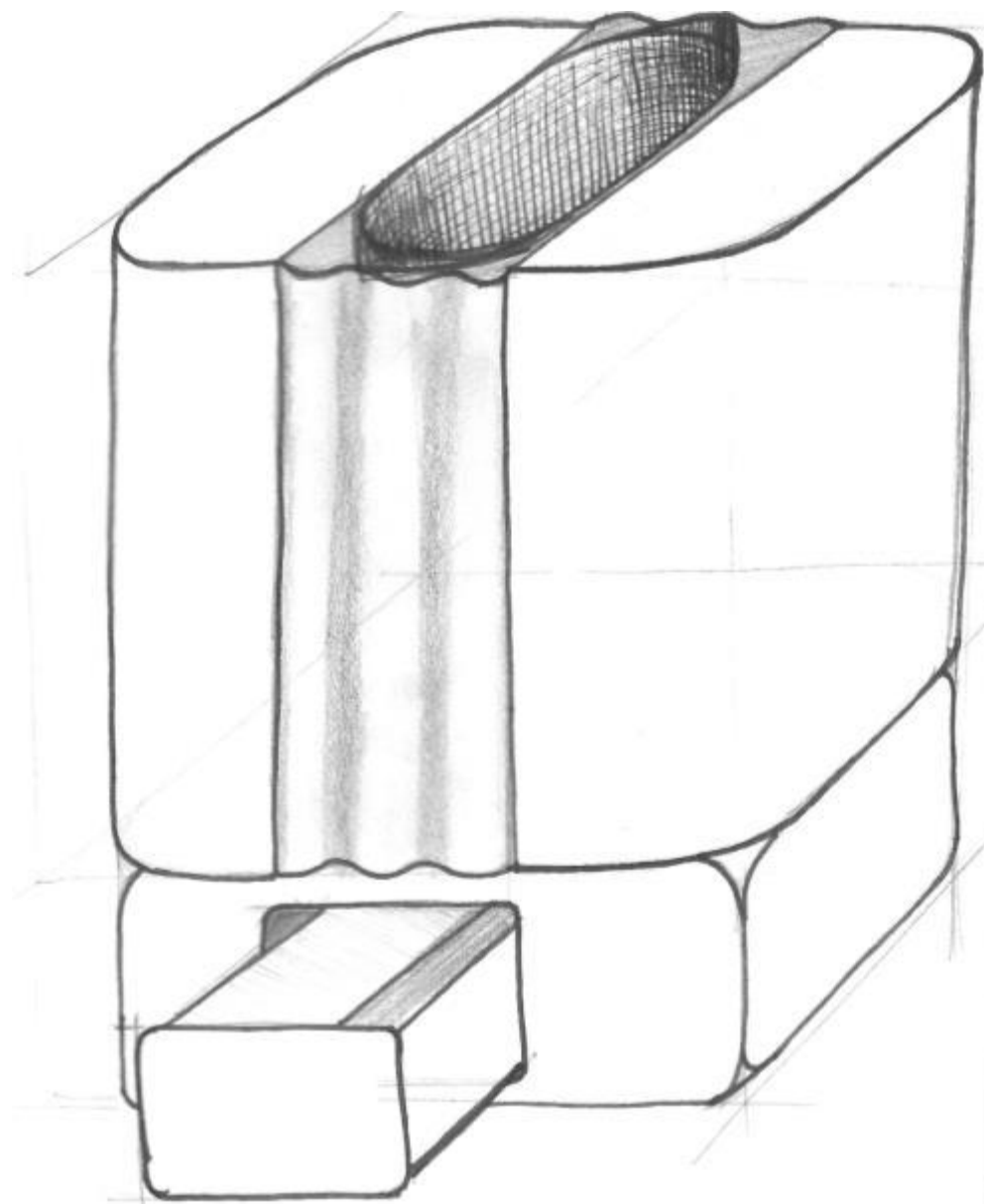
PUNTOS FUERTES:

- ☐ Torsión total de la malla de Nitinol.
- ☐ Ventilación continua.
- ☐ Compacto.

PUNTOS DÉBILES:

- ☐ Anclaje superior e inferior de la malla (impide muchos movimientos con el prototipo).
- ☐ No se pueden ordenar los restos compactados en el cajón.
- ☐ El material absorbente del cajón es un foco de proliferación bacteriana. No se puede extraer para limpiar.
- ☐ No ideado para uso industrial.

2º CONCEPTO // FUNCIONAMIENTO



FASE 2 CONCEPTUALIZACIÓN

El segundo concepto cambia la estructura interna de la compactadora debido a los problemas encontrados en el concepto anterior.

Sigue apoyándose en los puntos fuertes del primer concepto, intentando mejorar los fallos a través de la forma y la estructura interna.

El músculo adopta forma de bolsa rectangular. Esto permite que el aire caliente atraviese la malla de forma homogénea en todo momento. Se **disponen los restos** compactados **de manera idónea** para el proceso de deshidratación, sin necesidad de trasladarlos a otro compartimento.

Una vez se ha realizado la compactación y secado de los residuos, caen por acción de la gravedad al **cajón** situado en la parte **inferior**.

Los elementos electrónicos no entran en contacto con la humedad y no es necesario colocar un material absorben en el fondo del cajón, al caer los restos orgánicos ya secados.

2º CONCEPTO //ELEMENTOS

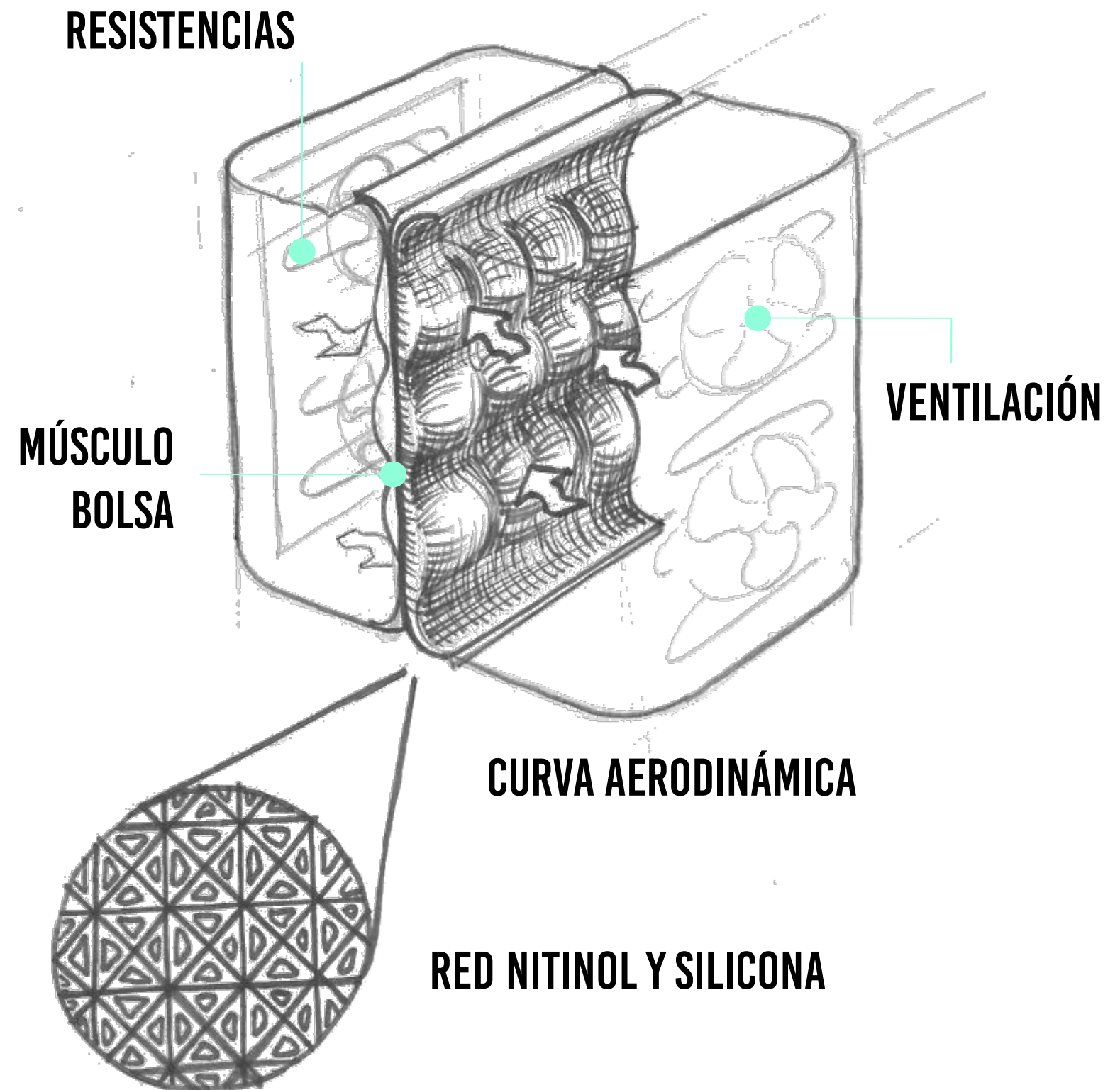
Las **resistencias** y el sistema de **ventilación** se colocan en los **laterales** del producto, creando una corriente mucho más efectiva que la ideada en el primer concepto.

En el medio se coloca el músculo de compactación en forma de **bolsa**. Los restos caen en ella hasta que el proceso acaba y ésta se abre por la parte inferior para dejarlos caer en el **cajón de desechos**.

La malla está cubierta de silicona con poros que permiten la **extracción de jugos** de los residuos.

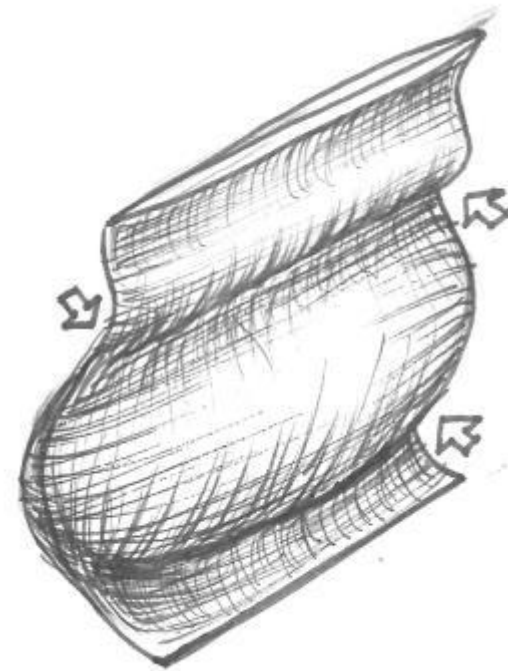
A través de ellos pasa la corriente de **aire** secando el aglomerado desde el inicio de la compactación. Se elimina la humedad por lo que se ayuda a ejercer una mejor presión sobre los restos orgánicos.

La curva de la estructura dirige el aire hacia el músculo de compactación, mejorando la fluidez de la corriente en el interior.



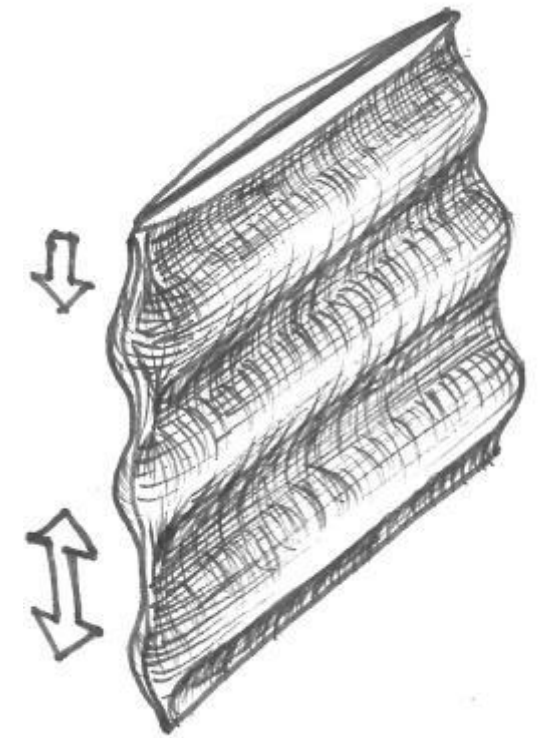
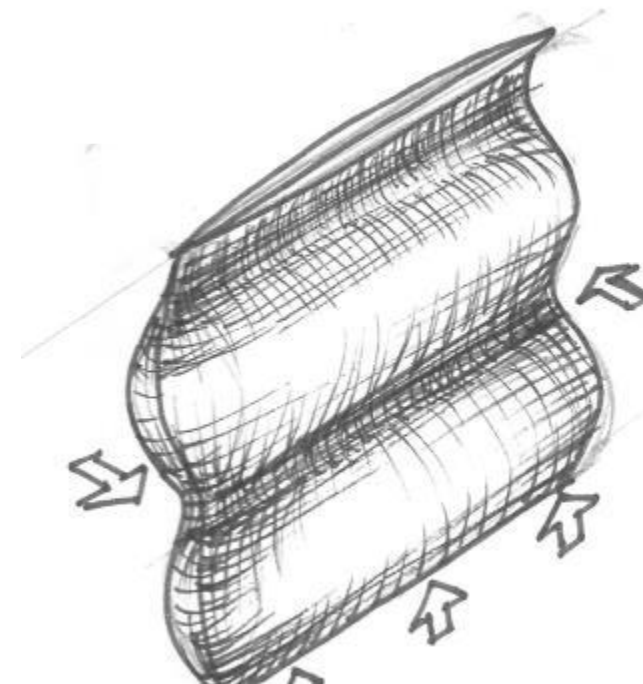
2º CONCEPTO // PROCESO

1º Los restos son compactados por toda la superficie para realizar una primera fase de reducción y eliminación de jugos.



2º Se crea una masa de residuos conforme se siguen aplicando fuerzas de compresión.

3º Se va dividiendo el aglomerado en diferentes partes para poder manipularlo de forma más sencilla.



4º Una vez se ha dividido en varios cilindros horizontales, se aplican pinzamientos. Se separan entre ellos y otros se contraen para crear desgarramientos. La presión ejercida es más puntual y por ello más efectiva.

2º CONCEPTO //CONCLUSIONES

Para ayudar en la elección del concepto, se han destacado sus puntos fuertes y débiles así como se hizo en el anterior.

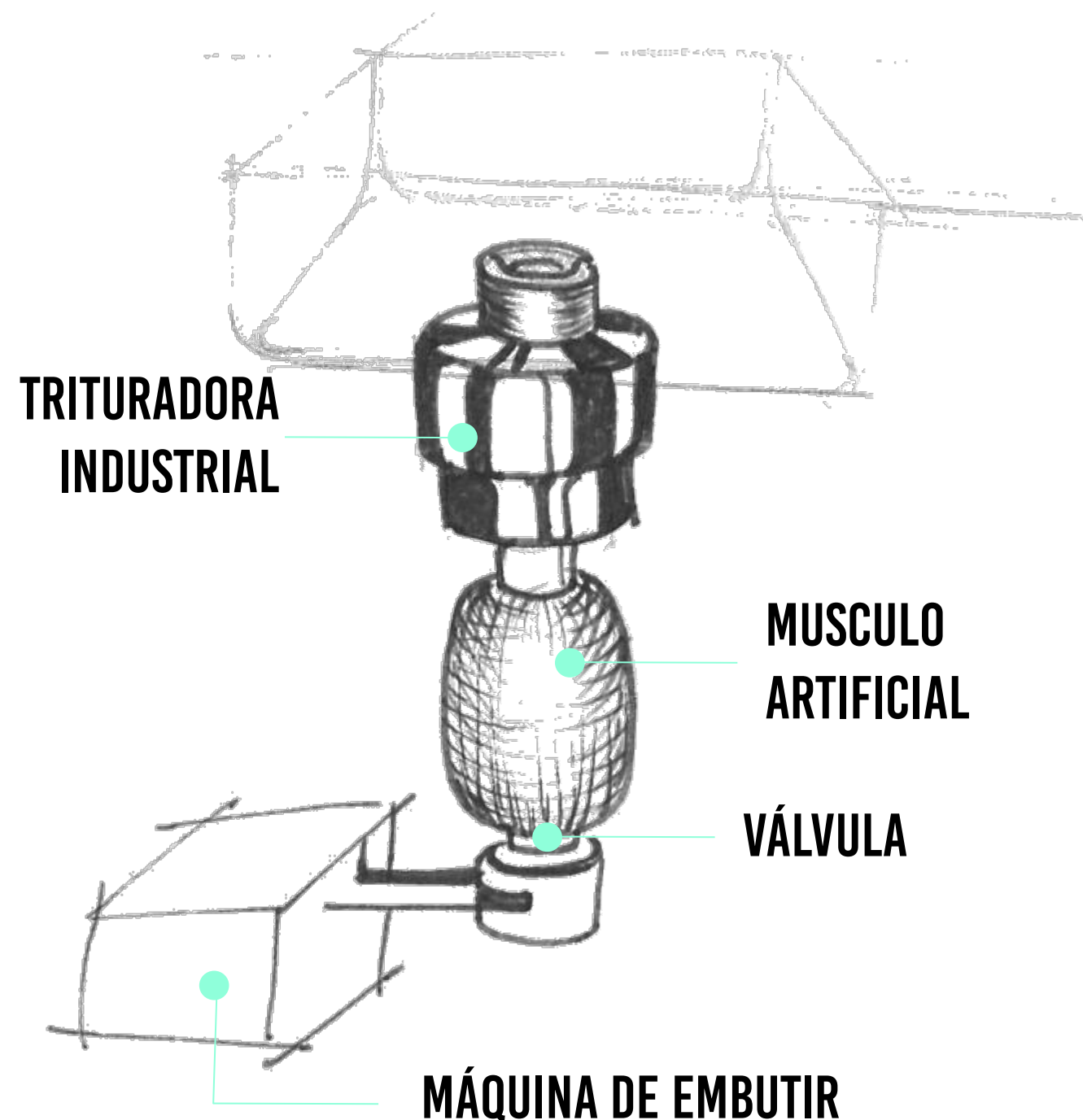
PUNTOS FUERTES:

- ☐ Disposición residuos para deshidratar sin necesidad de otro compartimento.
- ☐ Ventilación continua más efectiva.
- ☐ Mejor eliminación de humedad.

PUNTOS DÉBILES:

- ☐ Menor versatilidad de movimientos (torsión imposible).
- ☐ Inexistencia de prototipos que imiten este movimiento.
- ☐ Problema en la evacuación (no está bien definida).

3º CONCEPTO // FUNCIONAMIENTO



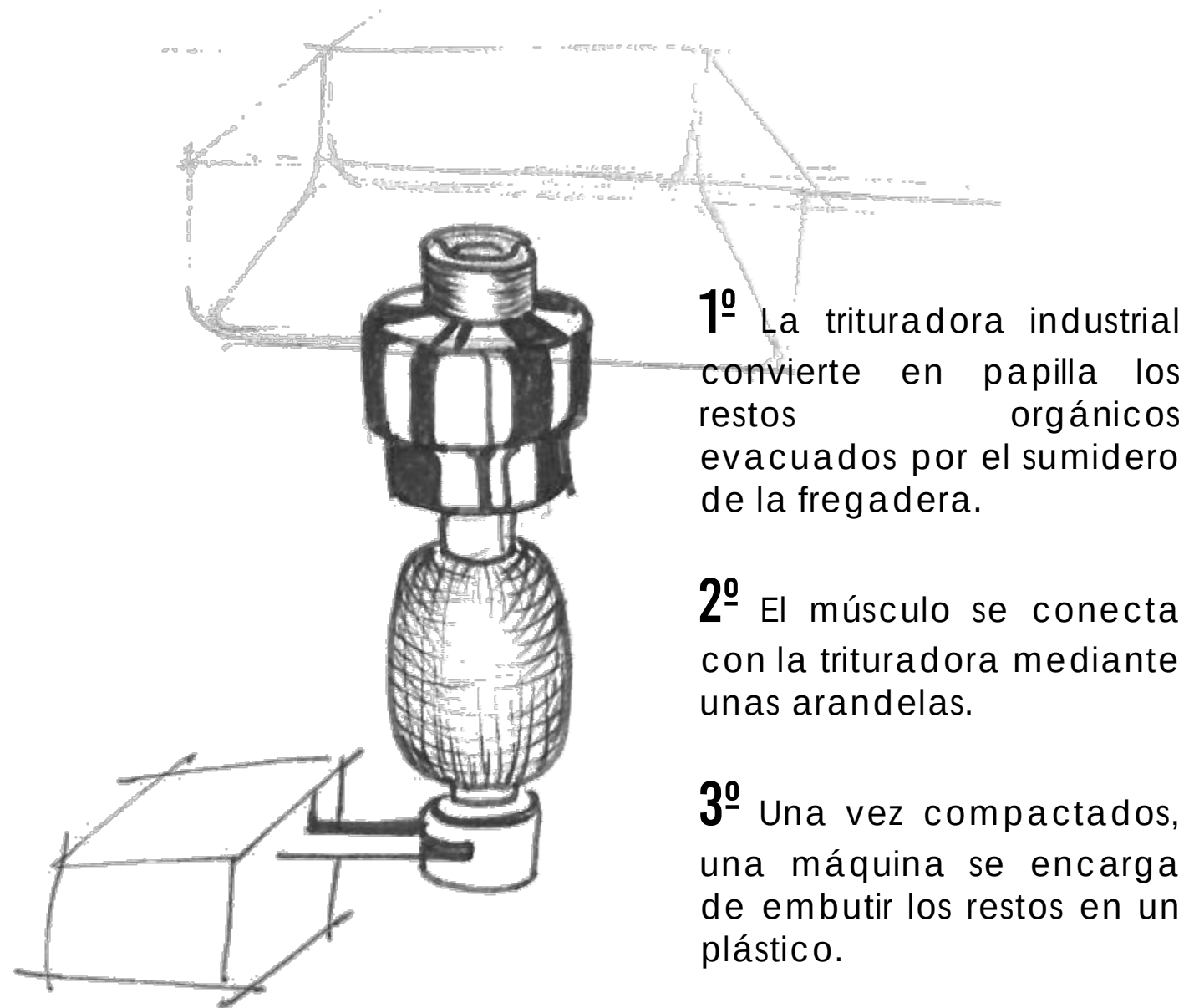
FASE 2 CONCEPTUALIZACIÓN

En este caso, debido al consumo energético que supondría el sistema de deshidratación, se optó por crear una solución alternativa a las dos anteriores.

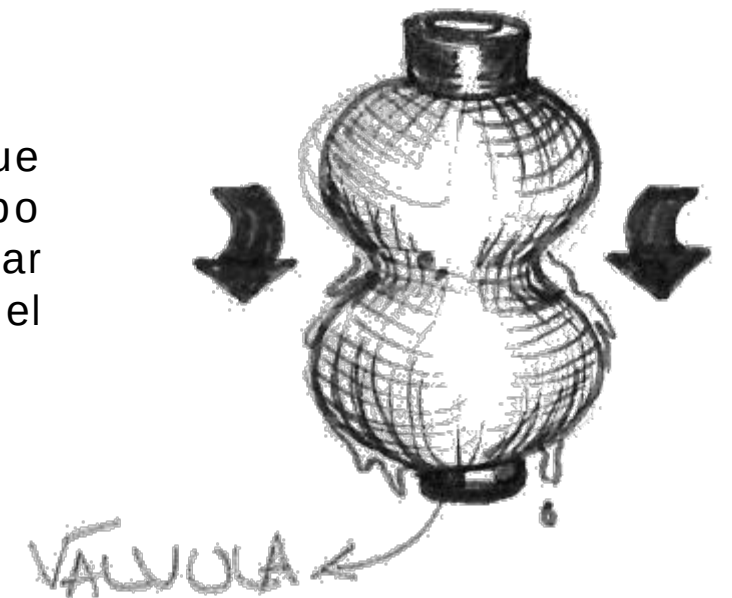
Además en los otros conceptos no se añadió el uso combinado con una trituradora para deshacer los residuos orgánicos. La **trituration** implicaría la obtención de una **masa más ligera** de desechos, y la posibilidad de una **compactación mayor**.

La humedad se eliminaría en una gran parte pero no al nivel de las dos ideas anteriores. Por ello podrían entrar en estado de descomposición y crear malos olores. Se ha pensado en añadir una **máquina de embutición** para introducir los restos compactados en un envoltorio de plástico y así evitar este problema y aumentar la higiene en su transporte.

3º CONCEPTO //ELEMENTOS INTERNOS



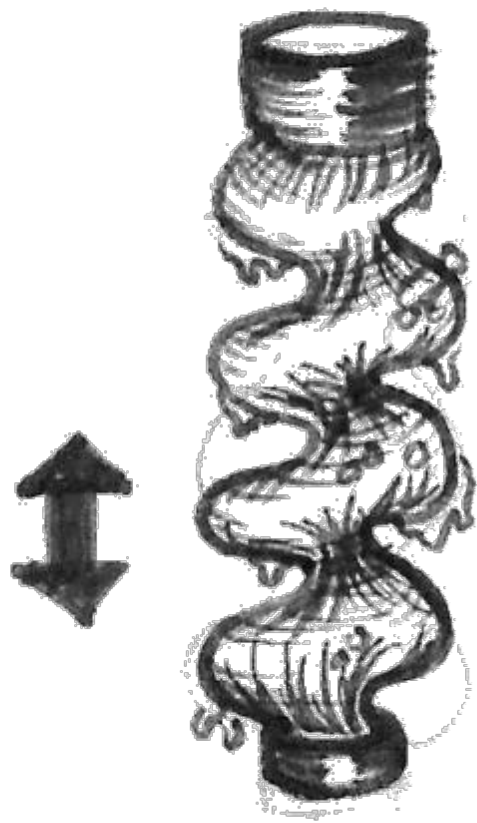
El primer movimiento que realiza es de tipo peristáltico, para llenar todo el volumen del músculo.



Una vez lleno, comienza a retorcerse, para ejercer presión en la masa resultante. En este paso se elimina gran parte de la humedad, segregando jugos a través de la red de Nitinol.



3º CONCEPTO //ELEMENTOS INTERNOS



Una vez se ha enrollado todo el músculo, se estira para provocar una mayor presión. Este movimiento ayuda a escurrir los posibles líquidos que quedasen en la masa de restos orgánicos.

Finalmente, da una forma orgánica a los restos para poder eliminarlos de manera fluida.

Estos salen a través de la válvula inferior que se abre al ejercer presión sobre ella.

Es entonces cuando la máquina de embutir los envuelve en una película plástica.



3º CONCEPTO //CONCLUSIONES

Se ha realizado una lista de puntos fuertes y débiles del concepto tal y como se hizo en los casos anteriores para poder hacer una mejor valoración:

PUNTOS FUERTES:

- ☐ Trituración óptima, produce papilla.
- ☐ Compactación más sencilla, menos procesos y menor fuerza requerida.
- ☐ Reutilización de residuos alternativa.
- ☐ Eliminación sistema deshidratación.

PUNTOS DÉBILES:

- ☐ Nueva máquina de embutición (consumo energético).
- ☐ Uso de trituradora industrial (consumo energético).
- ☐ Mayor número de elementos y piezas.

FASE 2

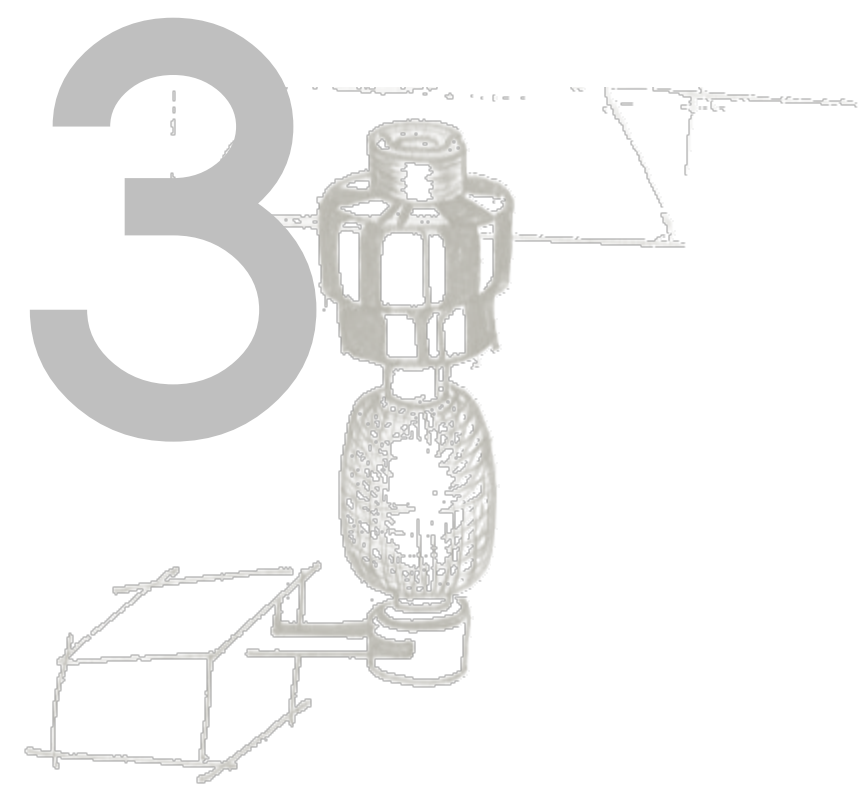
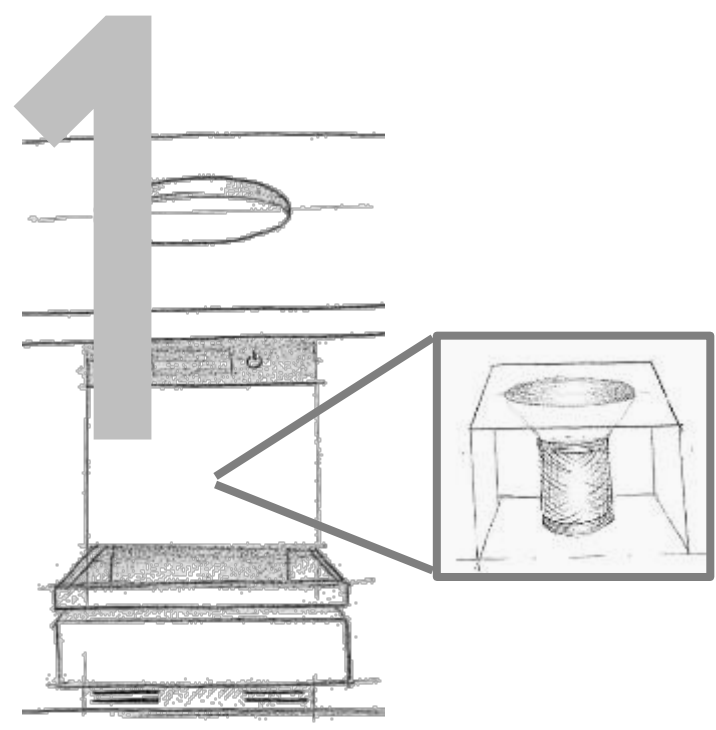
ELECCIÓN FINAL

Gracias a la valoración de los conceptos a partir de sus puntos fuertes y débiles, se puede elegir de manera sencilla aquel cuyos puntos fuertes destaquen sobre el resto. El concepto 3 resultó ser el mejor valorado, aunque se deba seguir trabajando para acabar de definir los posibles problemas funcionales.

PUNTOS FUERTES:



PUNTOS DÉBILES:



FASE 3

DESARROLLO DE PRODUCTO
TECNOLOGÍA Y EXPERIMENTACIÓN
DISEÑO FINAL

FASE 3

DESARROLLO DE PRODUCTO

En esta fase se va a profundizar en el diseño final del **concepto 3** teniendo en cuenta las limitaciones y posibilidades de la tecnología utilizada.

Una vez se hayan estudiado sus **características** y el proceso de **funcionamiento**, se realizarán los cálculos necesarios para desarrollar el concepto que ha sido elegido.

Para ello se ha buscado **Nitinol comercial** y se ha aplicado a los requisitos del concepto, formando así una demostración específica de la capacidad de esta tecnología en diseño de producto.

También se estudiarán los prototipos actuales realizados con Nitinol, para diseñar un músculo que realice los movimientos deseados con la disposición de los cables más adecuada.

FASE 3

DESARROLLO DE PRODUCTO

// ¿CÓMO FUNCIONA?

- 1º** Se eliminarán restos de comida de la pila por el desagüe con ayuda del agua del grifo.
- 2ª** La trituradora comenzará a trabajar una vez se haya llenado el volumen disponible; el grifo se mantiene abierto.
- 3ª** Una vez triturados los restos orgánicos, el flujo de agua los dirigirá a la compactadora para reducir su volumen y eliminar los jugos. A partir de entonces, se debe cerrar el agua del grifo.
- 4ª** Se realizarán entonces las funciones de destrozar, despedazar, aplastar y compactar a través de diferentes movimientos y ejerciendo unas fuerzas determinadas.
- 5º** Una vez vaciado, se comenzarán a embutir los residuos que pasarán a través de una válvula anti retorno. El plástico para embutir se colocará mediante cápsulas.
- 6º** Para acabar se cerrará el plástico que contiene los restos embutidos gracias a una selladora /grapadora industrial.

FASE 3

DESARROLLO DE PRODUCTO

3º CONCEPTO | REDISEÑO

En este apartado se desarrolla de **forma conceptual** el diseño elegido en la fase anterior.

A partir del proceso de funcionamiento se comienzan a realizar bocetos que permitan llevar a cabo la finalidad del producto. A continuación se explica el proceso de creación de los elementos necesarios y el posterior desarrollo de piezas.

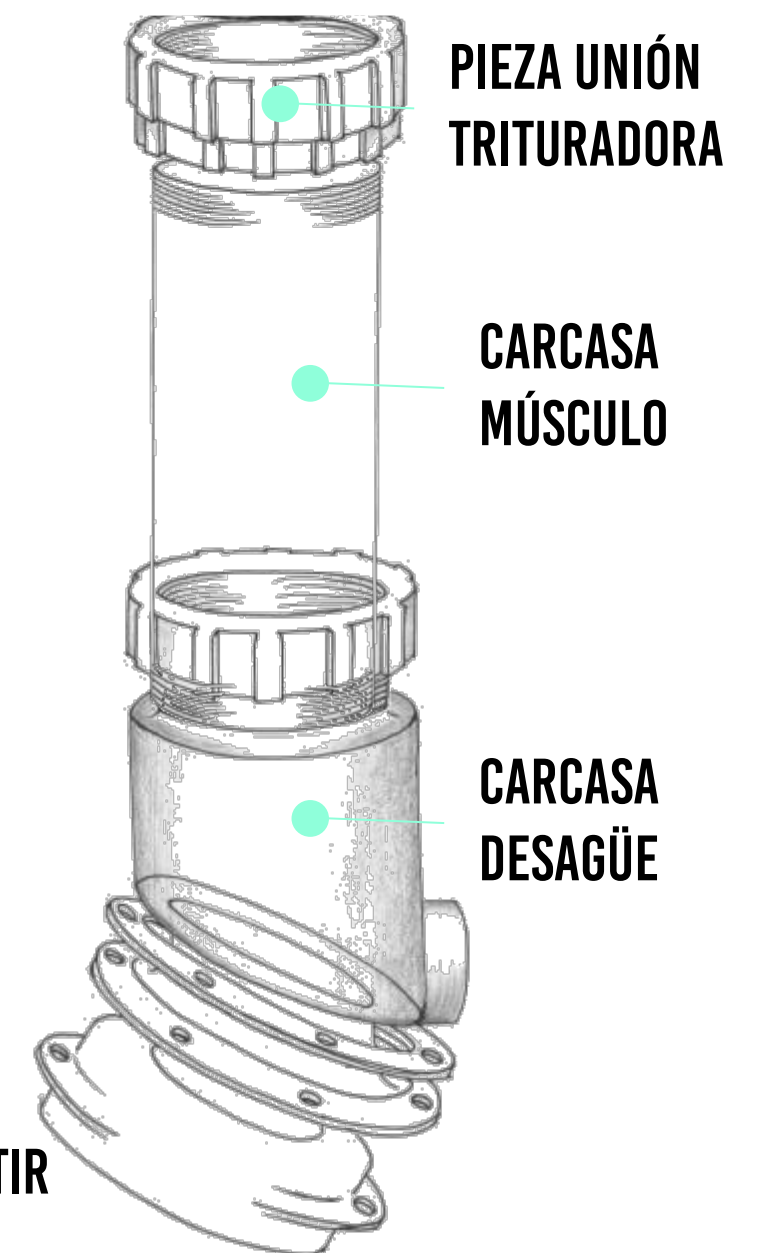
Partiendo de las medidas de una trituradora industrial, se ha desarrollado el tamaño del nuevo producto. Como dato principal se ha tenido en cuenta el **diámetro del desagüe de la trituradora**, para encajar la primera pieza de conexión.

A partir de esta pieza se ha pensado en la **carcasa** que contiene el músculo artificial, cuya **forma cilíndrica** favorece el transporte fluido de los restos triturados.

La carcasa era necesaria por varias razones: protección del músculo, mantiene la limpieza del entorno y dirige el líquido sobrante al desagüe.

El músculo posee en el extremo inferior una **válvula anti-retorno**. Esta pieza facilita la embutición de los residuos compactados en el film de plástico.

Por último, para la fase de sellado, se considera el acoplamiento de una **grapadora comercial** en la zona de salida de los residuos embutidos.



VÁLVULA EMBUTIR

FASE 3

DESARROLLO DE PRODUCTO

3º CONCEPTO | 1º BOCETO

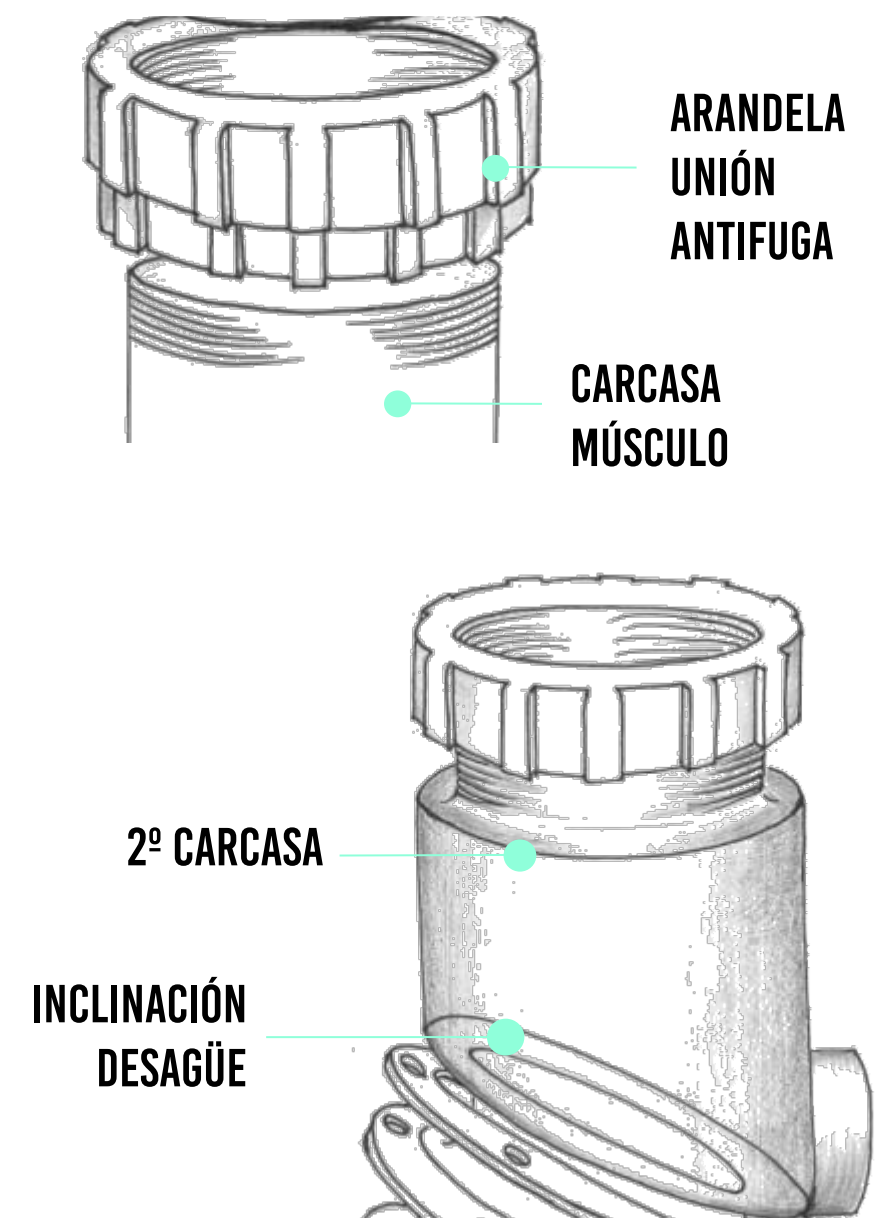
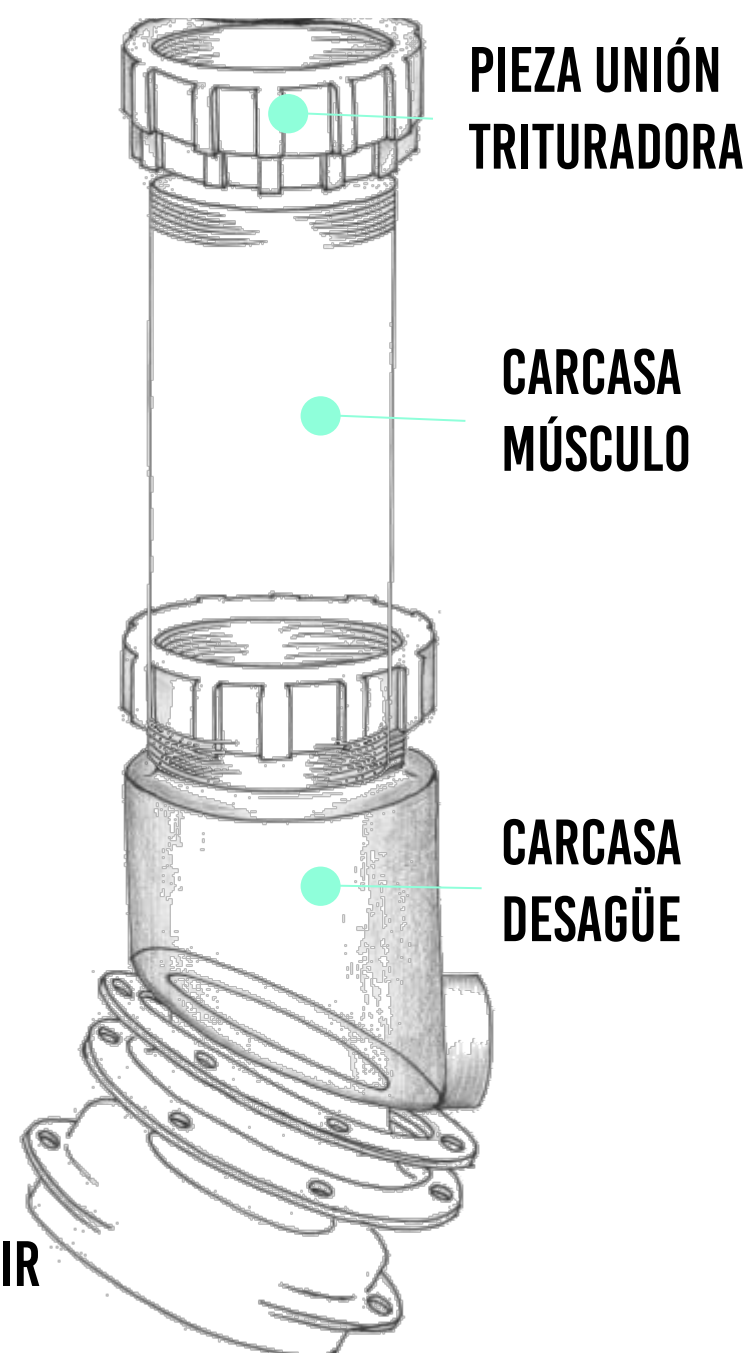
En el primer boceto se hizo uso de **piezas comerciales** para conectar la trituradora con otros elementos que se acoplasen a la misma.

Así se diseña un sistema de **uniones por rosca** que permiten cerrar herméticamente la carcasa del músculo y el tubo que conecta con la trituradora.

El músculo queda dentro su carcasa y se debe unir a otra que permita eliminar el agua sobrante. Al tener que ser también desmontable, esta **segunda carcasa** tiene una zona roscada en la parte superior.

Para **evacuar agua** de forma sencilla, se decidió inclinar la base de la segunda carcasa para ayudar en el proceso.

VÁLVULA EMBUTIR



FASE 3

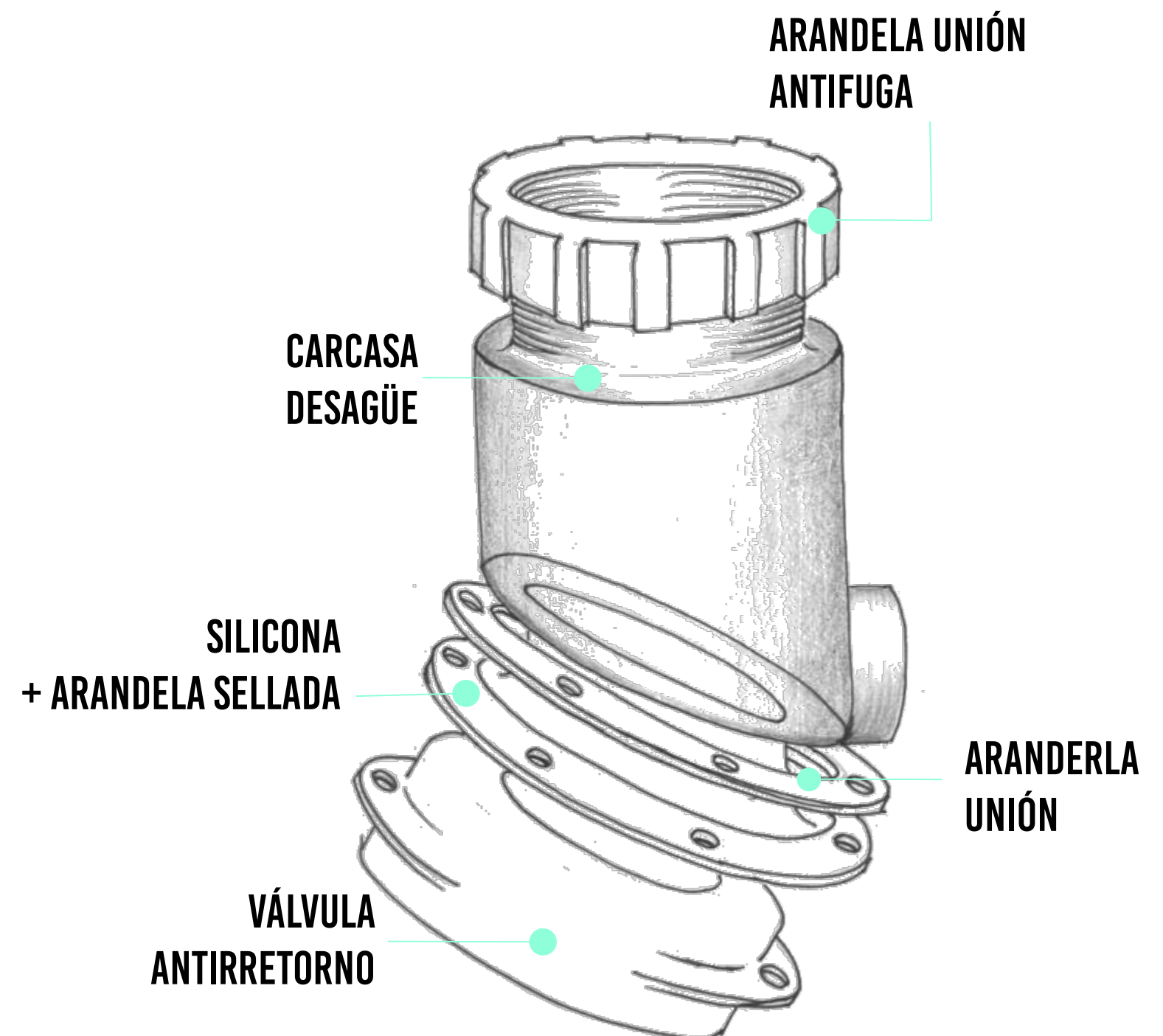
DESARROLLO DE PRODUCTO

3º CONCEPTO | 1º BOCETO

El músculo se une a la carcasa inclinada mediante tornillos. Esto es gracias a que el músculo queda unido a dos partes de **silicona** (una en la parte superior y otra en la inferior) que tienen dos **arandelas selladas** en sus extremos.

Sobre estas **arandelas** se encuentran otras semejantes **de unión**, para poder juntar el músculo con la válvula de embutir y con la carcasa que se enrosca al fregadero.

Una vez colocada la **válvula antirretorno** (comercial), se acoplará a ella la pieza que contiene las cápsulas de film para embutir. Esta pieza tendrá el mismo diámetro externo e interno que la válvula antirretorno.



FASE 3

DESARROLLO DE PRODUCTO

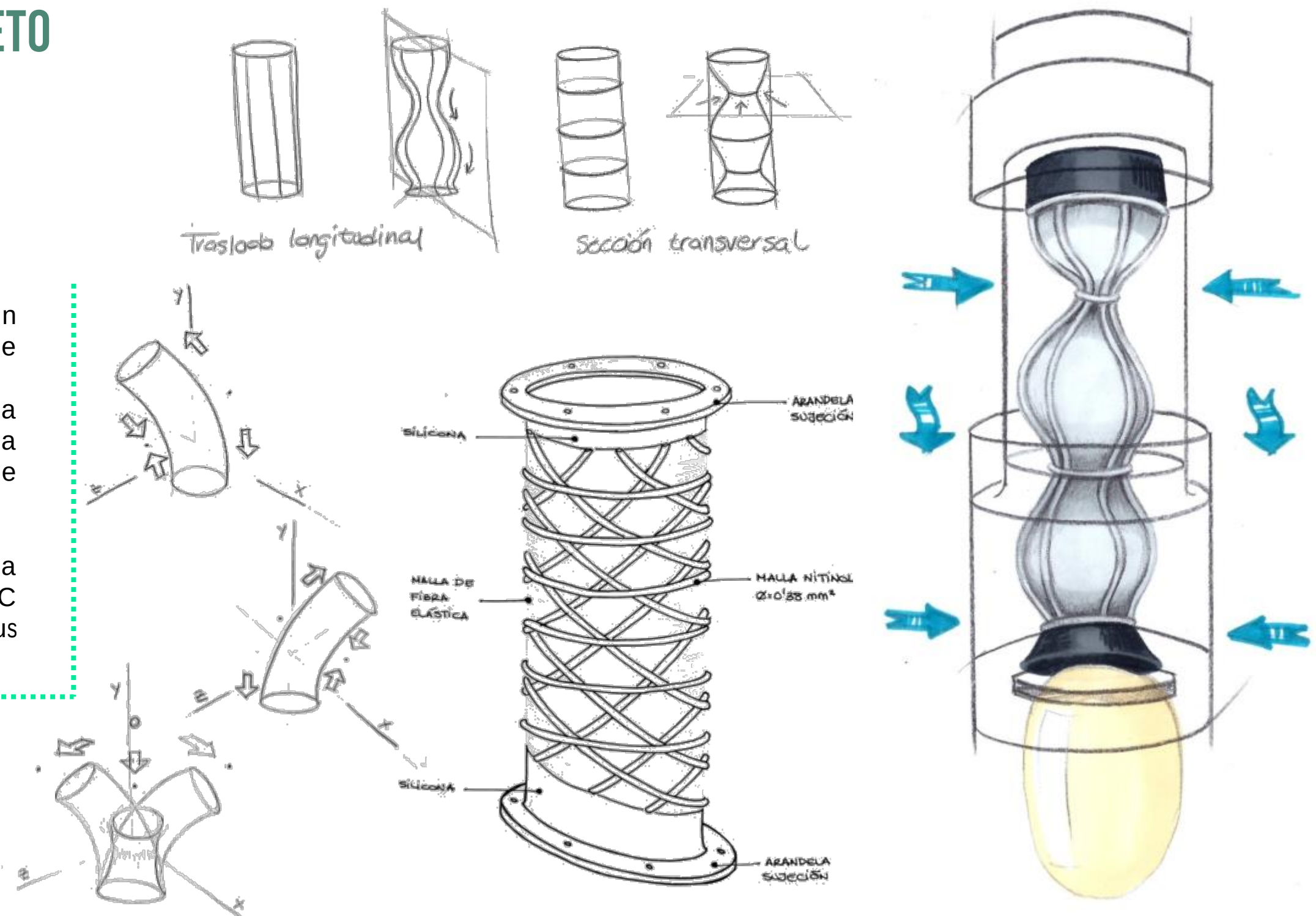
3º CONCEPTO | 1º BOCETO

MÚSCULO APADTADO:

Realizado en silicona y la malla de 4 cables de nitinol.

Entre la malla de nitinol + silicona existen huecos para permitir la extracción de jugos a través de una malla de nylon.

En los extremos se han sellado a la silicona dos arandelas de PVC para poder atornillarlo a sus correspondientes carcasas.



FASE 3

DESARROLLO DE PRODUCTO

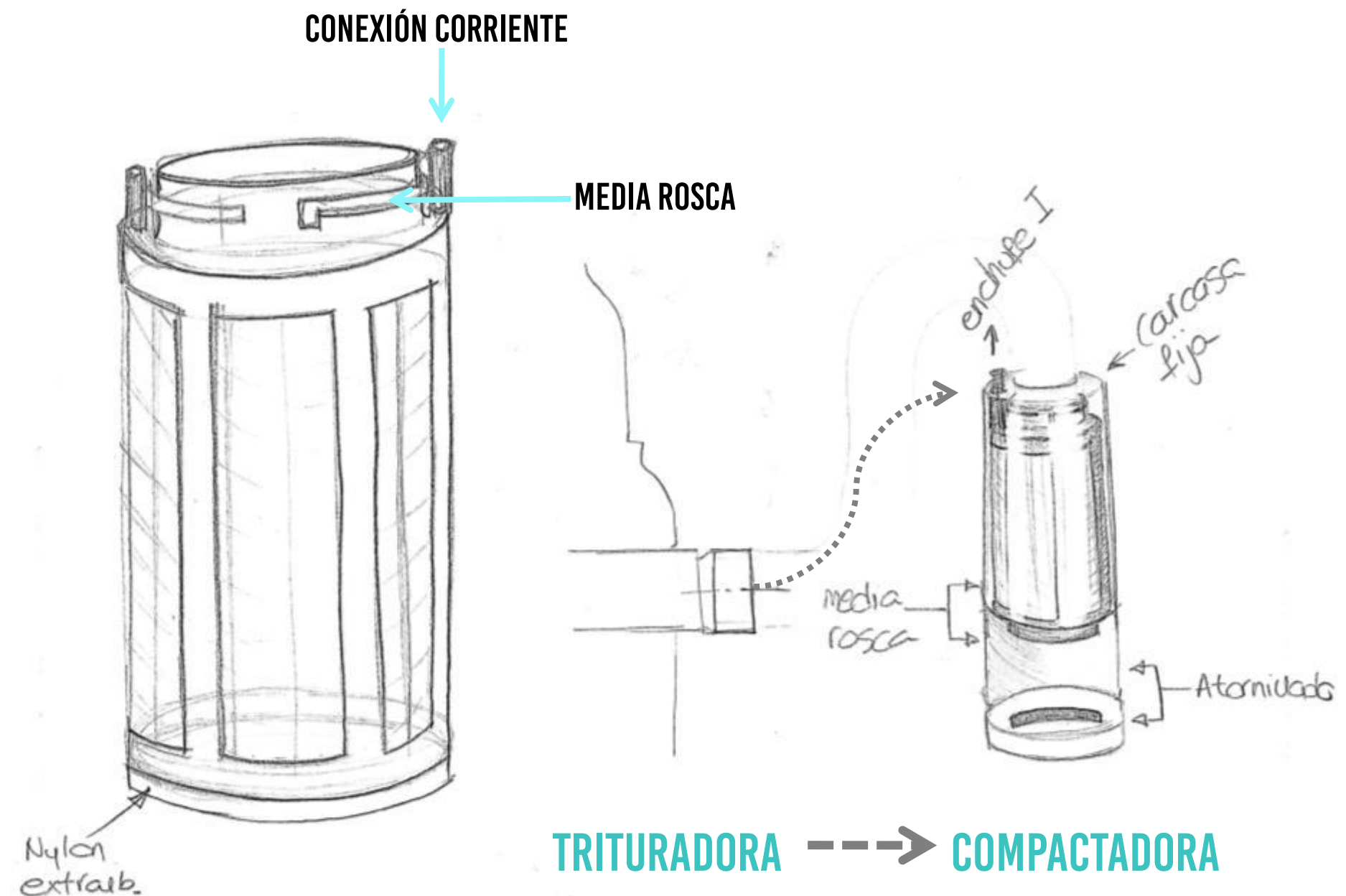
3º CONCEPTO | 2º BOCETO

En este segundo boceto se trabajó en la idea de **desmontar y montar** las piezas fácilmente. Este factor aumentaría la comodidad en el proceso de limpieza.

Para ello se eliminaron las roscas y se aplicaron sistemas de encaje por presión. Se observaron **filtros de nylon** comerciales con forma cilíndrica para diseñar uno similar para la compactadora.

Además se profundizó en las piezas que contienen los **elementos eléctricos** teniendo en cuenta la seguridad.

Se siguió diseñando el volumen de **forma cilíndrica** al mantener la fluidez de los residuos durante el proceso.



FASE 3

DESARROLLO DE PRODUCTO

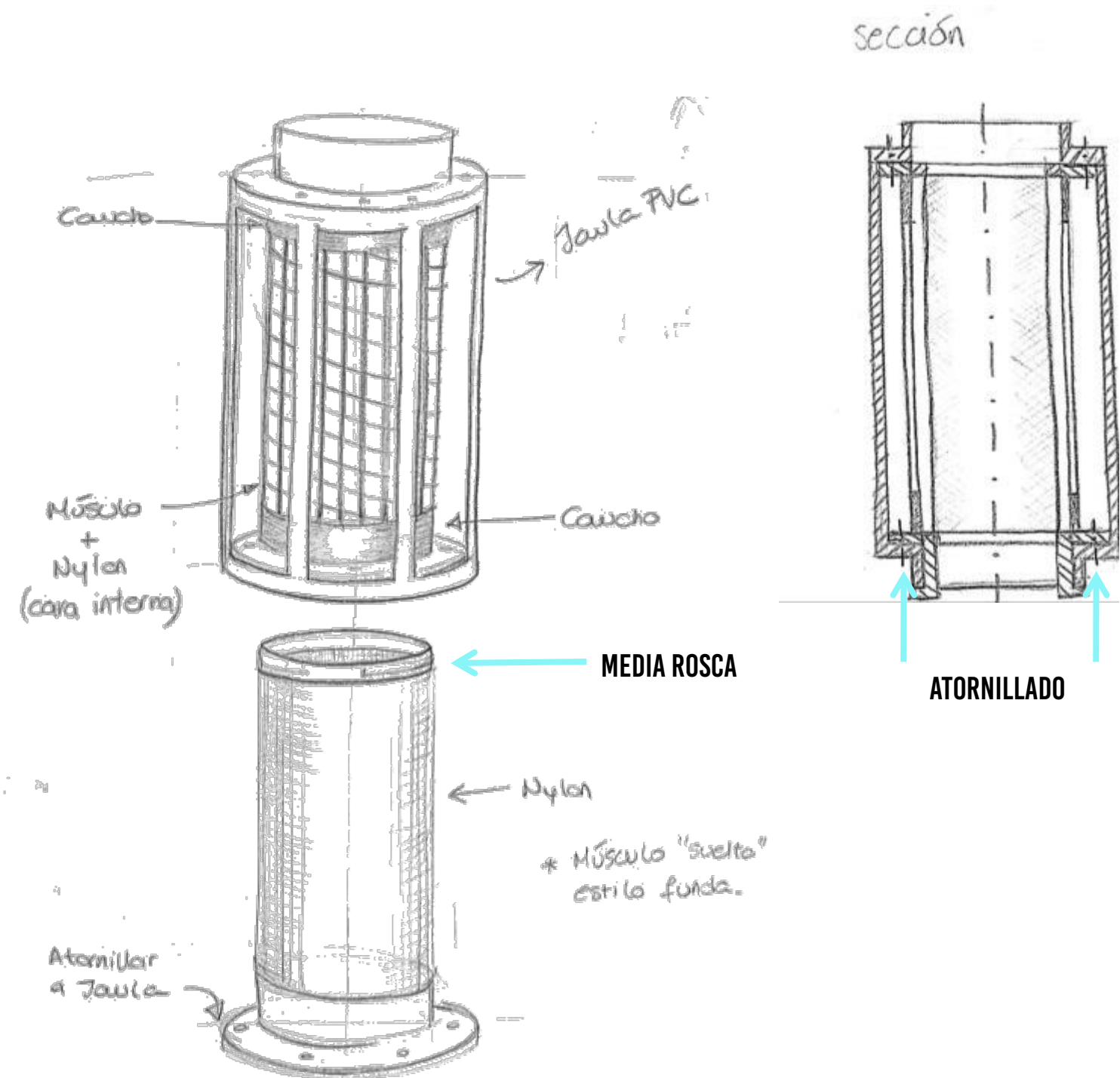
3º CONCEPTO | 2º BOCETO

Se puede apreciar en los bocetos que el músculo se atornilla a una **carcasa con forma de jaula** por la parte superior.

MÚSCULO ADAPTADO:

El músculo posee en sus extremos dos piezas cilíndricas de caucho para evitar tensiones.

En el interior del músculo se acopla el filtro de nylon extraíble. El filtro también va atornillado a la jaula que sujeta el músculo por la parte inferior. En el extremo superior posee una arandela con media rosca para encajarlo a su equivalente colocada en el músculo.



FASE 3

DESARROLLO DE PRODUCTO

3º CONCEPTO | 3º BOCETO

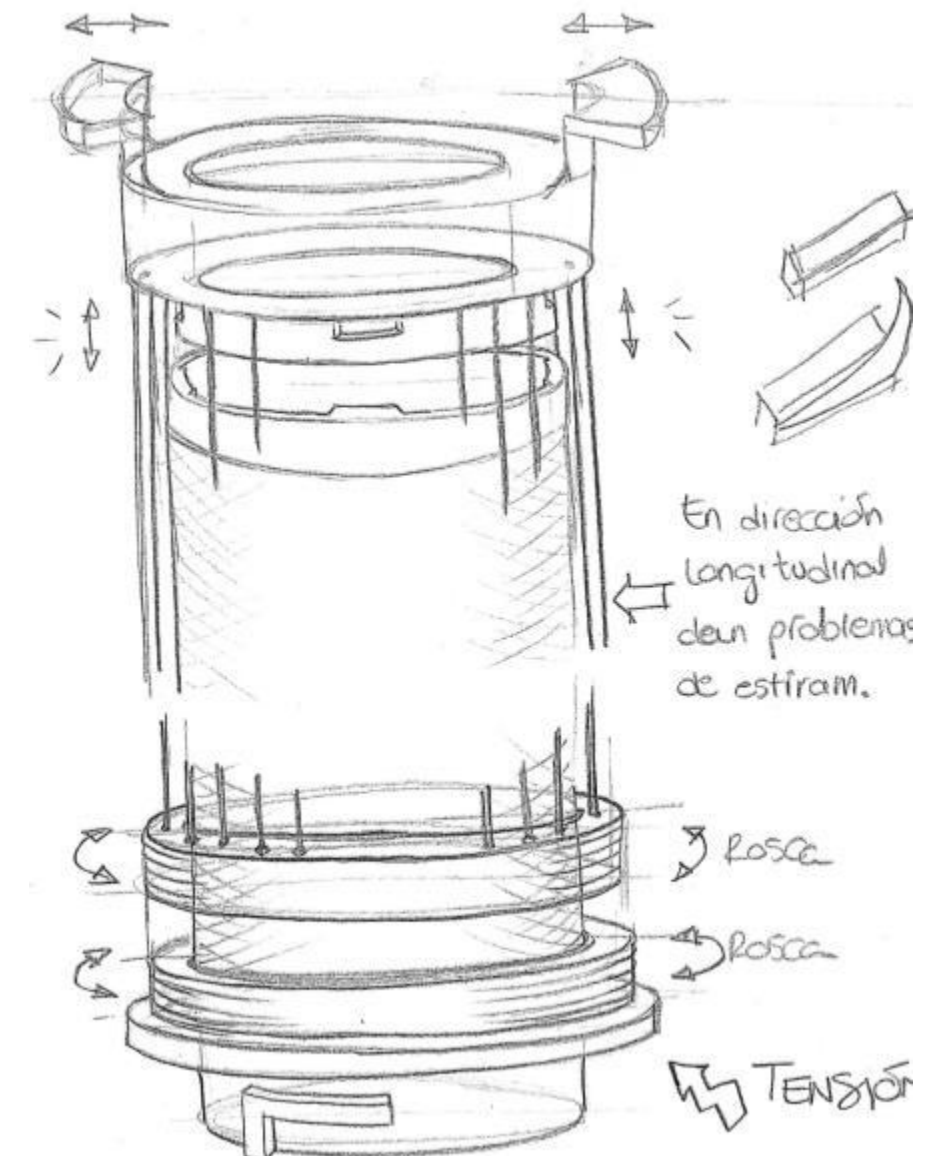
El tercer boceto se basa en la idea de poder **girar** la compactadora y **desencajarla** de los tubos a los que se acopla. Para ello la carcasa exterior se diseña con roscas de **medio giro** en sus extremos.

Las piezas internas se encajan mediante pestañas o roscas.

En la parte superior el músculo se encaja a la carcasa exterior gracias a dos **pestañas de seguridad**. El filtro se encaja por presión al músculo.

En la parte inferior el músculo y el filtro se unen por rosca a la carcasa exterior.

Este sistema de unión por rosca crea tensiones a la hora de funcionamiento, por lo que se decidió trabajar en un 4º boceto que simplificase estas uniones.



FASE 3

DESARROLLO DE PRODUCTO

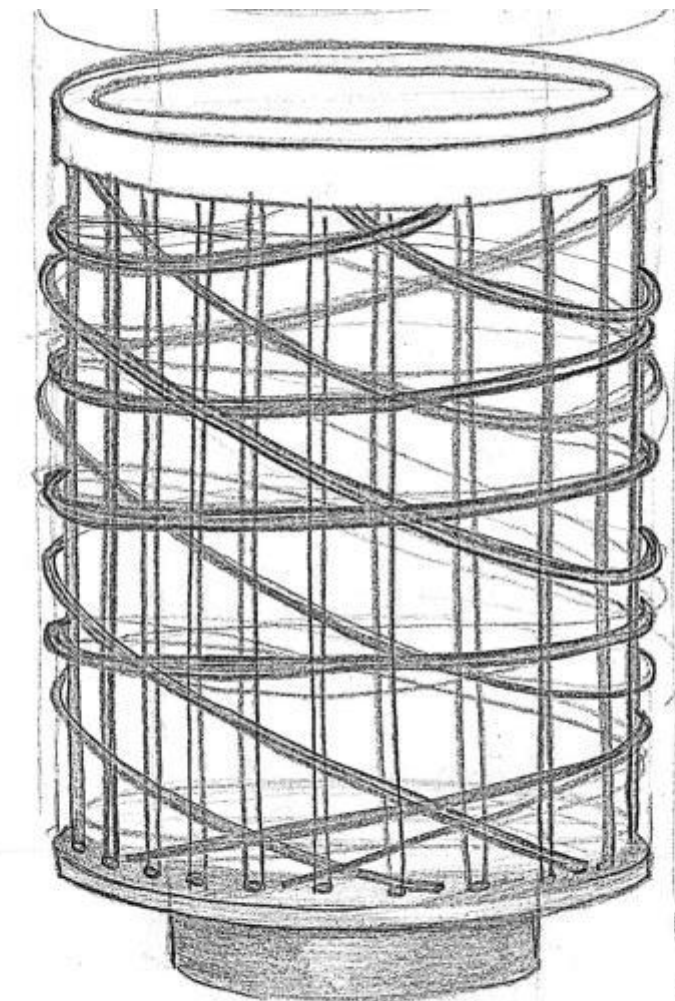
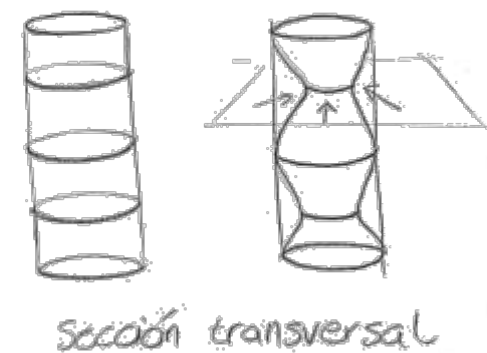
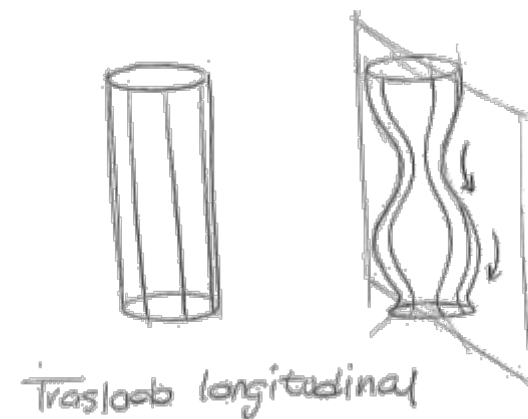
3º CONCEPTO | 3º BOCETO

MÚSCULO ADAPTADO:

La disposición de los cables de Nitinol en el músculo siguió con el patrón inicial aunque debido a la necesidad de crear movimientos fluidos se **añadieron más cables**.

Algunos de estos cables se presentan en forma de **espiral**. Tras observar los prototipos existentes se observó que esta forma permite la disminución de la sección transversal de manera versátil.

Se han eliminado las partes de caucho unidas a los extremos de los cables ya que no se realizarán movimientos bruscos. Los movimientos consistirán en **disminuir la sección** de forma progresiva y **trasladar** los residuos en dirección longitudinal.



No se estira
ni contrae
por cables
long.

FASE 3

DESARROLLO DE PRODUCTO

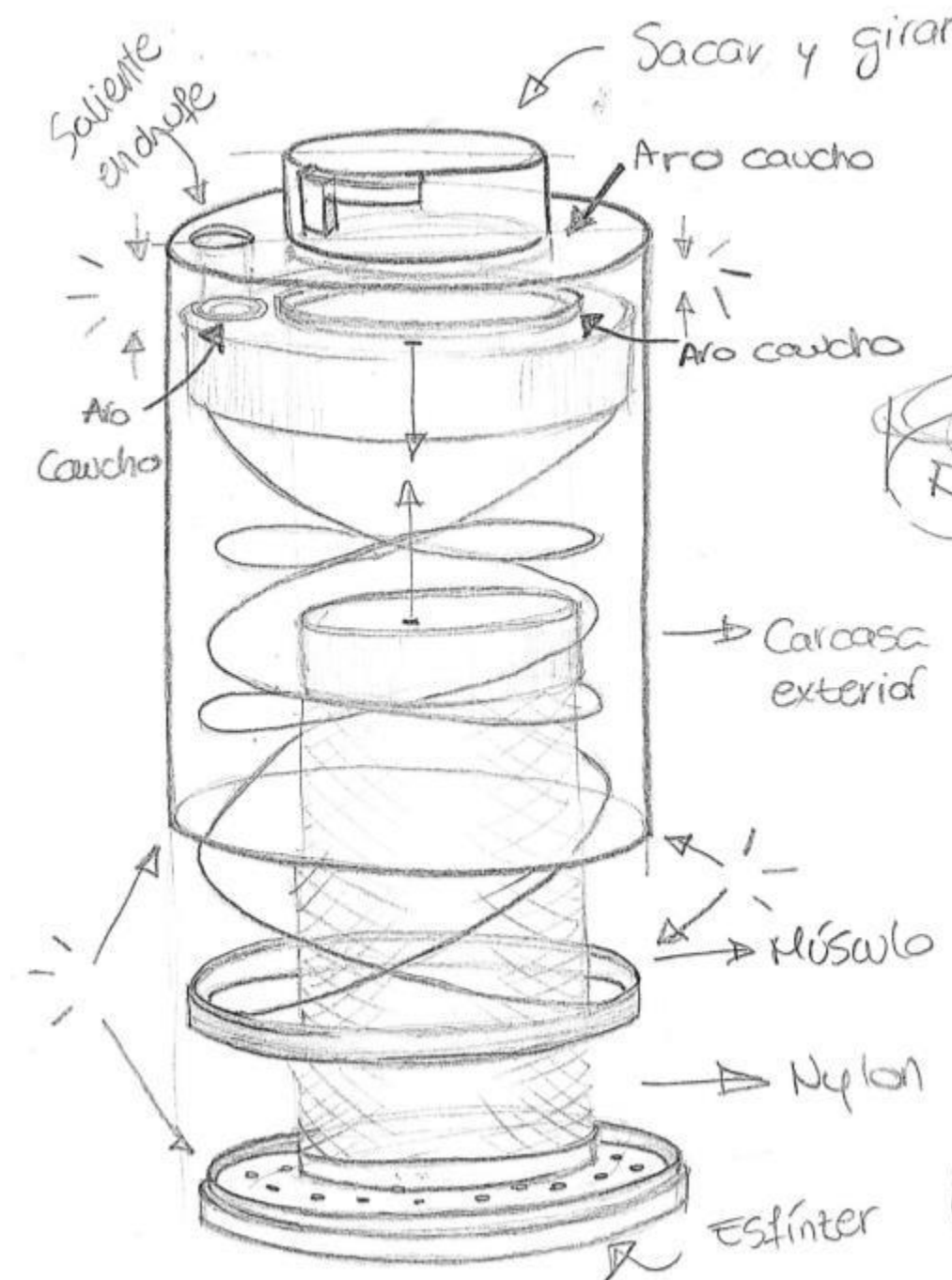
3º CONCEPTO | 4º BOCETO

En este último boceto se representan las **uniones por presión** entre las diferentes piezas.

Se prioriza la **higiene** por lo que era necesario este sistema de ensamblaje. Se facilita así el montaje de la compactadora creando piezas que se pueden extraer del conjunto para limpiarlas.

La parte encargada de embutir los residuos compactados se ha desarrollado para **evitar fugas y abrir la cápsula** que contiene el plástico.

Al tener que existir un aislamiento entre los líquidos y los elementos eléctricos, se han colocado en las uniones arandelas de caucho.



FASE 3

DESARROLLO DE PRODUCTO

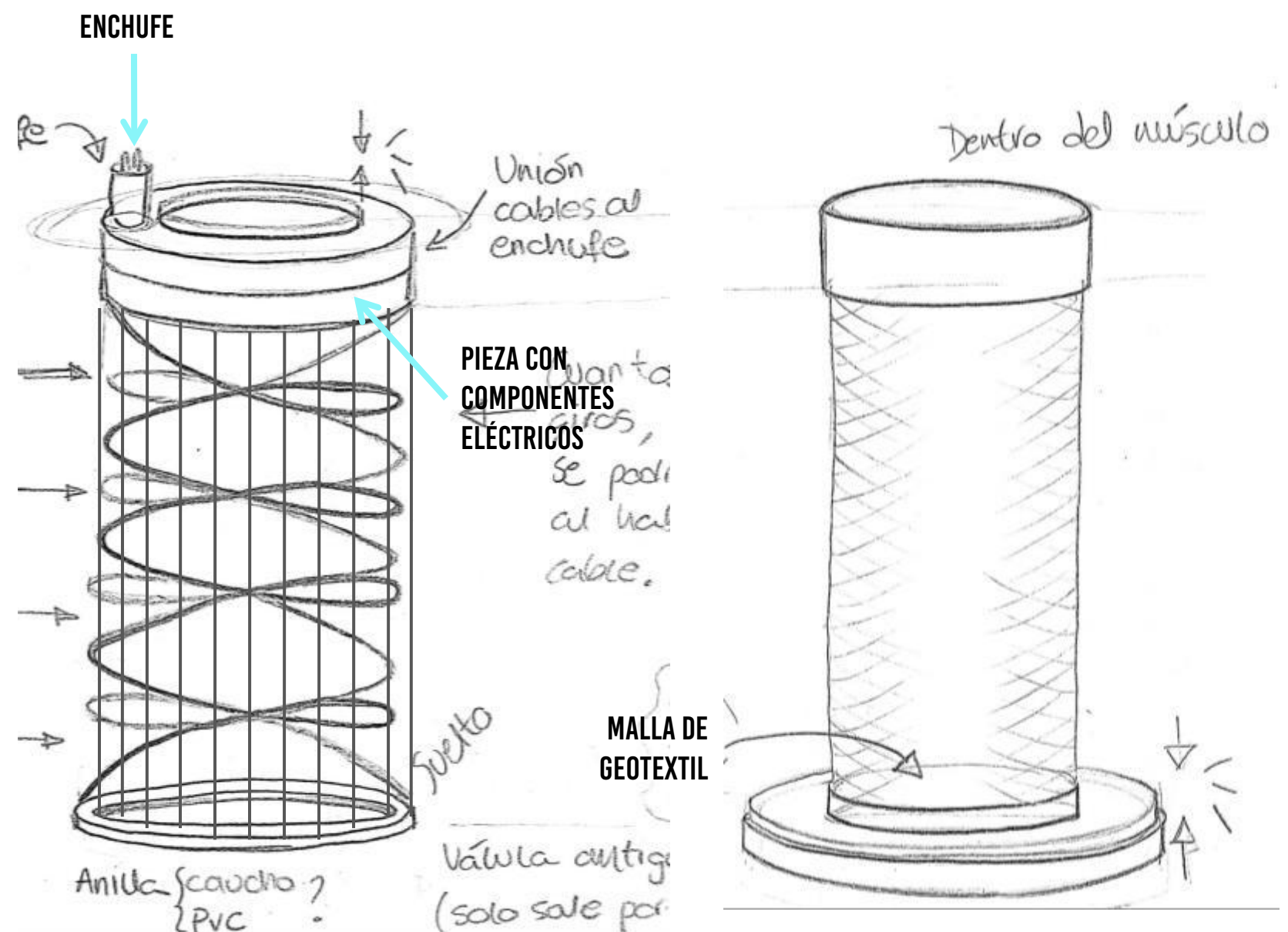
3º CONCEPTO | 4º BOCETO

MÚSCULO ADAPTADO:

El músculo se sujeta por la parte superior pero no por el extremo inferior, al no ser necesario gracias a los cables longitudinales de Nitinol que sujetan la estructura.

En los prototipos existentes de mallas de este cable, **un extremo es conectado a la corriente y el opuesto se deja libre**, permitiendo una mayor versatilidad de movimientos.

Se ha pensado en diseñar una pieza que conecte los cables de Nitinol a la corriente eléctrica. Dentro de esta pieza se encuentran los **elementos eléctricos** perfectamente **aislados**. En la parte superior un cilindro dirige el cable al exterior de las carcasas para no entrar en contacto con líquidos en ningún momento.



FASE 3

DESARROLLO DE PRODUCTO
TECNOLOGÍA Y EXPERIMENTACIÓN
DISEÑO FINAL

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

Para averiguar la fuerza necesaria para destruir los restos sólidos más duros, se hizo una **búsqueda** en internet. Los **huesos** humanos se rompen aproximadamente bajo una presión entre 130 y 205 MPa según las fuentes consultadas (UCSB science line y vídeo de BBC Earth Unplugged). A raíz de esta información se concluyó que con menos presión se podrían romper los huesos de los restos alimenticios.

La resistencia de los cables de nitinol comercial buscados es mucho mayor a este valor, por lo que no habría problemas de rotura en el músculo artificial.

Se ha observado que un cable de nitinol de $\varnothing=0.25\text{mm}$ es capaz de levantar aproximadamente 1Kg(65). Al ser escalable, se ha pensado en realizar diseños a base de mallas con cables de diámetros menores.

Si se utiliza el cable comercial de menor diámetro, con una simple regla de tres calcularemos el peso que es capaz de elevar.

■ $\varnothing=0.25\text{mm} \rightarrow 0.9 \text{ kg}$

■ $\varnothing=0.025\text{mm} \rightarrow 0.09 \text{ kg} = 90 \text{ g}$ (65)

A continuación se considerará el diseño de la malla teniendo en cuenta si resulta más eficiente la aplicación de muchos cables de $\varnothing_{\text{mín}}$ o menor cantidad de mayor diámetro.

Esta decisión dependerá de la fuerza a realizar para destrozar y procesar los residuos y del factor económico.

“ Los huesos de calidad media se rompen a una fuerza entre 130 y 205 Mpa.”

- UCSB science line
- BBC Earth Unplugged(67)

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

Para poder realizar los cálculos necesarios se buscaron datos de diámetro, fuerza, longitud y material del Nitinol comercial. Así se plantearon una serie de procesos a realizar con el músculo diseñado en el concepto final y se estudió su capacidad para compactar en cada situación. Estas son algunas de las empresas que ofrecen el producto:

Tabla extraída de la fuente: <http://www.jameco.com/Jameco/Products/ProdDS/357595.pdf>

Properties	Flexinol Name	025	037	050	075	100	125	150	200	250	300	375
Physical	Wire Diameter (µm)	25	37	50	75	100	125	150	200	250	300	375
	Minimum Ben Radius (mm)	1.3	1.85	2.5	3.75	5.0	6.25	7.5	10.0	12.50	15.0	18.75
	Cross-sectional Area (µm ²)	490	1,075	1,960	4,420	7,850	12,270	17,700	31,420	49,100	70,700	110,450
Electrical	Linear Resistance (Ω/m)	1,770	860	510	200	150	70	50	31	20	13	8
	Recommended Current [†] (mA)	20	30	50	100	180	250	400	610	1,000	1,750	2,750
	Recommended Power [†] (W/m)	0.71	0.78	1.28	2.0	4.86	4.4	8.00	12.0	20.0	39.8	60.5
Strength*	Max. Recovery Weight @ 600 MPa (g)	29	65	117	250	469	736	1,056	1,860	2,933	4,240	6,630
	Rec. Recovery Weight @ 190 MPa (g)	7	20	35	80	150	230	330	590	930	1,250	2,000
	Rec. Deformation Weight @ 35 MPa (g)	2	4	8	815	28	43	62	110	172	245	393
Speed	Typical Contraction Speed ^{††} (sec)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	LT Relaxation Speed ^{††} (sec)	0.16	0.25	0.3	0.5	0.8	1.6	2.0	3.5	5.5	8.0	13.0
	LT Alloy Thermal Cycle Rate (cyc/min)	52	48	46	40	33	23	20	13	9	7	4
	HT Relaxation Speed ^{††} (sec)	n.a.	0.09	0.1	0.2	0.4	0.9	1.2	2.2	3.5	6	10
	HT Alloy Thermal Cycle Rate (cyc/min)	n.a.	55	55	50	43	32	27	19	13	9	5

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

Tabla extraída de la fuente: http://bjcsty.en.alibaba.com/product/688540032-209280989/Gr7_Titanium_wires_in_coil.html

Grado	Resistencia a la tracción (min)		Fuerza yeild (min)		Elongación (%)
	MPa	MPa	MPa	MPa	
GR 1	35	240	20	138	24
GR 2	50	345	40	275	20
GR 3	65	450	55	380	18
GR 4	80	550	70	483	15
GR 5	130	895	120	828	10
GR 7	50	345	40	275	20
GR 9	90	620	70	438	15
GR 12	70	438	50	345	18

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

Empresa Baoji City Changshen Co.

GR5:

Resistencia a tracción: **130 a 895 Mpa**
Fuerza: **120 a 828 MPa**
Elongación : **10%.**

GR1:

35 a 240 Mpa
20 a 138 MPa
24%.

(66)

GR2:

50 a 345 Mpa
40 a 275 MPa
20%.

(66)

Búsqueda de **información** para averiguar la fuerza necesaria para destruir **restos sólidos duros**.

Huesos **130Mpa** < Cable Nitinol **895MPa**

“ Los huesos de calidad media se rompen a una fuerza entre 130 y 205 Mpa.

- UCSB science line
- BBC Earth Unplugged (67)

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

Tabla extraída de la fuente: http://www.dynalloy.com/flexwire_70_90.php

Diameter Size inches (mm)	Recommended Pull Force Pounds (grams)	Total Quantity Ordered 1-325ft (1-99m)	Total Quantity Ordered 328-3277ft (100-999m)	Total Quantity Ordered 3,280-32,797ft (1000-9999m)
0.001 (0.025)	0.02 (8.9)	\$3.05ft / \$10.00m	\$1.52ft / \$5.00m	\$1.45ft / \$4.75m
0.0015 (0.038)	0.04 (20)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.002 (0.050)	0.08 (36)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.003 (0.076)	0.18 (80)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.004 (0.10)	0.31 (143)	\$1.37ft / \$4.50m	\$0.73ft / \$2.40m	\$0.46ft / \$1.50m
0.005 (0.13)	0.49 (223)	\$1.37ft / \$4.50m	\$0.73ft / \$2.40m	\$0.46ft / \$1.50m
0.006 (0.15)	0.71 (321)	\$1.37ft / \$4.50m	\$0.73ft / \$2.40m	\$0.46ft / \$1.50m
0.008 (0.20)	1.26 (570)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.010 (0.25)	1.96 (891)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.012 (0.31)	2.83 (1280)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.015 (0.38)	4.42 (2250)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.020 (0.51)*	7.85 (3560)	\$3.05ft / \$10.00m	\$1.52ft / \$5.00m	\$1.45ft / \$4.75m

Observamos que la fuerza soportada no depende de la longitud si no del diámetro del cable de Nitinol.

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

* ROTURA HUESOS = 130 → 205 MPA ⁽⁶⁷⁾

Tabla extraída de la fuente: http://www.dynalloy.com/flexwire_70_90.php



Diameter Size inches (mm)	Recommended Pull Force Pounds (grams)	Total Quantity Ordered 1-325ft (1-99m)	Total Quantity Ordered 328-3277ft (100-999m)	Total Quantity Ordered 3,280-32,797ft (1000-9999m)
0.010 (0.25)	1.96 (891)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.012 (0.31)	2.83 (1280)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.015 (0.38)	4.42 (2250)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.020 (0.51)*	7.85 (3560)	\$3.05ft / \$10.00m	\$1.52ft / \$5.00m	\$1.45ft / \$4.75m

Un cable de sólo **0.25mm** es capaz de soportar 0.891kg de fuerza, **8.73N** → **8.73/0.05 = 174.6N/mm²** así que necesitaríamos:

205 MPa / 174.6N/mm² = 1.2 ~ 1 CABLE de Nitinol (de la longitud deseada)

Por 4.5\$ podemos obtener 1m de longitud. Si tenemos en cuenta que la altura deseada del músculo serán **0.5m** aproximadamente, invertiremos **2.25\$ por cable usado**.

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

* ROTURA HUESOS = 130 → 205 MPA ⁽⁶⁷⁾

Tabla extraída de la fuente: http://www.dynalloy.com/flexwire_70_90.php



Diameter Size inches (mm)	Recommended Pull Force Pounds (grams)	Total Quantity Ordered 1-325ft (1-99m)	Total Quantity Ordered 328-3277ft (100-999m)	Total Quantity Ordered 3,280-32,797ft (1000-9999m)
0.010 (0.25)	1.96 (891)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.012 (0.31)	2.83 (1280)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.015 (0.38)	4.42 (2250)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.020 (0.51)*	7.85 (3560)	\$3.05ft / \$10.00m	\$1.52ft / \$5.00m	\$1.45ft / \$4.75m

Un cable de sólo **0.31mm** es capaz de soportar 1.28 kg de fuerza, **12.54N** → **12.54/0.08 = 156.75N/mm²** así que necesitaríamos:

205 MPa / 156.75N/mm² = 1.3 ~ 1 CABLE de Nitinol (de la longitud deseada)

Por 6.75\$ podemos obtener 1m de longitud. Si tenemos en cuenta que la altura deseada del músculo serán **0.5m** aproximadamente, invertiremos **3.375 \$ por cable**

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

* ROTURA HUESOS = 130 ⁽⁶⁷⁾ → 205 MPA

Tabla extraída de la fuente: http://www.dynalloy.com/flexwire_70_90.php



Diameter Size inches (mm)	Recommended Pull Force Pounds (grams)	Total Quantity Ordered 1-325ft (1-99m)	Total Quantity Ordered 328-3277ft (100-999m)	Total Quantity Ordered 3,280-32,797ft (1000-9999m)
0.010 (0.25)	1.96 (891)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.012 (0.31)	2.83 (1280)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.015 (0.38)	4.42 (2250)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.020 (0.51)*	7.85 (3560)	\$3.05ft / \$10.00m	\$1.52ft / \$5.00m	\$1.45ft / \$4.75m

Un cable de **0.38mm** es capaz de soportar hasta 2.250kg de fuerza, **22N** → **22/0.113 = 194.7N/mm²** así que necesitaríamos:

205 MPa / 194.7N/mm² = 1 CABLE de Nitinol (de la longitud deseada)

Por 6.75\$ podemos obtener 1m de longitud. Si tenemos en cuenta que la altura deseada del músculo serán 0.5m aproximadamente, invertiremos **3.375\$**.

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//NITINOL COMERCIAL:

* ROTURA HUESOS = 130 → 205 MPA ⁽⁶⁷⁾

Tabla extraída de la fuente: http://www.dynalloy.com/flexwire_70_90.php

Diameter Size inches (mm)	Recommended Pull Force Pounds (grams)	Total Quantity Ordered 1-325ft (1-99m)	Total Quantity Ordered 328-3277ft (100-999m)	Total Quantity Ordered 3,280-32,797ft (1000-9999m)
0.010 (0.25)	1.96 (891)	\$1.37ft / \$4.50m	\$0.81ft / \$2.65m	\$0.48ft / \$1.59m
0.012 (0.31)	2.83 (1280)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.015 (0.38)	4.42 (2250)	\$2.06ft / \$6.75m	\$1.17ft / \$3.85m	\$0.72ft / \$2.35m
0.020 (0.51)*	7.85 (3560)	\$3.05ft / \$10.00m	\$1.52ft / \$5.00m	\$1.45ft / \$4.75m

Un cable de sólo **0.5mm** es capaz de soportar hasta 3.560 kg de fuerza, **35N** → **35/0.196 = 178.6N/mm²** así que necesitaríamos:

205 MPa / 178.6N/mm² = 1.15 ~ 1 CABLE de Nitinol (de la longitud deseada)

Por 10\$ podemos obtener 1m de longitud. Si tenemos en cuenta que la altura deseada del músculo serán 0.5m aproximadamente, invertiremos **5\$** en cable para el músculo artificial.

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

NITINOL COMERCIAL | CONCLUSIONES

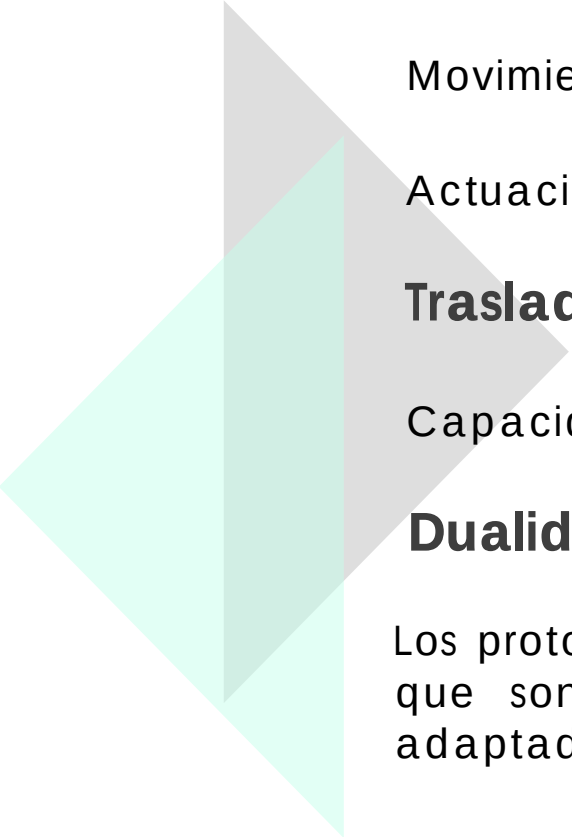
Tras observar los resultados obtenidos, se llega a la conclusión de que el precio de cada cable es aproximadamente el mismo.

Por ello se utilizará el cable de **Nitinol de $\varnothing=0,25$ mm** para la realización del músculo de compactación. Aunque también se podrían combinar con los de **$\varnothing=0,51$ mm** para aportar una mayor resistencia por sección. (65)
A continuación se realizará el diseño de la malla y del resto de componentes del diseño.

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//PROTOTIPOS FUNCIONALES DE NITINOL | OBJETIVOS



Movimientos **orgánicos**, versátiles y sin limitaciones.

Actuación en sección **transversal y longitudinal**.

Traslado en el eje direccional de restos orgánicos.

Capacidad de **resistencia** muy alta.

Dualidad eléctrica – térmica.

Los prototipos funcionales de Nitinol cumplen estos objetivos por lo que son idóneos para la realización de un músculo artificial adaptado a la función de una compactadora.

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//PROTOTIPOS FUNCIONALES DE NITINOL:

Estos prototipos en forma cilíndrica se apoyan en varios cables de Nitinol para crear movimientos más complejos. Están **bioinspirados en gusanos de tierra**.

El primer ejemplo (cilindro gris) está realizado con **un solo cable** enrollado alrededor de la malla gris. Cuando se le aplica una pequeña corriente realiza un movimiento de **alargamiento** que a la vez **disminuye la sección** del cilindro.

El segundo prototipo (cilindro naranja) tiene **tres cables** en posición longitudinal que permiten **doblar** la malla naranja. **a un lado o a otro**.

El tercer ejemplo (cilindro negro) es más sofisticado, ya que **combina cables en diferentes posiciones** para cambiar el diámetro de su sección en varias partes del mismo. Además sigue una secuencia que le permite trasladarse.

Link vídeo:

<https://www.youtube.com/watch?v=EXkf62qGFII>

Más información:

<http://www.neoteo.com/meshworm-un-robot-capaz-de-moverse-como-una-lombri>

<http://news.mit.edu/2012/autonomous-earthworm-robot-0810>



Ejemplo 1



Ejemplo 2



Ejemplo 3



FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//PROTOTIPOS FUNCIONALES DE NITINOL:



Además se ha comprobado la resistencia de los prototipos realizados con Nitinol al aplicarles una fuerza bastante elevada con un martillo. El prototipo no sufre daños y puede seguir funcionando.

Conclusiones prototipos “guasno”:

- ☐ Permitido movimiento de estirar-contrair.
- ☐ Pueden doblarse en 3D.
- ☐ Varían su sección en diferentes partes siguiendo una secuencia.
- ☐ Soportan grandes fuerzas.

Link vídeo:
<https://www.youtube.com/watch?v=MbZ77lx8frA>

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//PROTOTIPOS FUNCIONALES DE NITINOL:



Altas temperaturas → Fase austenítica

Bajas temperaturas → Fase martensítica

Forma de estrella: molde cable + horno a alta temperatura (austenita)

Se somete el molde en agua fría (martensita)

A temperaturas altas siempre estará en fase austenítica (memoria forma estrella)

La fase martensítica permite su manejo y deformación a temperatura ambiente.

Link vídeo:

<https://www.youtube.com/watch?v=s62PL5vmfNw>

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//PROTOTIPOS FUNCIONALES DE NITINOL:



Memoria de forma → **pétalos abiertos** (austenita)

Pétalos cerrados en fase martensita a temperatura ambiente.

Al aplicar calor mediante un secador los pétalos recuperan su forma configurada (pétalos abiertos en fase austenita)

Al enfriarse a temperatura ambiente vuelve a la fase martensita y los pétalos se cierran.

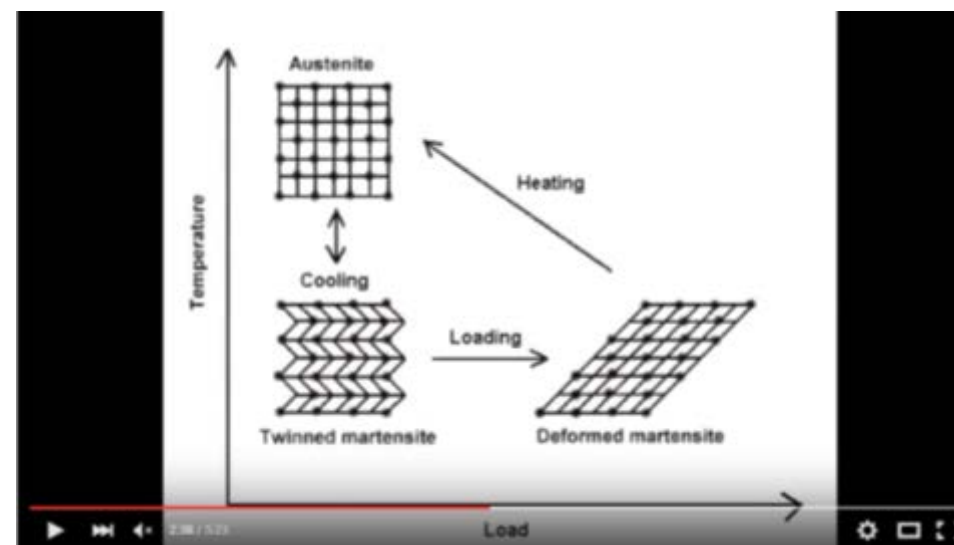
Link vídeo:

https://www.youtube.com/watch?v=bvw7_a2gU24

FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//PROTOTIPOS FUNCIONALES DE NITINOL:



Antes de realizar movimientos aplicando corriente al cable, se somete al proceso de configuración de forma.

Para ello se enrolla el cable a modo de muelle y se aplica calor. Después se sumerge en agua fría para que se produzca el cambio de fase de austenita a martensita. Una vez sellada la forma de muelle, se puede manipular el cable.

Memoria de forma → **muelle** (austenita)

Muelle estirado en fase martensita a temperatura ambiente.

Al aplicar **corriente** el muelle se contrae **hasta recuperar su forma inicial**.

Link vídeo:

<https://www.youtube.com/watch?v=MbZ77lx8frA>



FASE 3

TECNOLOGÍA Y EXPERIMENTACIÓN

//PROTOTIPOS FUNCIONALES DE NITINOL:

Prototipo de una **aleta de calamar** (fig.1): uso de un cable de Nitinol (52% Níquel) para el diseño de una aleta capaz de **doblarse hacia ambos lados**. Se usaron dos cables divididos por un sustrato elástico y todo ello recubierto por una capa de material a modo de piel. Las propiedades del cable son:

Ancho: 14mm
Diámetro: 0.2mm
Longitud: 48mm
Número de cables: 2
Longitud del segmento elástico: 50mm
Grosor de la piel: 0.6-0.7mm
Grosor del segmento elástico: 0.36mm

Tras someter el cable a pulsaciones con diferentes valores de voltaje, se llegó a obtener un **doblado** del prototipo (fig.2) de **más de 90°** hacia ambos lados. Este hecho ocurría al inducir voltajes de $U_2 = 11\text{ V}$, $t_{on} = 0.06\text{ s}$

Información en anexo: "A micro-robot fish with embedded SMA wire"

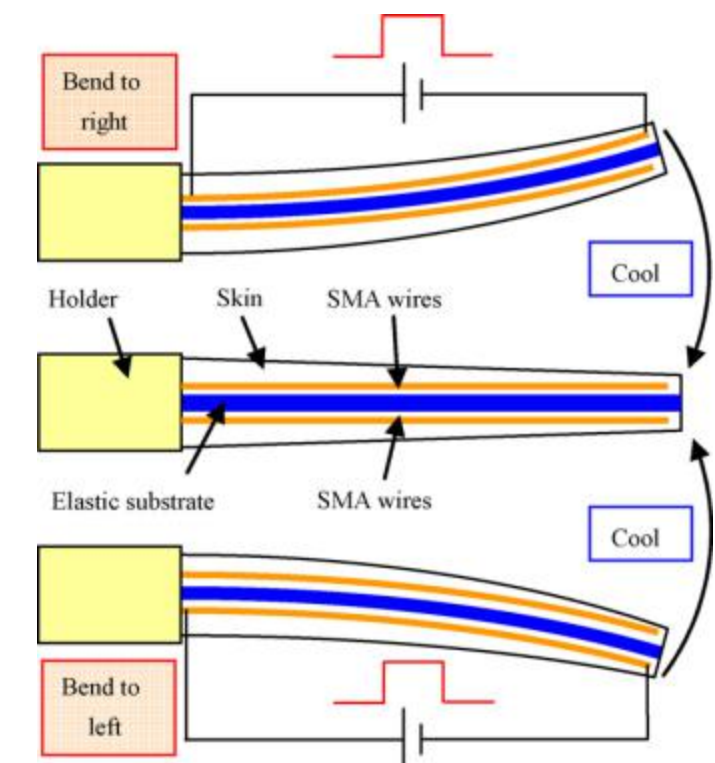


Figura 1

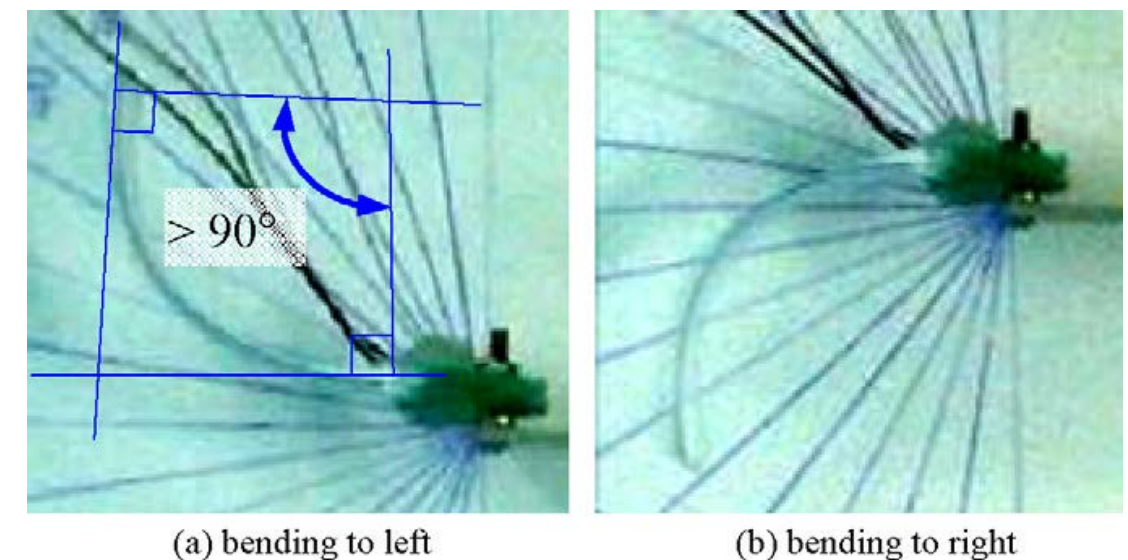


Figura 2

FASE 3

**DESARROLLO DE PRODUCTO
TECNOLOGÍA Y EXPERIMENTACIÓN
DISEÑO FINAL**

FASE 3

DISEÑO FINAL

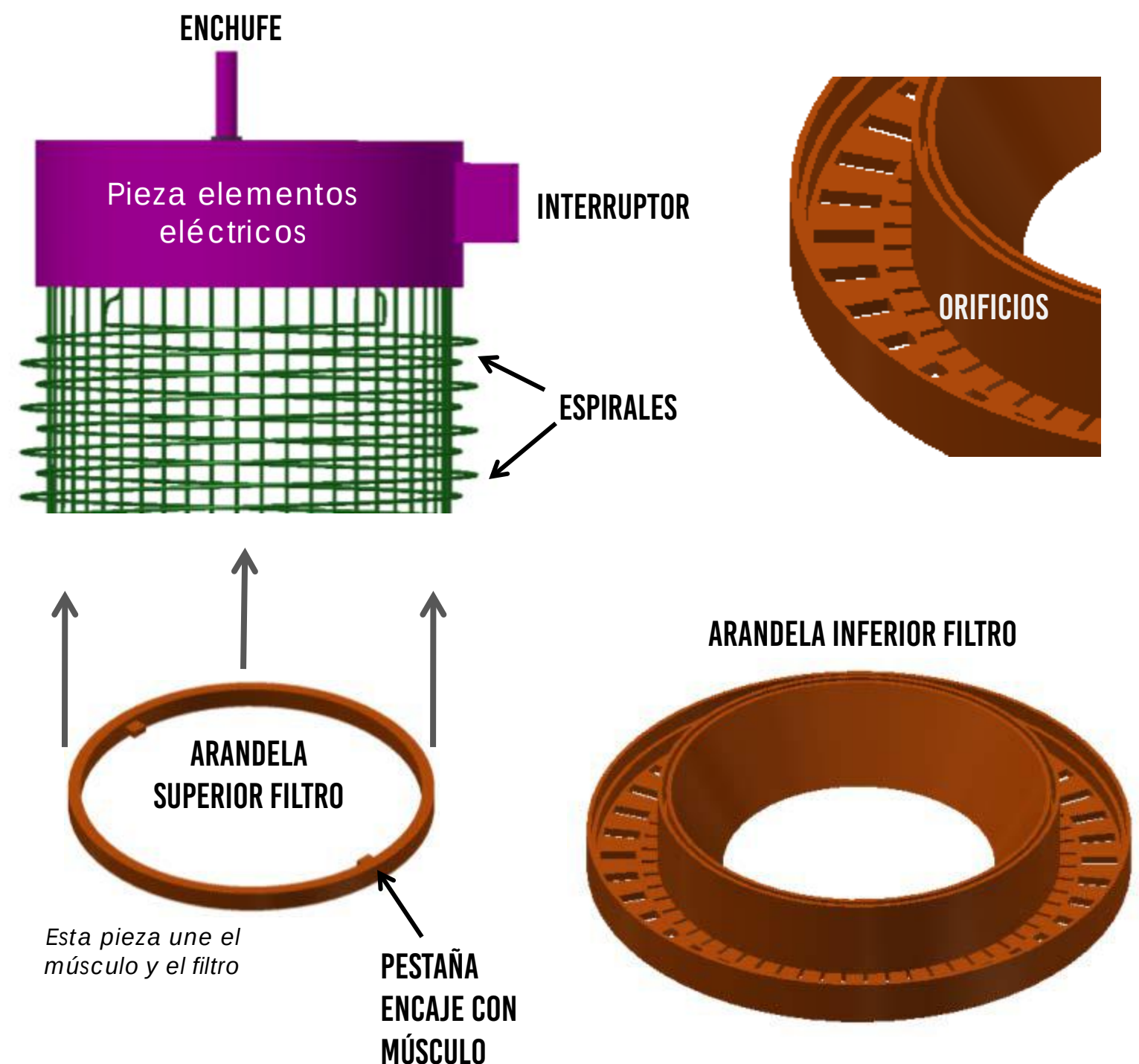
DISEÑO DE LAS PIEZAS

Tras estudiar los prototipos funcionales se desarrolló el **músculo** definitivo, con **dos espirales concéntricas**, una de mayor diámetro que otra. De forma tangente a ellas se reparten cables **longitudinales** que permitirán el traslado de residuos.

Los cables se sujetan a la pieza de componentes eléctricos en la parte superior y a una anilla de plástico en la parte inferior.

El **filtro de geotextil** queda encajado a la pieza de los componentes eléctricos por la parte superior mediante presión. La pieza inferior del filtro se encaja a la carcasa exterior y a la embutidora también por presión. Esta pieza posee unos **orificios** que dejan pasar los jugos y líquidos extraídos de los residuos.

Información en anexo: Planos WasteCompactor



FASE 3

DISEÑO FINAL

DISEÑO DE LAS PIEZAS

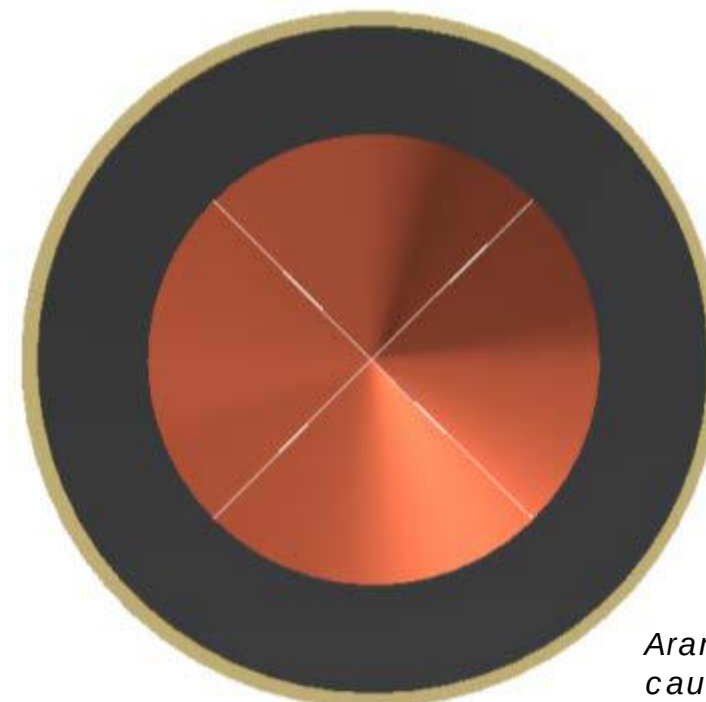
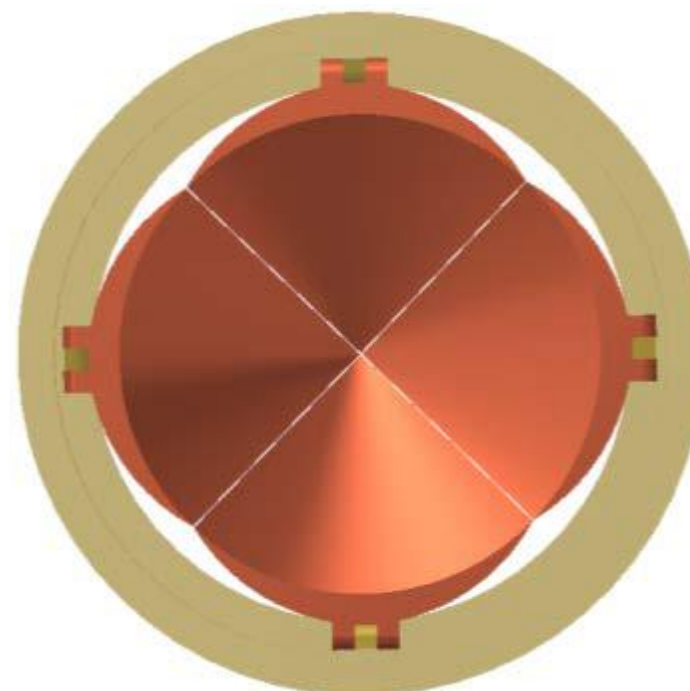
Para evitar que los residuos se fugasen durante la compactación era requerido colocar una válvula de seguridad que tan sólo se abra una vez ha acabado el proceso.

Al quedar huecos entre estas cuatro piezas se colocó una arandela de caucho sobre ellas.

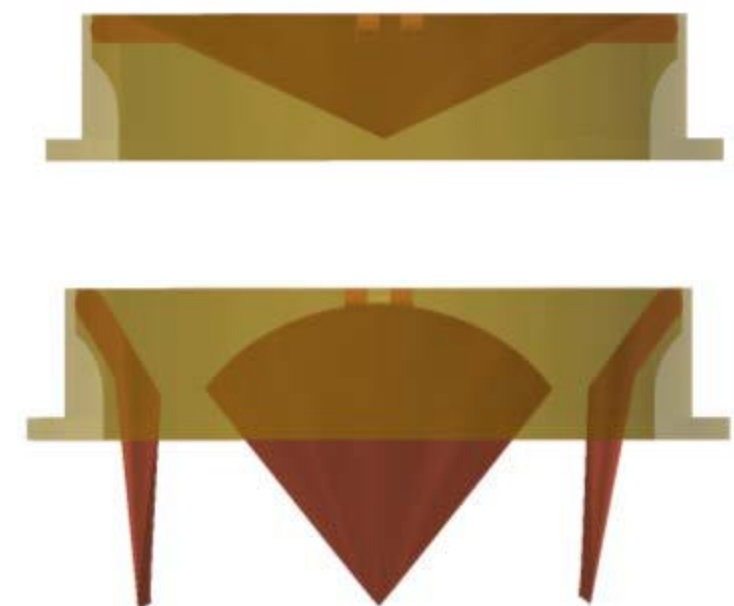
Esta válvula se encaja en la carcasa de embutir, sobre la cápsula de plástico.



Información en anexo: Planos WasteCompactor



Arandela de caucho



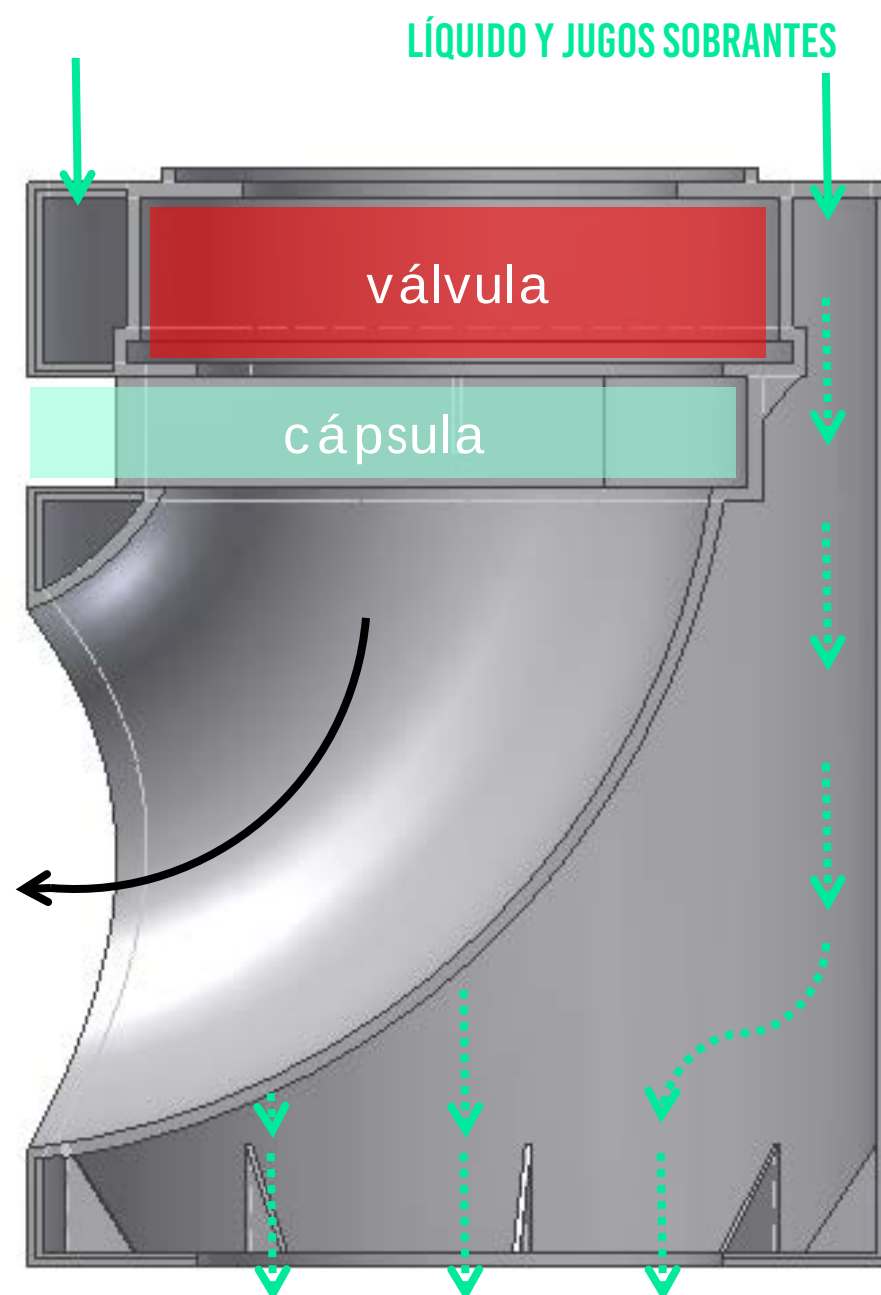
La arandela consta de cuatro piezas concéntricas que se abaten cuando empiece la embutición de residuos. Además se encargan de abrir la cápsula con el plástico al ser puntiagudas.



FASE 3

DISEÑO FINAL

DISEÑO DE LAS PIEZAS

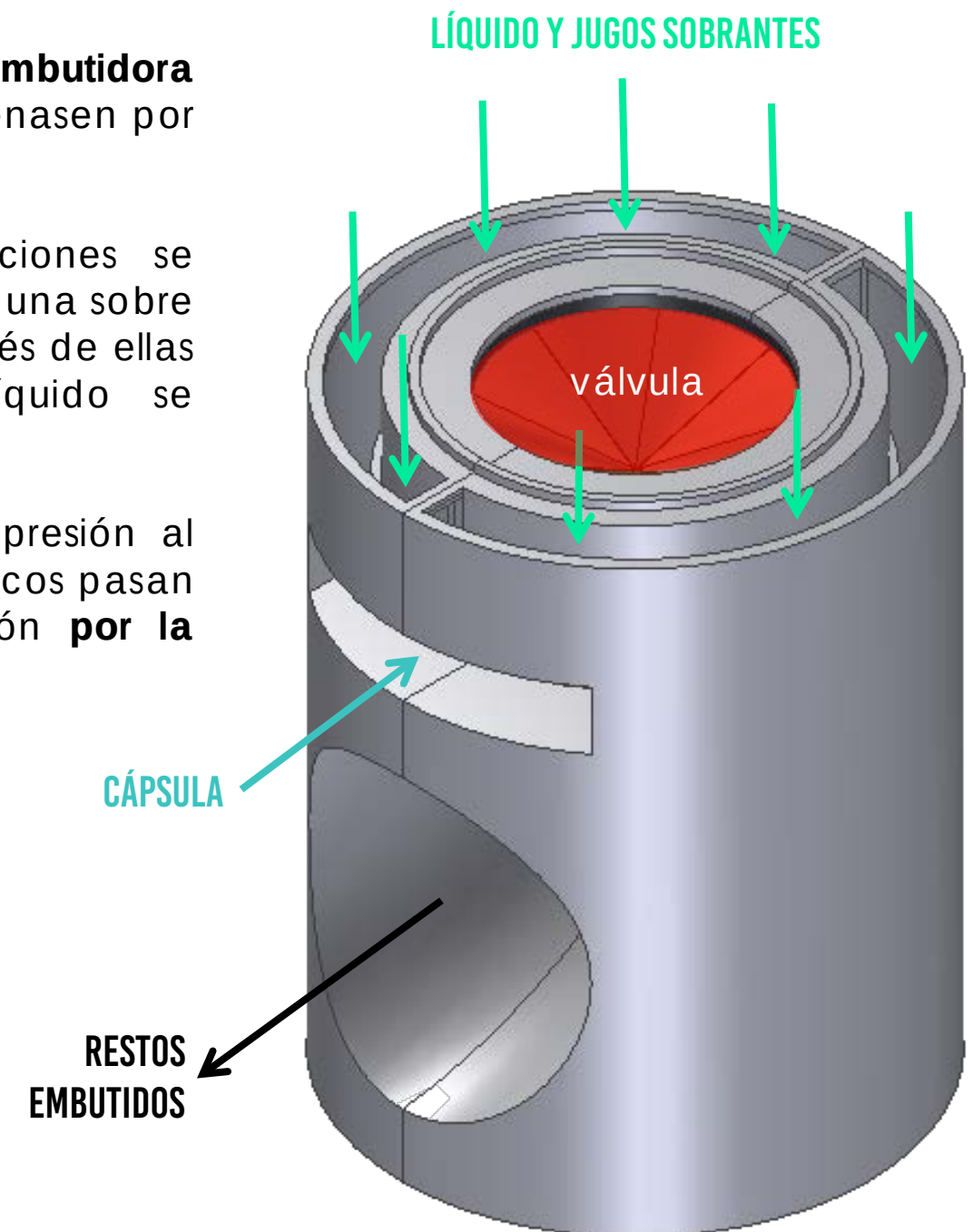
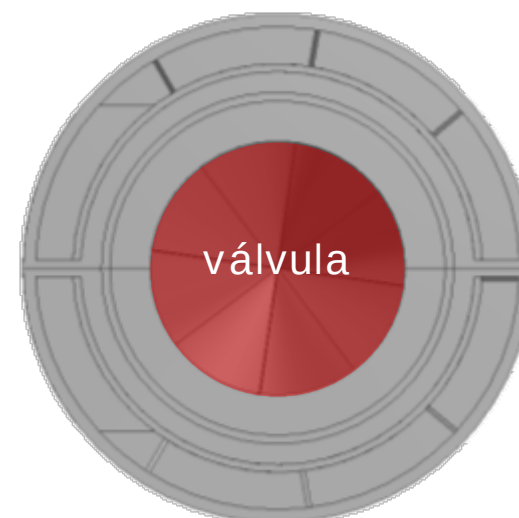


Información en anexo: Planos WasteCompactor

El diseño de la **embutidora** debía permitir a la vez que se drenasen por el **desagüe** los líquidos sobrantes.

Para conseguir estas dos funciones se colocaron la válvula y la carcasa una sobre la otra, en la parte central. A través de ellas pasarían los residuos y el líquido se desearía por los laterales.

Esta carcasa se une mediante presión al filtro de nylon. Así los **restos** orgánicos pasan a través de él y a continuación **por la válvula y la cápsula**.



FASE 4

MODELADO 3D

SÍNTESIS

CONSIDERACIONES FINALES

WasteCompactor.

“

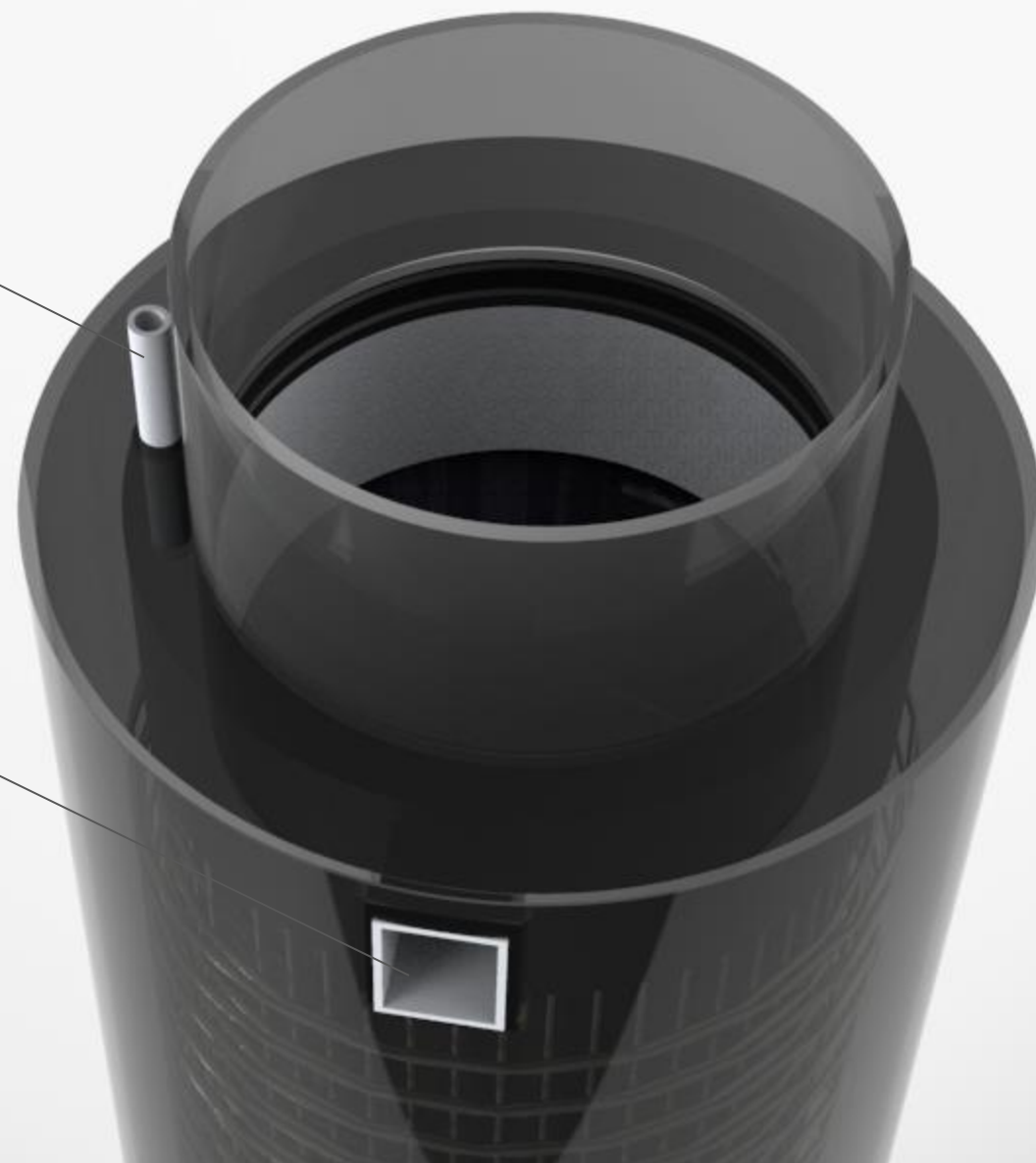
Se encarga de compactar y embutir restos orgánicos.

”



Cilindro que extrae los cables de los elementos eléctricos de forma que no entren en contacto con el agua.

Interruptor para activar la compactadora.



Espacio para situar los elementos eléctricos.

Posee un sensor de llenado que le permite programar el inicio de la compactación.



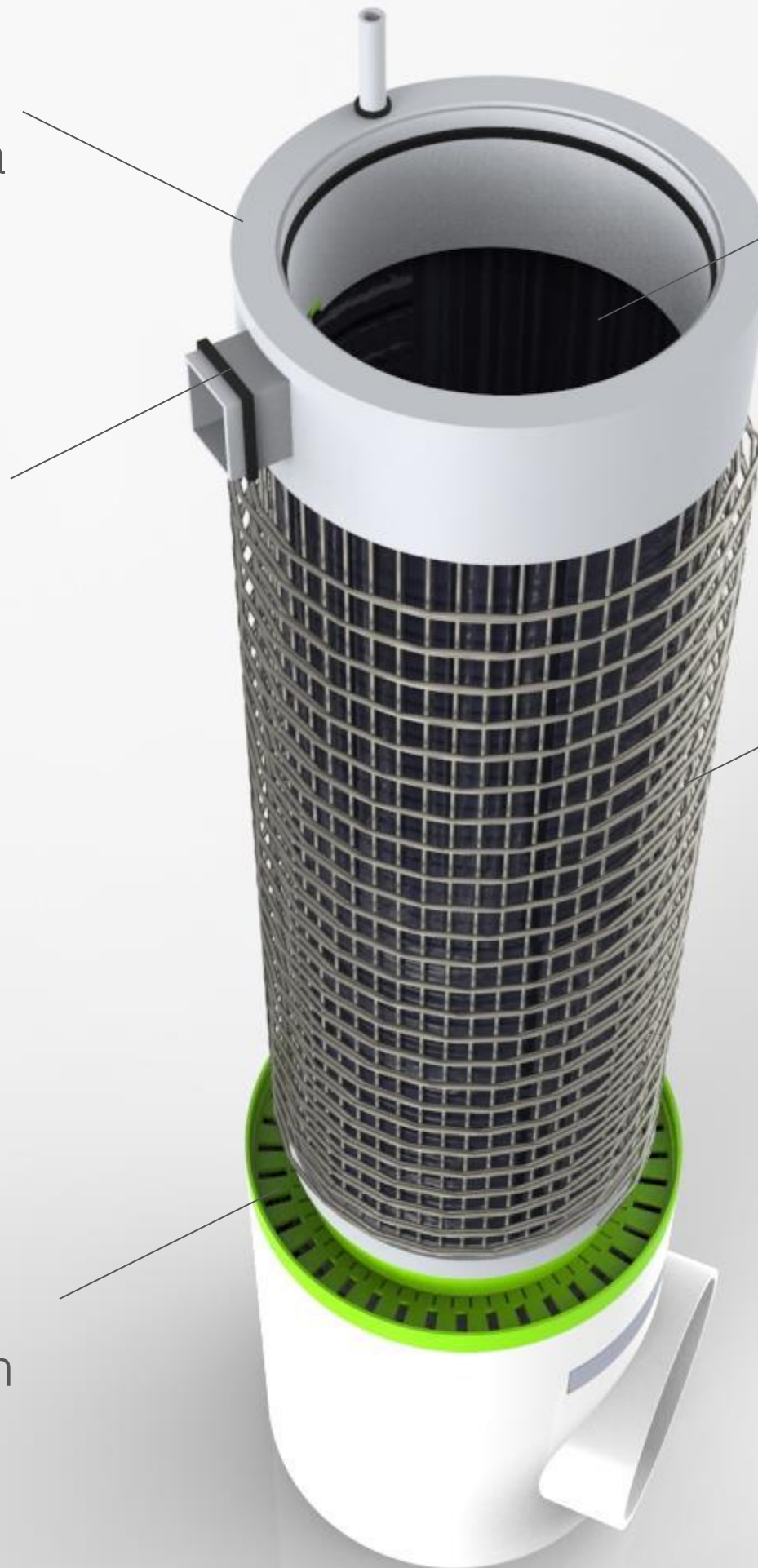
Pieza que contiene los
elementos eléctricos.
Sellada de forma hermética
con arandela de caucho

Filtro: resiste la
compactación del músculo
que lo rodea y permite la
extracción del líquido.

En las zonas de contacto
carcasa exterior y músculo
se han colocado piezas de
caucho para evitar fugas.

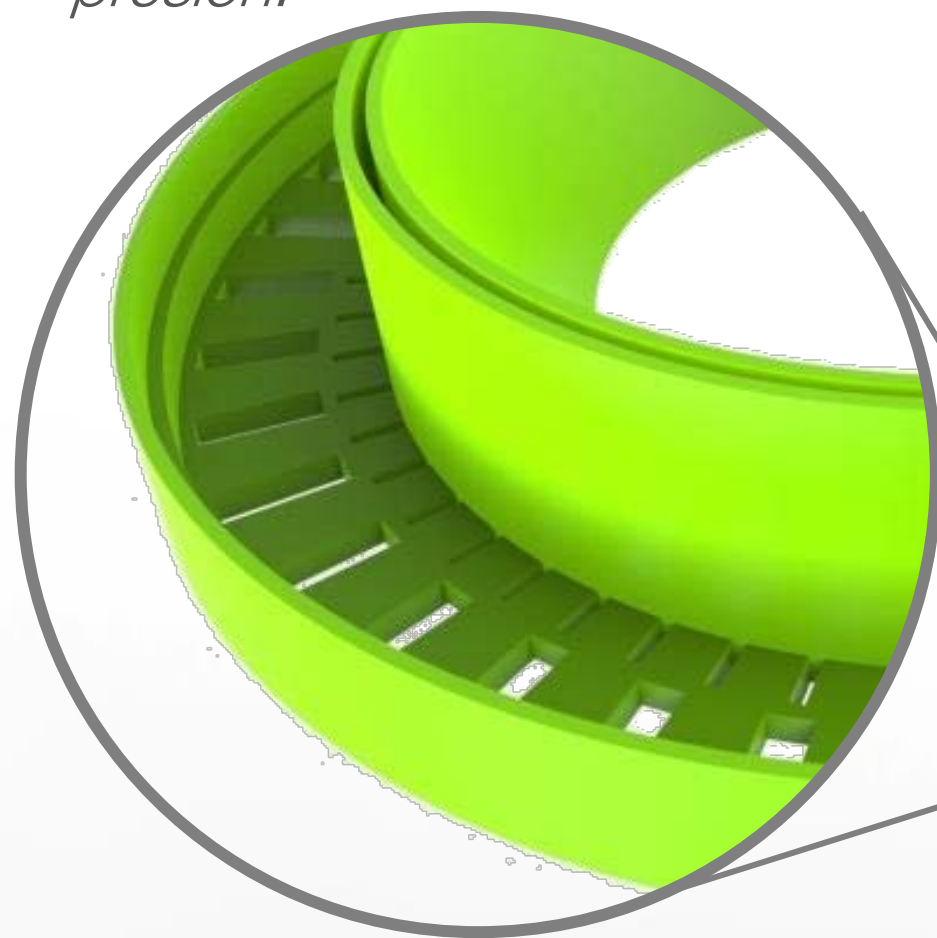
Malla de cables de Nitinol.
Actúan por corriente o
temperatura del agua
gracias a la propiedad de
memoria de forma.

El agua y los jugos son
extraídos y drenados por
estos orificios colocados en
la base del filtro



Arandela de unión con la
pieza que contiene los
elementos eléctricos del
músculo.

*Uniones mediante labios
para encajar piezas por
presión.*

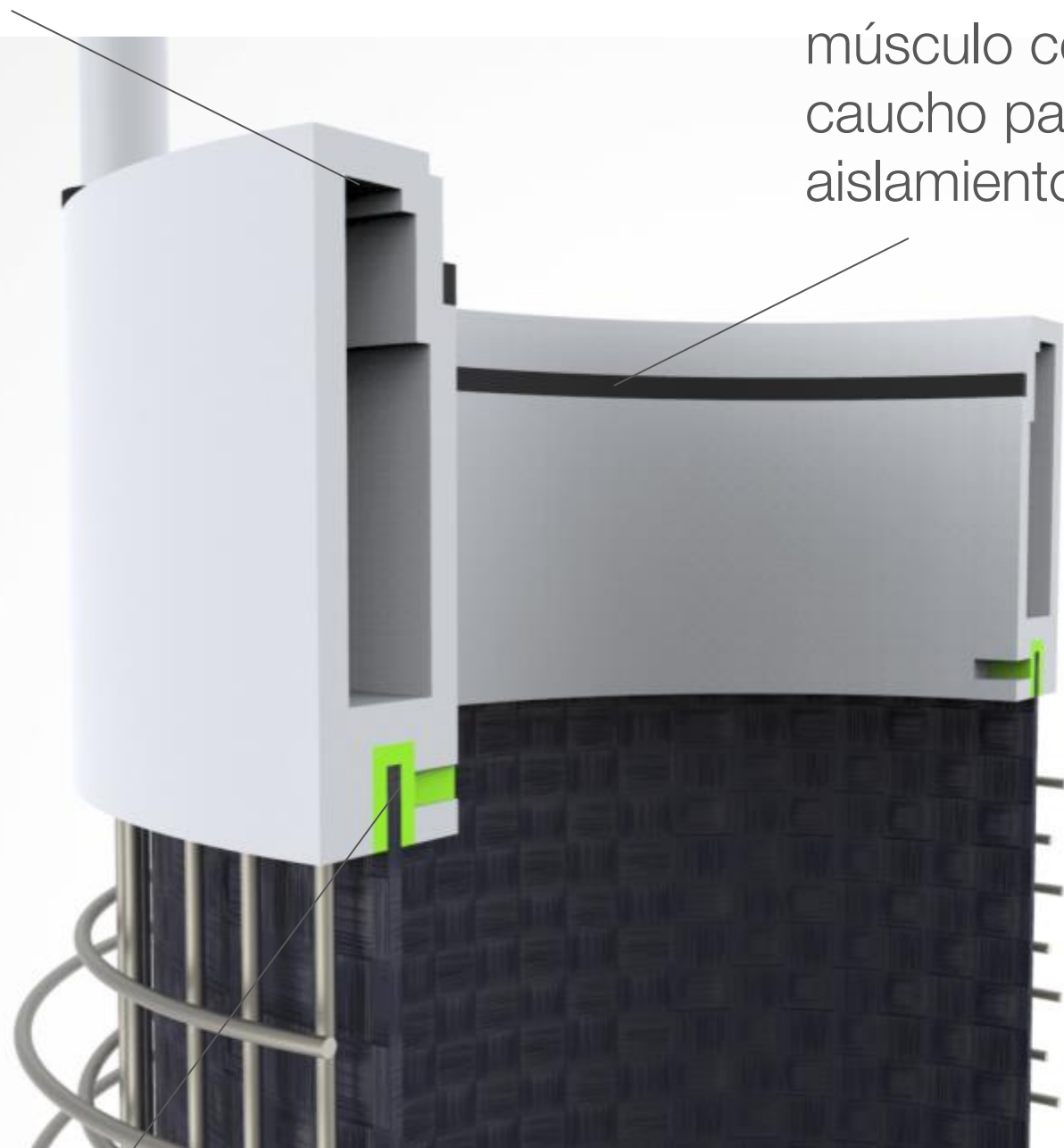


*Pestañas para unir con la
pieza superior con un
sistema de medio giro.*

Filtro de Nylon que extrae los
jugos de los restos
compactados.

Espacio para colocar los
elementos eléctricos.

Unión carcasa exterior y
músculo con arandela de
caucho para asegurar el
aislamiento.



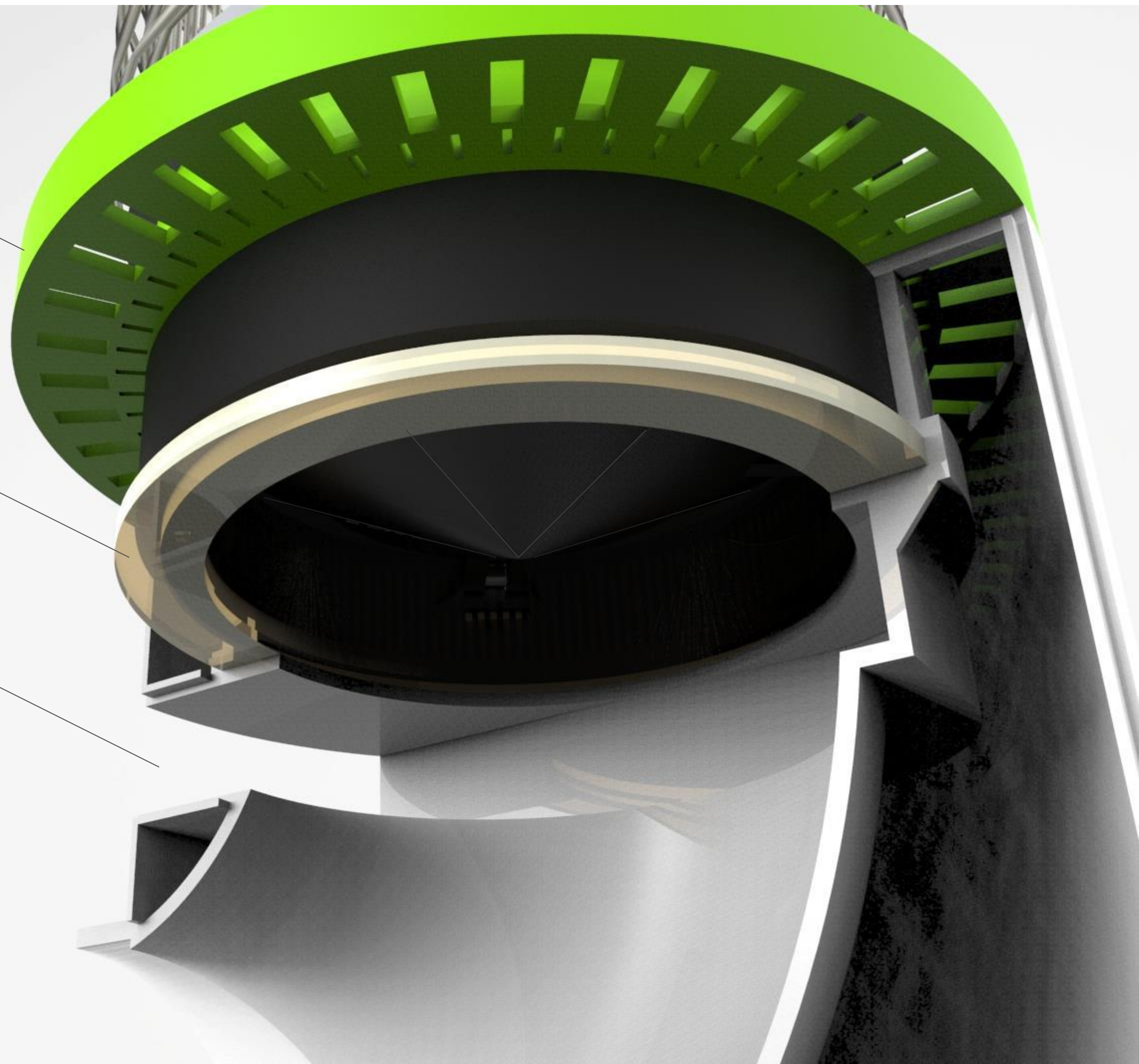
Unión del filtro y el músculo por sistema de media rosca.



Base del filtro: permite el paso de los jugos extraídos y del agua.

Válvula de seguridad: se abre una vez ha finalizado el proceso de compactado.

Hueco para introducir la cápsula que contiene el plástico para embutir.



FASE 4

MODELADO 3D

SÍNTESIS

CONSIDERACIONES FINALES

//MATERIALES

SELECCIÓN

En éste análisis se describe cada material aplicado a las piezas de producto.

Para ello se han tenido en cuenta las necesidades de aislamiento entre uniones, la resistencia térmica, de impacto y la rigidez requeridas en cada parte.

Según la función que desempeñan se ha decidido fabricar la pieza en un material u otro.

Una vez designado el material se explica el proceso de fabricación de la pieza.

FASE 4



FASE 4

//MATERIALES

MATERIALES Y PROCESO DE FABRICACIÓN:

Para la realización de este producto se ha elegido una serie de materiales que cumplan con los requisitos exigidos.

● **ABS:** es un termoplástico resistente a impactos. Posee además una alta resistencia química, **baja absorción de agua**, es **duro, rígido, tenaz** y tiene buena estabilidad dimensional. (70)

Podemos observar en la tabla el alto módulo de tracción y su resistencia, que lo hacen idóneo para la presión que se va a ejercer en la compactadora.

Es importante destacar el alargamiento hasta rotura del 45%, lo que permite aplicar fuerzas de tracción elevadas sin provocar fracturas en el material al resultar éste muy resistente.

Propiedades físico-mecánicas	
Alargamiento a la Rotura (%)	45
Coeficiente de fricción	0.5
Módulo de tracción (GPa)	2.1-2.4
Resistencia a tracción (MPa)	41-45
Resistencia al impacto Izod (J/m)	200-400
Absorción agua 24h (%)	0.3-0.7
Densidad (g/cm ³)	1.05
Resistencia radiación	Aceptable

(70)

FASE 4

//MATERIALES

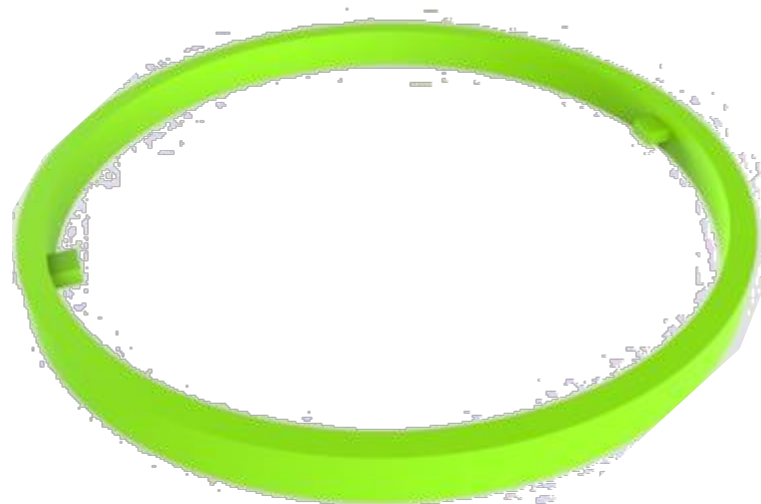
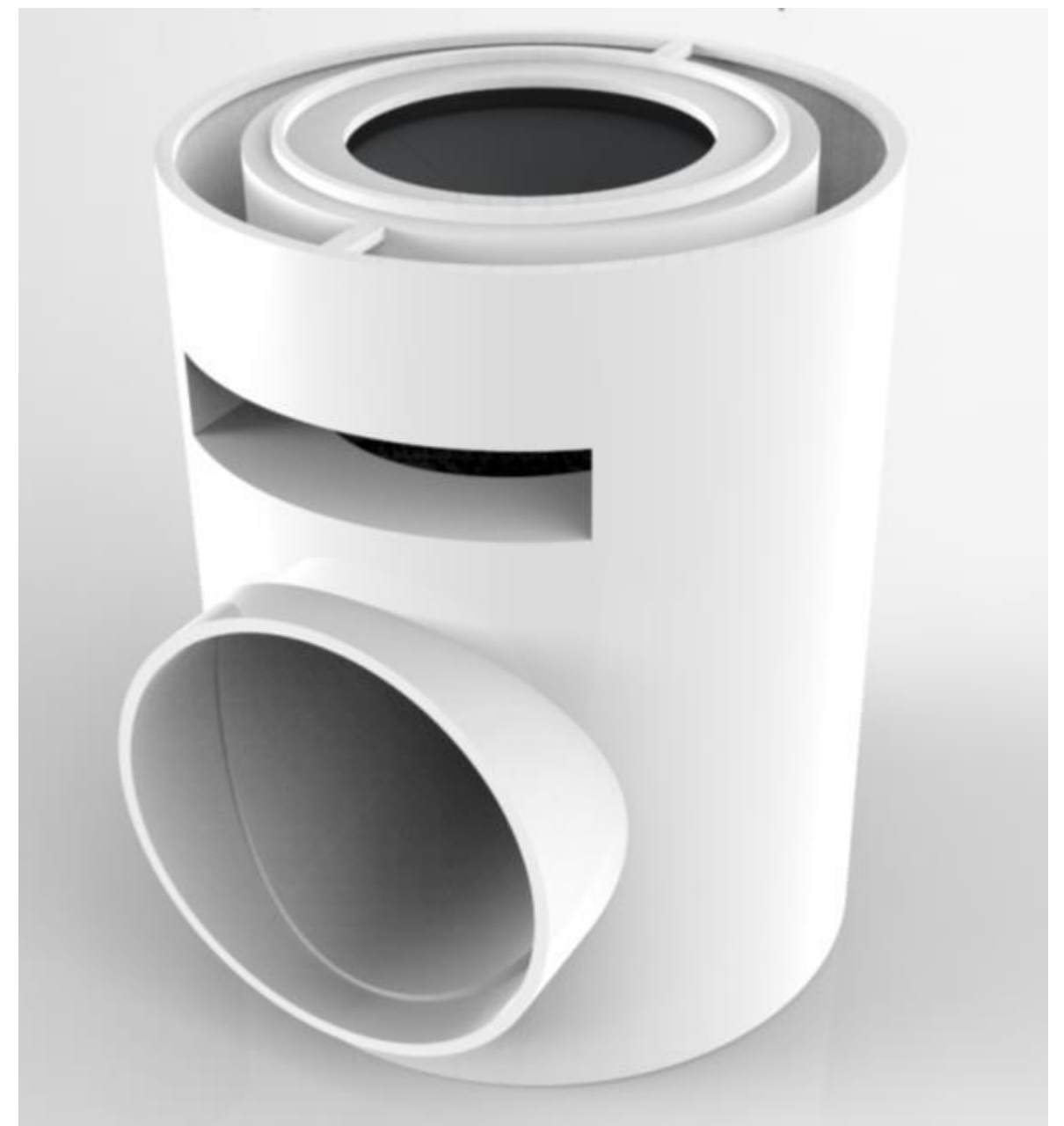
MATERIALES Y PROCESO DE FABRICACIÓN:

Se ha utilizado para el diseño de la arandela superior del filtro y para la carcasa que se encarga de embutir los restos compactados.

Las piezas a fabricar para el diseño se realizan mediante procesos de **moldeo por inyección y extrusión**. (70)

Otra característica a favor de la aplicación de este material para la producción de un elevado número de piezas es su bajo coste.

Carcasa embutidora



Arandela unión filtro

FASE 4

//MATERIALES

MATERIALES Y PROCESO DE FABRICACIÓN:

● CAUCHO SINTÉTICO:

Ha sido utilizado para la fabricación de las **arandelas de seguridad** que impiden el paso de líquidos entre carcasas. Aportan estanqueidad en la **zona** donde se colocan los **elementos eléctricos** y en la parte superior de la **válvula** para evitar fugas.

Soporta químicamente los aceites y grasas que son utilizados junto a los alimentos además de ser un buen aislante eléctrico. Se mantiene flexible a bajas temperaturas, tiene buena resistencia al calor y al envejecimiento.(70)

La fabricación de la goma se realiza a partir de la materia prima (látex) que es mezclada con **químicos** y procesada mediante un triturado para realizar una **masa**. A continuación se le añaden otros químicos para hacerla más flexible y se corta en porciones de menor tamaño. (71)



(71)



(71)



(71)

Estas porciones se someten a **compresión por rodillos** para reducir su grosor y hacerla más homogénea. (71)

El siguiente paso es el **moldeo por inyección**: gracias a la temperatura y la forma del molde, la masa cobra la forma y textura deseada. Se inyecta aire caliente para realizar un tubo hueco y posteriormente se enfría en agua para que no se peguen las paredes. Una vez enfriado el tubo se deshincha.(71)



(71)

FASE 4

//MATERIALES

MATERIALES Y PROCESO DE FABRICACIÓN:

Los operarios ensamblan los **tubos** de caucho deshinchado en unos macizos de **aluminio** que ayudarán a preservar su forma cilíndrica durante su etapa de curación. En esta fase se determina el diámetro de la goma. Son entonces introducidos en un **horno a vapor** que determinará su elasticidad y fuerza tensil.(71)

Finalmente se extraen los tubos de aluminio y los de caucho se **cortan** con la anchura deseada.(71)

Este material es propio de las piezas que **evitan la salida de líquidos**. Las arandelas antifugas existentes en la zona de conexión con el fregadero y entre la carcasa de SAN y ABS en la parte inferior entre otras. Estas piezas aportan estanqueidad al diseño, al estar sometido al constante flujo de agua.(71)



(71)



(71)

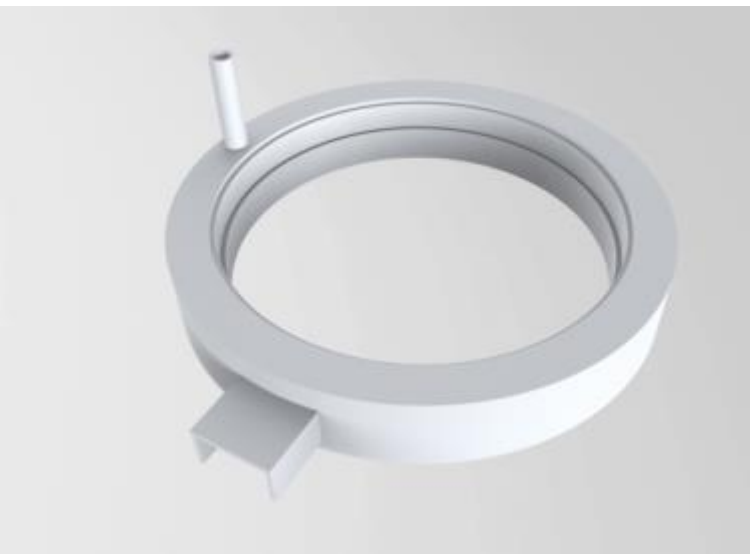
*Arandelas de seguridad
antifugas*



FASE 4

//MATERIALES

MATERIALES Y PROCESO DE FABRICACIÓN:



● **PC:** es un polímero de alta **resistencia al impacto** y rigidez. Además posee buena estabilidad dimensional, buenas propiedades de aislamiento eléctrico y resistencia térmica. (70)

Debido a las ventajas que presenta, se ha fabricado con este material la pieza que soporta las partes móviles de la válvula de seguridad.



Propiedades físico-mecánicas	
Alargamiento a la Rotura (%)	100 - 150
Coeficiente de fricción	0.31
Módulo de tracción (GPa)	2.3-2.4
Resistencia a tracción (MPa)	55 -75
Resistencia al impacto Izod (J/m)	600-850
Resistencia a compresión (MPa)	>80
Límite elástico (MPa)	65
Resistencia abrasión	10mg/1000 ciclos

(70)

También las carcasas que contienen los elementos eléctricos y que sujetan los cables de Nitinol se han fabricado en policarbonato. La tabla muestra grandes ventajas en comparación al ABS, por lo que en este caso es idóneo aplicarlo en dichas piezas.

FASE 4

//MATERIALES

MATERIALES Y PROCESO DE FABRICACIÓN:

● **SAN:** gracias a su alta resistencia térmica, este material es el más adecuado para la pieza que actúa como **carcasa del músculo artificial**. Su transparencia permite observar el funcionamiento del mismo. Este hecho ayuda a la visualización del proceso de compactación, además de la rápida detección de un problema en caso de avería.(70)

Posee **buenas propiedades mecánicas** (resistencia al impacto y tenacidad) y de resistencia química.(70)

Esta pieza se fabrica de manera sencilla mediante **termoconformado**. (70)



FASE 4

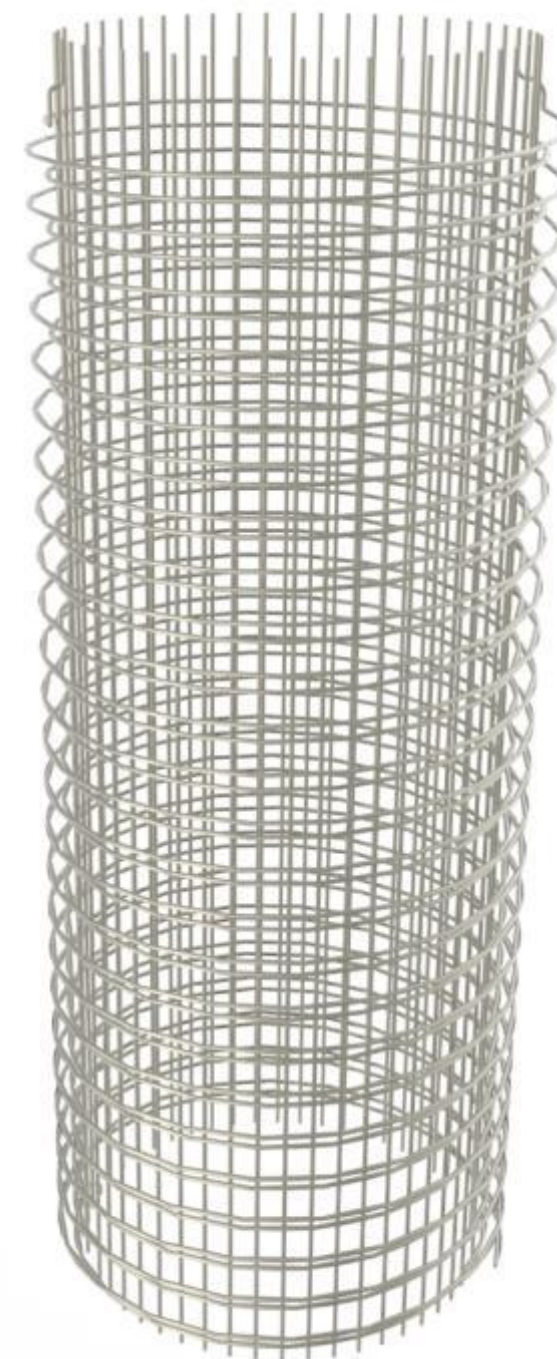
//MATERIALES

MATERIALES Y PROCESO DE FABRICACIÓN:

● **Nitinol:** en este material se fabrica el músculo en forma de malla de la compactadora. Al ser un material tan resistente (más que los restos orgánicos sólidos) permite crear una presión lo suficientemente alta como para extraer los líquidos y reducir el volumen al mismo tiempo. (65)

Se han dispuesto los cables de esta manera para poder ejercer presión en tres dimensiones.

Malla Nitinol



FASE 4

//MATERIALES

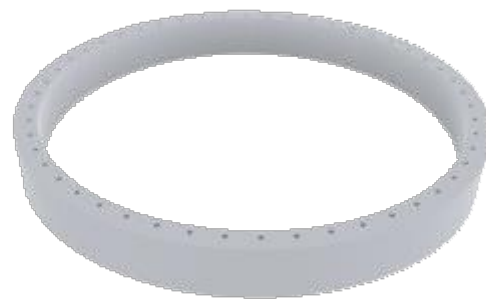
MATERIALES Y PROCESO DE FABRICACIÓN:

● **PVC:** posee una óptima resistencia mecánica y al impacto. Además es un material duradero y resistente a la corrosión. Es idóneo para aplicar en objetos o entornos en contacto con líquidos o en presencia de humedad. (70)

La base del filtro y la arandela inferior del músculo se fabrican mediante termoconformado. (70)

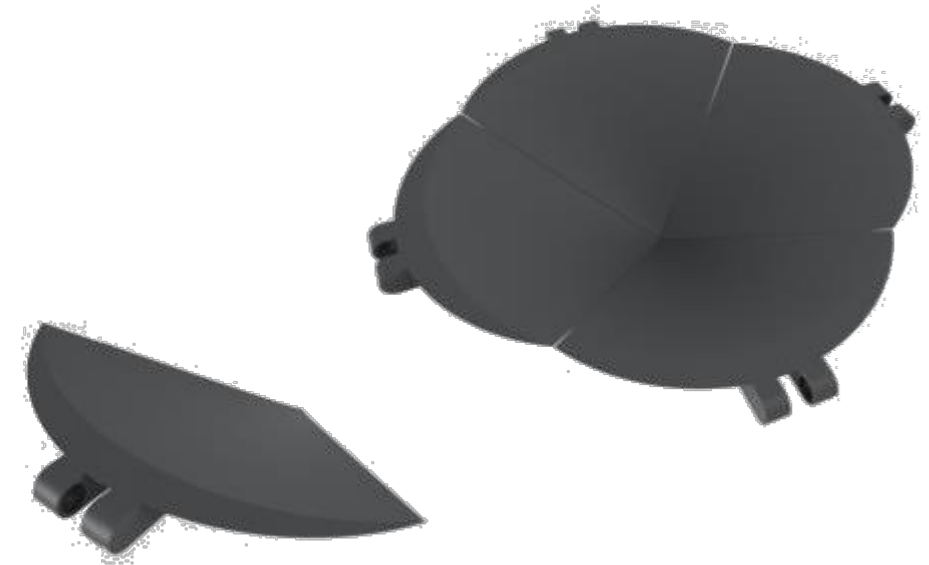


Base filtro



Arandela base músculo

● **POM:** se trata de un polímero de alta rigidez, baja fricción y muy buena estabilidad dimensional. Al estar dirigido a la producción de piezas móviles y de precisión se ha decidido diseñar con este material las cuatro piezas que se abren y cierran de la válvula de seguridad. (70)



Piezas móviles válvula

FASE 4

//MATERIALES

MATERIALES Y PROCESO DE FABRICACIÓN:

● **Polipropileno:** este polímero es muy utilizado para la fabricación de geotextiles. Estas membranas se encargan de separar, filtrar y drenar partículas. Son usados en construcción, pero también existen aplicaciones en productos como depuradoras ya que el tipo de filtrado depende del tamaño de sus poros.

Posee resistencia mecánica ante tracción, punzonamiento y desgarró, por lo que lo hace idóneo para aplicar en este producto.

Fuente:

https://es.wikipedia.org/wiki/Geotextil#Geotextiles_seg.C3.BA_n_su_forma_de_fabricaci.C3.B3n

Geotextil de polipropileno

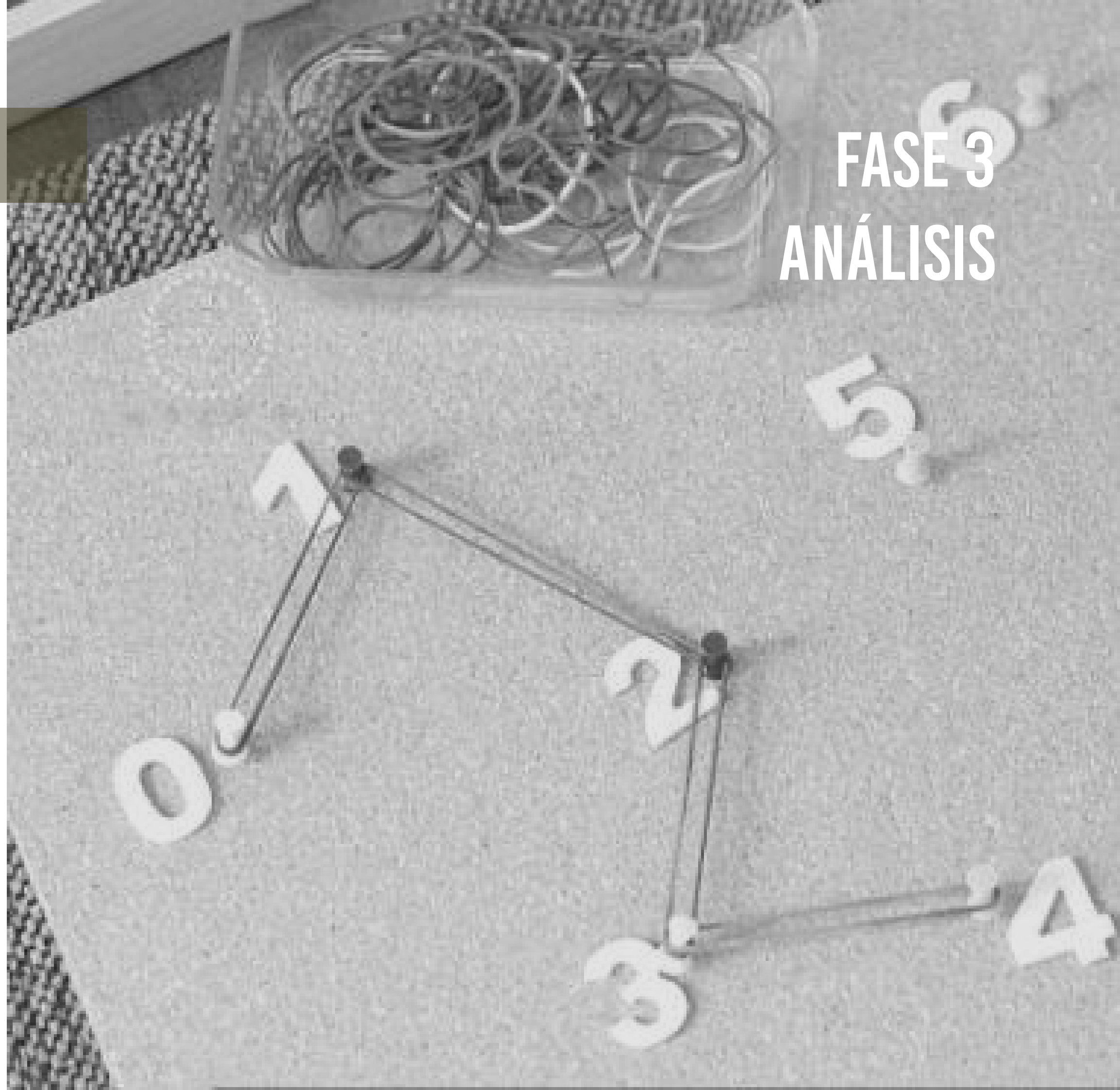


//USO

FASE 3 ANÁLISIS

En este apartado se explica la secuencia de uso del nuevo producto así como el proceso de eliminación de los residuos.

Se desarrolla el paso de los restos a través de la trituradora hasta la compactadora y las funciones que debe llevar a cabo el usuario para el correcto funcionamiento.



FASE 4

//USO

SÍNTESIS

SECUENCIA DE USO:

1º Abrir el agua del grifo.

2º Encender la trituradora.

3º Encender la compactadora.

4º Introducir la cápsula en la ranura de la compactadora.

5º Arrastrar los restos de comida hacia el desagüe y ayudar a su eliminación presionándolos un poco por el sumidero.

6º Al haber eliminado todos los residuos orgánicos esperar unos minutos y cerrar el agua del grifo.

7º La compactadora comenzará a trabajar una vez esté llena, gracias al sensor de llenado. Si quedan restos triturados sin compactar, se acumularán en la tubería y serán compactados en el siguiente ciclo. Esto es posible gracias a una llave de paso colocada en la tubería.

8º Cuando haya acabado el proceso, la grapadora sellará la bolsa.

9º Una vez finalizada la embutición, apagar la compactadora y entregar los restos embutidos al sistema de recogida,

//ENTORNO

APLICACIÓN

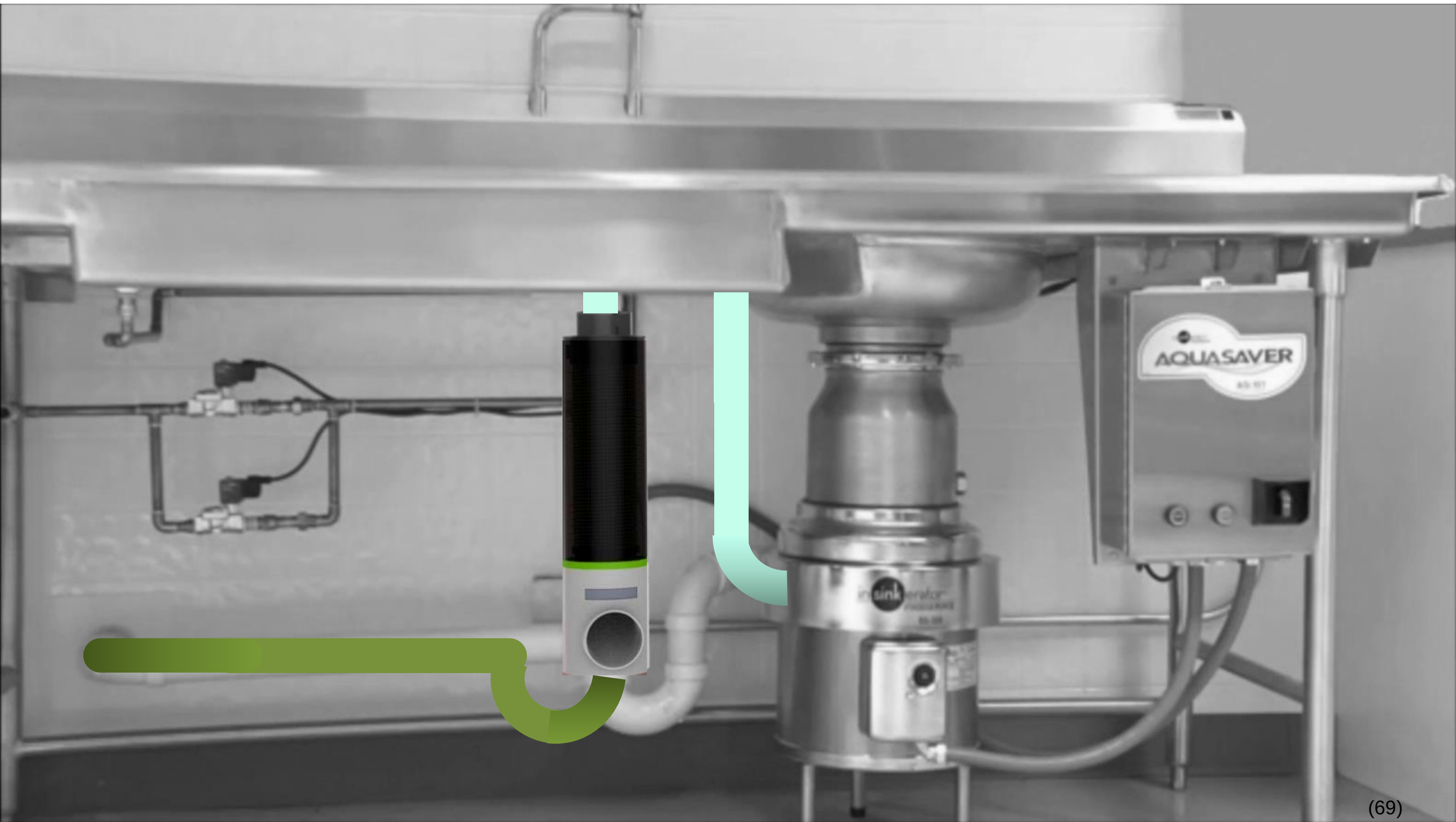
El producto está destinado a un **entorno industrial**, en el cual se eliminan grandes cantidades de restos orgánicos en poco tiempo. Tras haber realizado el estudio del entorno más apropiado en la primera fase, se ha decidido aplicar el producto en ámbitos como la hostelería, sanidad, en colegios, universidades, centros penitenciarios, etc.

Estos entornos se verían favorecidos al hacer uso de este producto debido a las numerosas ventajas que presenta en la eliminación de residuos orgánicos.

Tampoco se descarta su futura introducción en el **entorno doméstico** facilitando así la vida a un mayor número de usuarios además de favorecer el medio ambiente de forma más amplia.

FASE 4





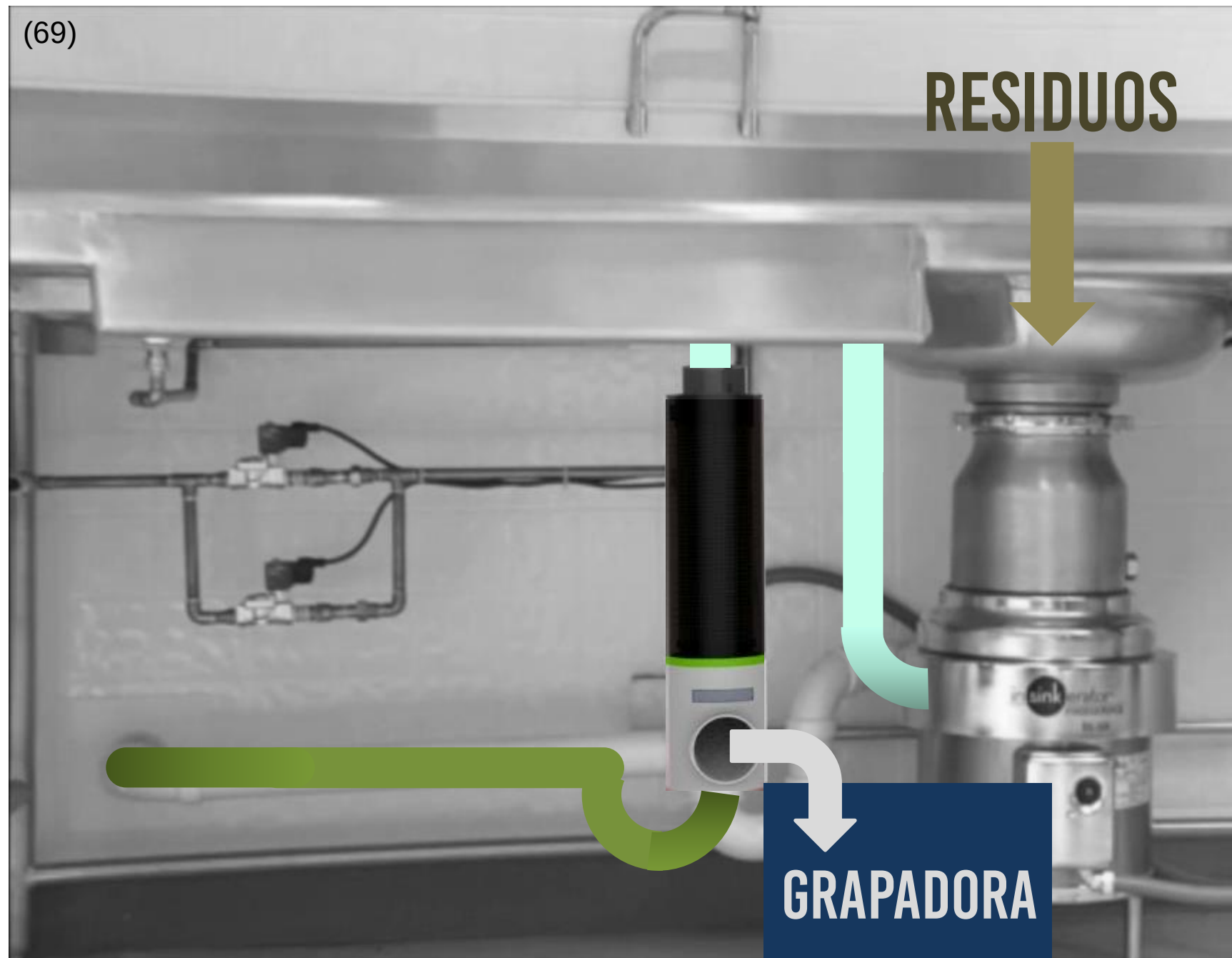
//ENTORNO

APLICACIÓN

La compactadora debe estar conectada a la trituradora para poder realizar la compactación de los residuos.

Los residuos se eliminan por la fregadera, que se conecta directamente a la trituradora. Desde ahí un tubo (azul) lleva los residuos triturados a la compactadora y cuando el sensor de llenado indica que el volumen del músculo está completo, se comienza a compactar la masa de residuos.

El tubo de desagüe (verde) está conectado a la compactadora, eliminando así todo líquido sobrante. El orificio frontal de la compactadora extrae los restos orgánicos ya embutidos, que serán sellados por la grapadora acoplada al mismo.



//ENTORNO

APLICACIÓN



En estas imágenes se aprecia la instalación en un entorno doméstico. De esta forma se introduce en el hogar una herramienta que ayuda a dar una segunda vida a los residuos orgánicos, por ejemplo utilizándolos para compost. En vez de tener que manejar los residuos y separarlos manualmente, el diseño se encarga de recoger todo lo que se deseché por la fregadera y **automáticamente envasarlo para reutilizarlo.**

Los usuarios podrán adquirir un **nuevo hábito** que protege al medioambiente **sin** obligarse a las **cambiar pautas** diarias de gestión de residuos, haciéndolo muy fácil de adquirir por la sociedad. Es de hecho una medida que aumenta la comodidad de esta tarea, así como la higiene.

FASE 4

//FORMAL - FUNCIONAL

SÍNTESIS

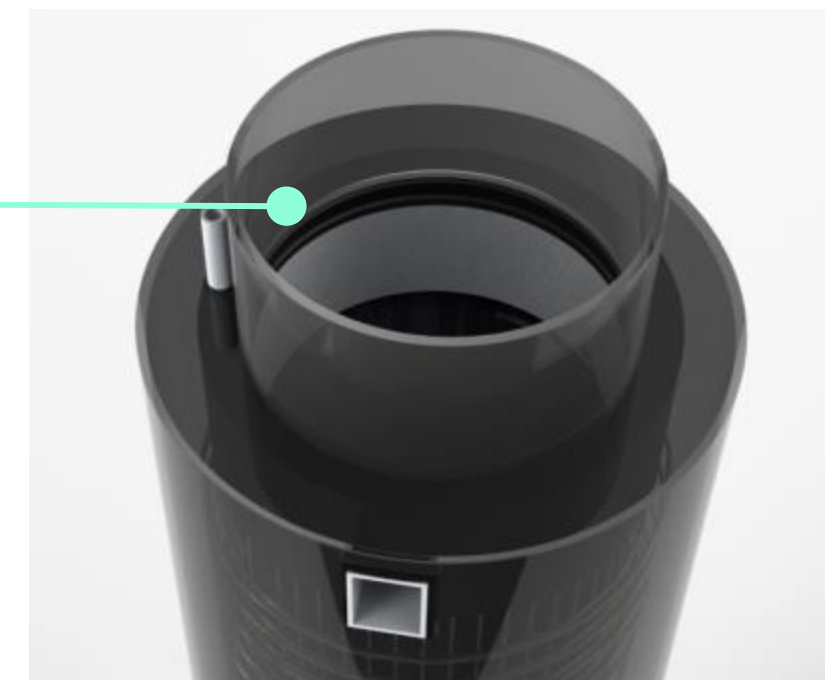


El proceso al cual se someten los residuos orgánicos determinan la forma de las diferentes piezas que componen el producto.

El **orificio de entrada** en la parte superior tiene el mismo diámetro del agujero de salida de la trituradora. De esta manera se conectan a través de un tubo de pvc que lleva los residuos desde la trituradora hasta la compactadora.

La **forma cilíndrica** aporta **fluidez** en el transporte de los restos. Además el músculo gracias a esta geometría puede ejercer presión en **tres direcciones**, ayudando a la compactación.

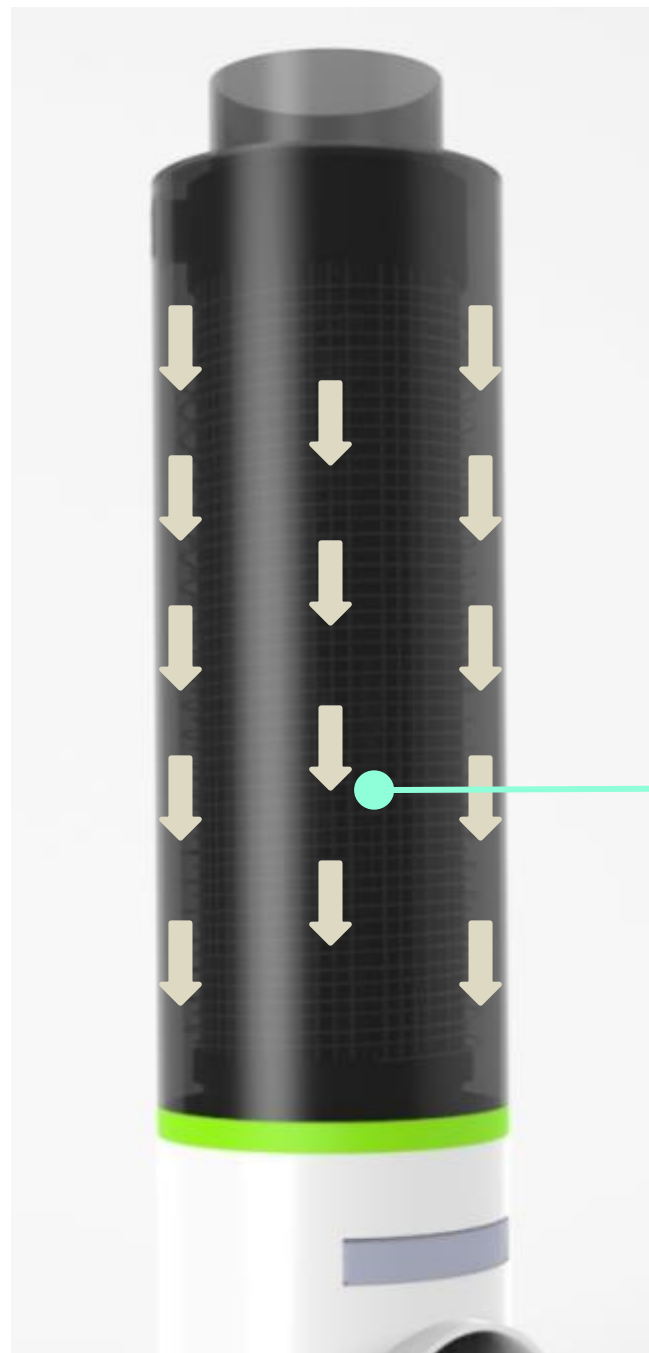
Debido a estos factores principales, el resto de las piezas también han seguido esta forma cilíndrica, creando continuidad entre ellas mediante sistemas de encaje y presión.



FASE 4

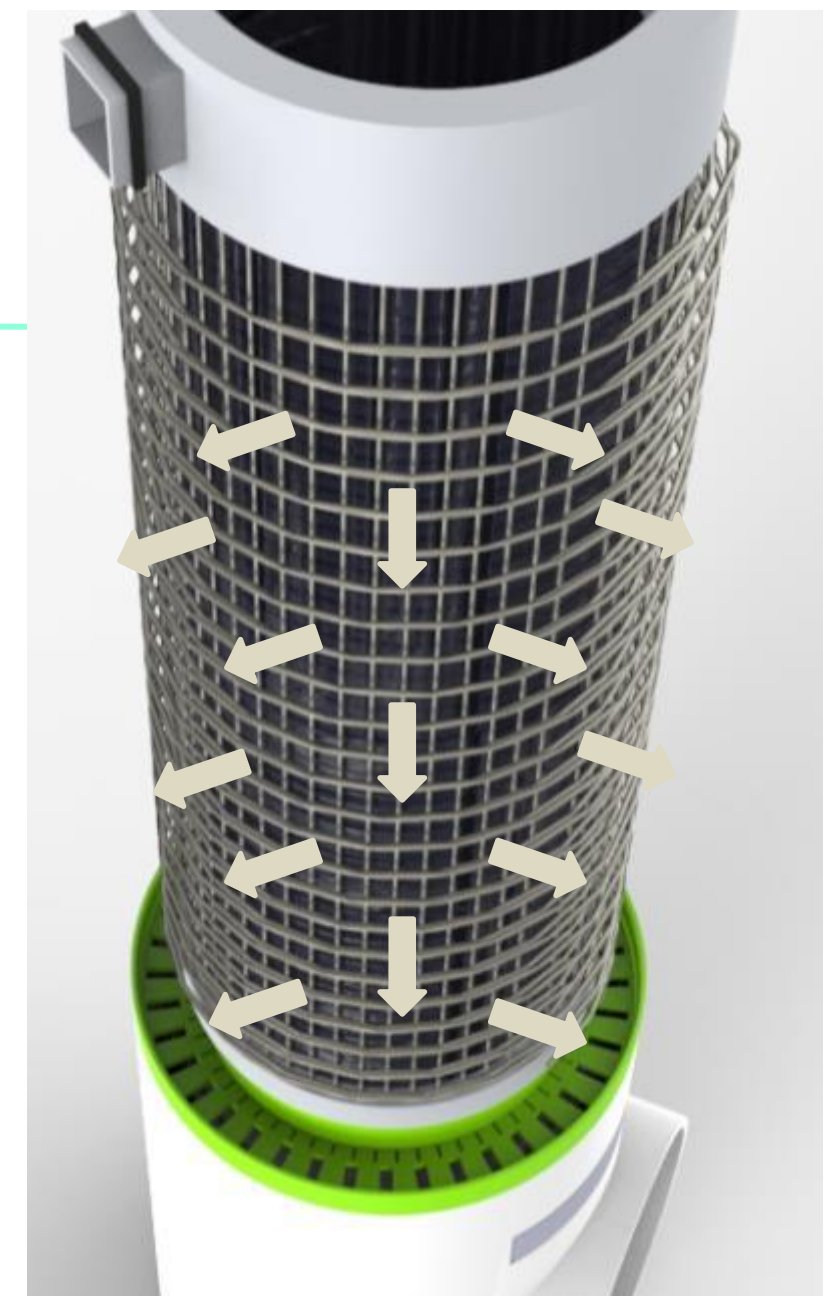
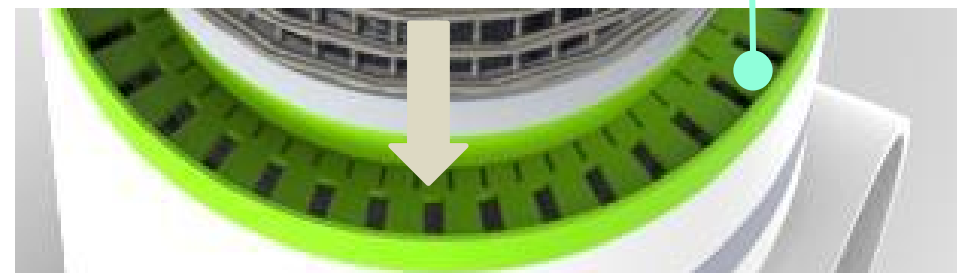
//FORMAL - FUNCIONAL

SÍNTESIS



Los **cables** del músculo de enrollan alrededor del filtro para ejercer fuerzas compactadoras. Los cables están recubiertos de un plástico para evitar cortocircuitos en el momento de extracción de jugos.

Los jugos salen a través de las paredes de la membrana de geotextil. La **carcasa exterior** evita que se manche el entorno en el momento de funcionamiento del músculo. Además dirige los líquidos **hacia los orificios** de la parte inferior.



FASE 4

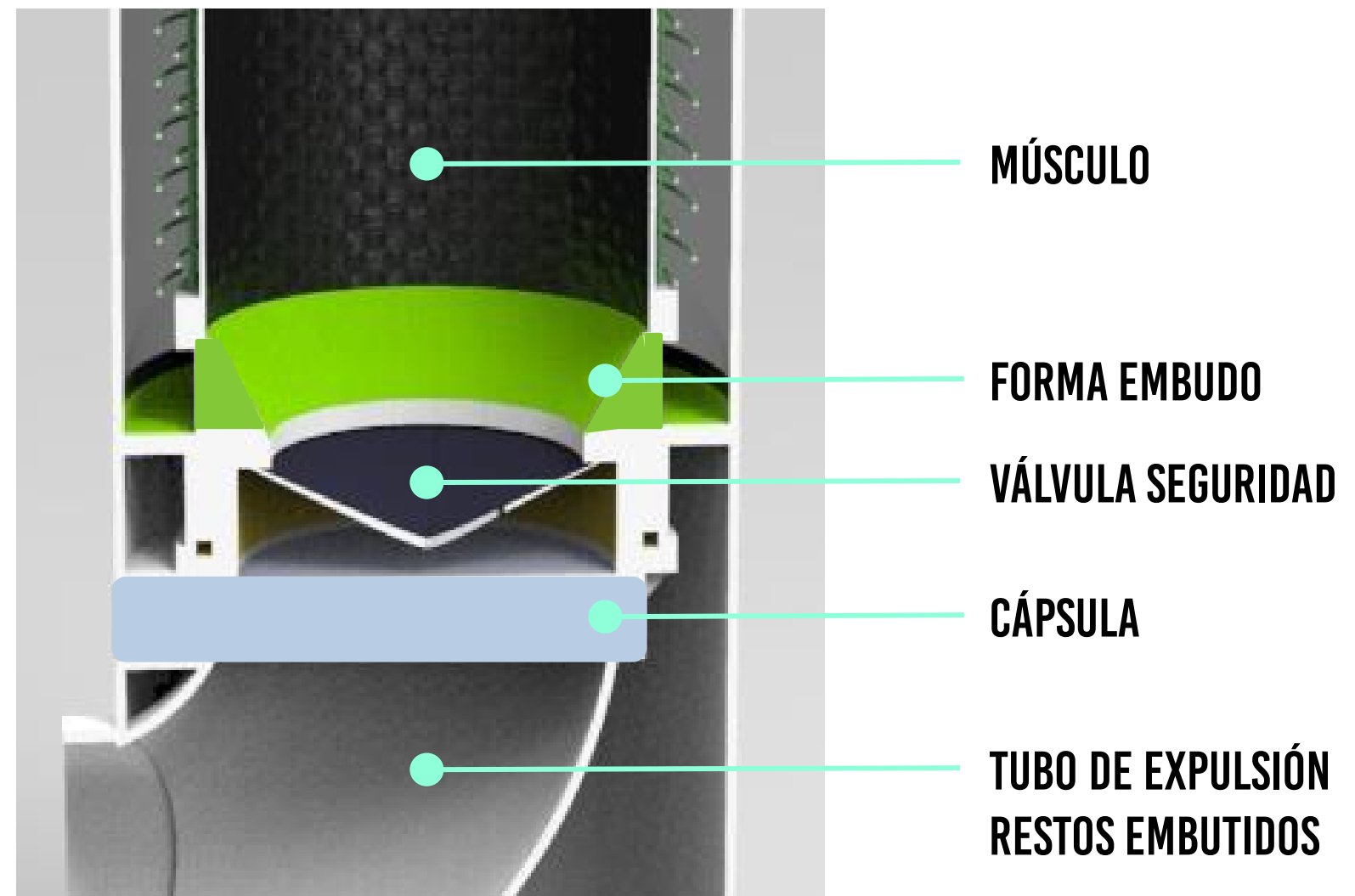
//FORMAL - FUNCIONAL

SÍNTESIS

El musculo finaliza en un **embudo** que dirige los restos compactados hacia la válvula de seguridad. Este embudo es parte del filtro, y posee orificios en la circunferencia exterior que permiten la eliminación de los líquidos. Esto es posible ya que las paredes de la carcasa exterior dirigen los jugos hacia estos orificios inferiores.

Debajo de la **válvula de seguridad** se coloca la **cápsula** que contiene el plástico que guardará los restos compactados. La cápsula se abre por la acción de las **pestañas** de la válvula, que en el momento de abrirse **rompen la cápsula** y sujetan el plástico. La válvula no se abre hasta que la presión ejercida sobre ella sea muy elevada (sucede durante el movimiento peristáltico)

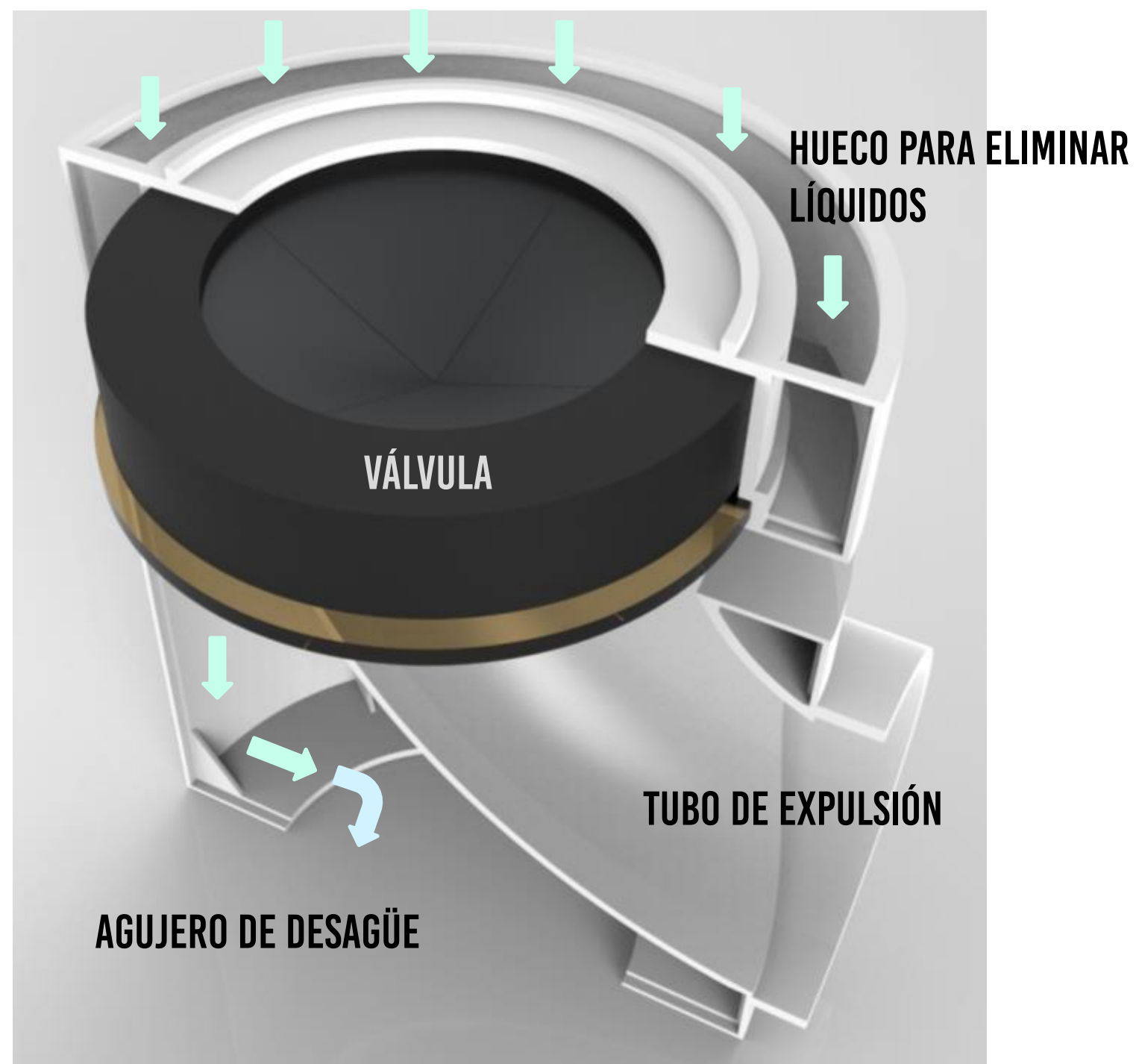
En este momento el músculo recrea el **movimiento peristáltico** e introduce los restos en el plástico. Una vez embutidos, son expulsados por el tubo inferior.



FASE 4

//FORMAL - FUNCIONAL

SÍNTESIS



Mientras los residuos son eliminados por el tubo de expulsión, los líquidos caen a la parte inferior de la carcasa blanca donde se sitúa un agujero conectado al tubo de desagüe.

Gracias a la **posición vertical** del producto, los residuos y líquidos fluyen hacia el desagüe por acción de la gravedad. Por ello se diseñó con esta forma que se apoyaba en este factor para facilitar el vaciado de la compactadora.

Las diferentes **piezas se colocan de forma transversal** y así los residuos pasan por las diferentes fases hasta llegar al embutido final.

Una vez se ha conseguido el embutido, una grapadora industrial sellará el plástico.

FASE 4

//COSTE

SÍNTESIS

Considerando el material, dimensiones y tiempo de montaje, el coste del producto asciende a **67.30€**.(68)
(Información en anexo: Precio aproximado WasteCompactor)

El **público objetivo** son profesionales dedicados a la **hostelería**, **empresas** que suministren **electrodomésticos** industriales o que se dediquen a las **instalaciones** de cocinas industriales.

El otro público objetivo serían **particulares o comunidades** que utilicen el producto en un entorno doméstico para mejorar su calidad de vida y que estén concienciados con el medio ambiente.

PROFESIONALES HOSTELEROS
EMPRESAS DE INSTALACIÓN
EMPRESAS FABRICACIÓN DE
ELECTRODOMÉSTICOS

PÚBLICO OBJETIVO

PARTICULARES
COMUNIDADES



67,30 €

FASE 4

CONSIDERACIONES FINALES

8.1- Generales:

Las conclusiones sacadas del trabajo se centran en las ventajas que puede llegar a aportar por un lado, la tecnología de músculos artificiales que tras meses de investigación demostraron ser un gran apoyo para la innovación en el desarrollo de productos en general y por otro lado el potencial que tiene el Nitinol tras observar los prototipos funcionales existentes.

Además en relación al diseño final, se ha conseguido implantar una tecnología que aún no está presente en ningún producto de en forma de malla, aunque sí sea utilizado cable de Nitinol como apoyo combinado con otros mecanismos o de manera independiente en el ámbito médico.

Cada año se persigue reducir aun más el volumen de basura generado, basándose en el reciclaje y reutilización de envases, cartones, vidrio, etc. Pero este producto consigue reducir y reutilizar restos orgánicos que son directamente desperdiciados, o reusados pero no de manera jerarquizada como pasa con los anteriores. Se ayuda a gestionarlos de una manera a la que resulta fácil acostumbrarse.

8.2 - Personales:

En el ámbito de la ecología y de impactos medioambientales nocivos, existen una gran cantidad de necesidades que pueden ser cubiertas mediante el avance tecnológico y el diseño de productos, hecho que no habría podido destacar si no los hubiese estudiado en profundidad.

En este tipo de trabajos más extensos que los anteriores te das cuenta de que cada parte es igual de importante y que el orden seguido en las metodologías aplicadas ayuda plasmar la información de forma que se facilite la obtención de resultados.

Tras meses de trabajo y la cantidad de información buscada, se ha podido adquirir una gran cantidad de conocimientos acerca de una tecnología que desconocía por completo además de reconocer que cuanta más información se encontraba, más mejoras se querían aplicar al producto en la fase conceptual.

Hasta el último día del trabajo se han leído noticias, visto vídeos o imágenes que aportan algo más al proyecto, haciendo del diseño un proceso que no tendría fin.

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ANEXO COMPACTADORAS



1- Domésticas

2 - Comerciales

3 - Industriales



TRASH COMPACTORS





Almost everything normally placed in your kitchen garbage can be placed in a trash compactor, with the exception of paint, oil, aerosol cans and other hazardous materials.

Six bags reduced to one. And five fewer trips to the garage.

Broan Elite XE and Broan Elite trash compactors take convenience, hygiene and style to a new level. But beautiful lines, rich finishes and automatic cycling features are just part of the story. Inside is a clean compartment, a crushing mechanism with 3,000 pounds of continual force, electronic controls, and odor reduction systems. But what you take outside is what really makes a difference.

Broan helps reduce your waste volume by 75%, and while that's fewer steps to the garage, it's also less volume at the curb, and a smaller bundle in the truck that hauls it away. And that's when it all makes sense: if everybody reduced volume, fewer trips would be needed to the landfill, which means less fuel, less traffic, and a cleaner environment all the way around.



Personalize your style.

Broan trash compactors let you make your own design statement. If you prefer to have appliances blend in seamlessly with your cabinetry, select a trash compactor designed to accept a wood insert door front. Your cabinetmaker simply creates an insert with a profile that matches your doors or drawers. Of course, the coordinated look can be achieved as well with appliance matching solids in rich gloss black or white, or classic stainless steel. Whatever you choose, Broan has you covered.



Broan Elite XE and Broan Elite with door tray for custom wood insert. Shown: Model 15XEWt



Broan Elite XE and Broan Elite with stainless steel door. Shown: Model 15XEss and 15SS



Broan Elite XE and Broan Elite with appliance matching gloss white finish. Shown: Model 15XEWH and 15WH



Broan Elite XE and Broan Elite with appliance matching gloss black finish. Shown: Model 15XEBL and 15BL



Broan Elite XE

Beauty. Brawn. And intelligence, too.

Broan Elite XE models are available in stainless steel, white or black. For a custom look, select the WT model with a door tray that accepts a wood insert to match your cabinetry.

Broan Elite XE. Beauty that performs—automatically.

Broan makes everything about trash removal easier. It starts with a reversible door that opens like a refrigerator, simplifying access to an easy-to-reach and clean compartment. To handle the load, ball-bearing slides enable the trash bucket to glide out effortlessly. Our unique drop-down bucket front means there's no awkward lifting over the side, and conveniently placed electronic controls and our auto-delay function let you program the compactor to start when you're away. Then, the touch of a single button sets it for duty, and you can forget about it—you'll never come home to an overflowing waste receptacle again. But best of all, Broan Elite XE compactors keep odors in check. Our exclusive system absorbs odors for 30 days, rotates a fresh segment into place automatically every month, and lets you know when it's time for replacement.

Stainless
Steel

Appliance
White

Appliance
Black



Broan Elite XE Features

3000 lbs. of continual compaction force and $\frac{3}{4}$ horsepower motor deliver powerful performance and 6 to 1 compaction ratio.

1.55 cubic foot, painted steel trash bucket holds 30 lbs. of compacted trash.

Programmable compaction cycle for automatic operation with 5-minute memory back-up during a power outage.

Six-month, auto advance, odor control system with disc change indicator.

Full extension, ball-bearing drawer slides provide effortless gliding of trash bucket.

Stainless steel compacting plate with antimicrobial protection.

Insulated door with magnetic gasket for quiet cycling (excludes WT models).

Activation button with status LED.

Fully-enclosed, adjustable height, painted metal cabinet with fingerprint resistant coating.

Reversible 170° hinged door.

Child lock with removable key provides peace of mind.

Integral bag storage compartment means bags are always within reach.

Optional toe kick kit for freestanding installations (see page 10 for details).

Full extension ball-bearing
drawer slides



Programmable compaction cycle
with five-minute memory back-up
during power outage



A six-month, odor-absorbing
disc automatically advances and
features a replacement indicator



Antimicrobial protected,
dimpled, stainless steel
compacting plate crushes
bottles and cans





Broan Elite

Proof that a trash compactor
can look smashing.

Broan Elite Trash Compactors feature flat-front doors in stainless steel, white or black. Choose a model with a door tray for custom wood insert, as shown here. See page 3 for more ideas.

Broan Elite. Convenience made easy in a few simple steps.

Like its more automated sibling, Broan Elite trash compactors simplify waste containment and removal. A full-swinging, reversible door opens to an easy-to-clean compartment and a full-extension trash bucket. Its simplified control panel requires just two settings to start the process. Turn the activation key, close the door and touch one button. That's it. Removing the compacted bag is easy, too—lower the bucket front and slide the bag forward to the floor. There's no more lifting over the side. Broan Elite compactors also use our exclusive six-month odor control system. Rotate the dial once a month and a fresh segment is ready to work.

Stainless
Steel

Appliance
White

Appliance
Black



Broan Elite Features

3000 lbs. of continual compaction force and $\frac{3}{4}$ horsepower motor delivers powerful performance and 6 to 1 compaction ratio.

1.55 cubic foot, painted steel trash bucket holds 30 lbs. of compacted trash.

Six-month, manual advance, odor control system.

Full extension, ball-bearing drawer slides provide effortless gliding of trash bucket.

Painted steel compacting plate to crush bottles and cans.

Magnetic door gasket for a positive seal.

Fully-enclosed, adjustable height, painted metal cabinet with fingerprint resistant coating.

Reversible 170° hinged door.

Child lock with removable key provides peace of mind.

Integral bag storage compartment means bags are always within reach.

Optional toe kick kit for freestanding installations (see page 10 for details).

Full extension ball-bearing
drawer slides



Simplified two-step
control panel



Painted steel compacting plate
crushes bottles and cans





Beauty that stands on its own.

When it's not convenient or possible for built-in installation, Broan Elite offers the perfect solution—a Toe Kick Kit that allows the compactor to stand alone. All models feature finger-print resistant finishes on the top and sides. Cap your compactor with our Hard Maple Cutting Board or create a custom top to match your existing décor. Model 15XEBL



Adjustable feet on the optional toe kick allow precise height and leveling adjustment. Model 15TCTK

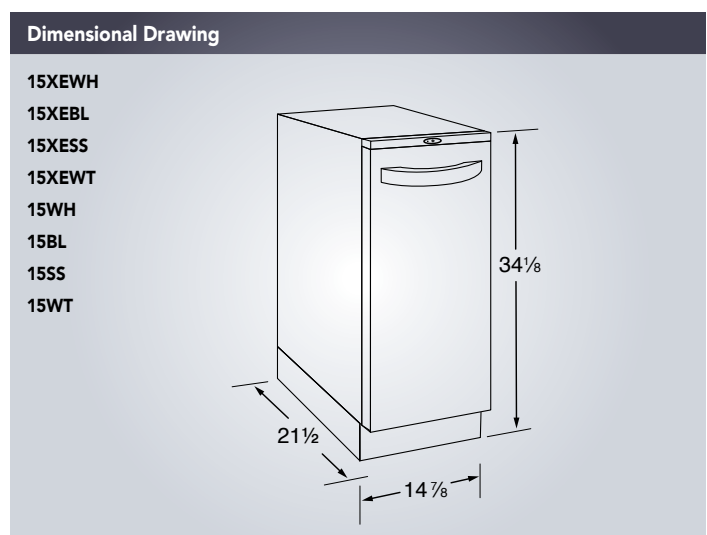
Our optional, one-inch thick, Hard Maple Cutting Board provides a generous 320 square inches of food preparation space. A full perimeter groove prevents liquids from reaching the edge of the board. The cutting board rests on non-skid rubber feet, and lifts off for easy cleanup. Model 15TCBB

Broan Trash Compactors Specifications and Accessories

Model Number	Door Width and Finish	Compacting Power	Motor Horse Power	Compacting Ratio	Dimensions	Electrical	Odor Control	Programmable Operation
Broan Elite XE								
15XEWH	15" Automatic Compactor, White Door	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	•
15XEBL	15" Automatic Compactor, Black Door	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	•
15XESS	15" Automatic Compactor, Stainless Steel Door	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	•
15XEWt	15" Automatic Compactor, with Door Tray for custom wood insert	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	•

Broan Elite								
15WH	15" Compactor, White Door	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	
15BL	15" Compactor, Black Door	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	
15SS	15" Compactor, Stainless Steel Door	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	
15WT	15" Compactor, with Door Tray for custom wood insert	3000 lbs.	3/4 hp	6:1	14 $\frac{7}{8}$ " x 34 $\frac{1}{8}$ " x 21 $\frac{1}{2}$ "	120V	•	

Accessories	
15TCBL	Compactor Bags for 15" models, quantity 12
15TCOD	Odor Control Disc
15CTK	Free standing Toe Kick Kit for 15" models
15TCBB	Hard Maple Cutting Board for 15" models, 21-1/2" x 15" x 15/16"



Broan® is America's leading brand of residential ventilation products including range hoods, ventilation fans, heater/fan/light combination units, balanced ventilation systems, built-in heaters, whole-house fans, electric and solar-powered attic ventilators and trash compactors.

NuTone® is America's leading brand of residential built-in convenience products including door chimes, central vacuum systems, intercom systems, ceiling fans, ironing centers and ventilation fans.



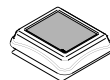
VENTILATION
FANS



CHIMES



TRASH COMPACTORS



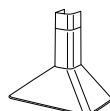
SOLAR-POWERED
ATTIC VENTILATORS



INTERCOMS



BALANCED
VENTILATION SYSTEMS



RANGE HOODS



IRONING CENTERS



HEATERS



CEILING FANS



VENTILATION
FAN/LIGHTS



CENTRAL VACUUMS

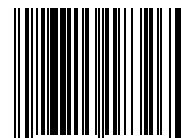
Make yours a Broan-NuTone home.

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Hartford, WI 53027 **800-558-1711**
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The Compactor Guy Inc.

Is Pleased To Provide The Following

**Indoor / Outdoor / Drive thru Lobby Pack
TCG-DA1100 Compactor Proposal**

FOR

Website Visitors

2008 / 2009



Our Newest Design is NOW Available

**Two Color Choices
Cobalt Grey & Dessert Tan**



Pricing For the Year 2008 / 2009

Welcome Online Visitor:

We would like to introduce the Lobby Pack TCG – DA1100 public use compaction unit. This unit is an easy to use compactor and has many user-friendly features. The cubes that it compacts are less weight and easier to handle than other indoor compacting units currently on the market. It even costs less. The unit operates with a standard wall outlet and is ready to plug in and operate. The lobby packs require no special wiring or a dedicated line. Two units can be plugged into one outlet as the unit does not require high amperage.

The Compactor Guy Inc. is the Compactor Equipment leader in North America, servicing customers with compactor and baler needs. Throughout the country we provide rentals, leasing and purchasing programs to such customers as B.Braun Medical, Apotex Inc. Hospital for Sick Children, Oshawa Foods, A & P Services Canada, CHIP REIT Hotels, Westin Hotels, Cineplex Odeon, McDonalds Restaurants, as well as many independent businesses in the market place.

With any offering in this quote, The Compactor Guy Inc. will provide everything necessary for a complete installation in compliance with WSIB regulations.

Should you have any questions or concerns please feel free to contact me. I look forward to continuing and enhancing our business relationship into the future.

Regards,

THE COMPACTOR GUY INC.

C.A. (Sandy) Bock
President

Advantages, Benefits & Savings, Lobby Pack TCG-1000 Cost Savings & Revenue Enhancements

- ◆ Lobby-Packs can reduce labor for trash related tasks by up to 75% or more
- ◆ Allows Housekeeping to schedule trash detail (usually just one or two trips to the compactor or waste bin per day)
- ◆ Frees up dining area space to allow for more dine-in guests (1 Lobby-Pack can replace the trash volume requirements of many traditional trash bins while also emptying each unit much less.
- ◆ Hand Pick Haulage costs are greatly reduced as many less trash bags and less space required to store trash prior to pick up.

Customer Stated Benefits

- ◆ Eliminates unsightly, overflowing trash receptacle.
- ◆ Positive interaction between Patrons and Lobby Pack Unit increasing Patrons use.
- ◆ Potential for Customer Beneficial promotional messages.
- ◆ Patrons no longer have to experience the unpleasant smells & unsightliness of employees constantly emptying the trash bins.
- ◆ The waste deposit door automatically opens so patrons no longer have to touch an unsanitary waste deposit door with their hands

Safety, Sanitation & Security

- ◆ Eliminates bags of trash accumulating in the large plastic carts, waiting to be taken to the disposal area. This reduces fire hazards and unsanitary conditions.
- ◆ Unit can be adjusted to compact from 20 to 50 lbs thus eliminated any heavy lifting of overweight cubes of trash.
- ◆ Receiving cube has a telescoping handle and wheels built right into it. Simply extend the handle and easily roll it to the trash bin.

Method of Acquiring Equipment

Lobby Pack Model TCG - DA1100 **Indoor / Outdoor Drive thru Waste Compactor**

Pricing is Per Unit.

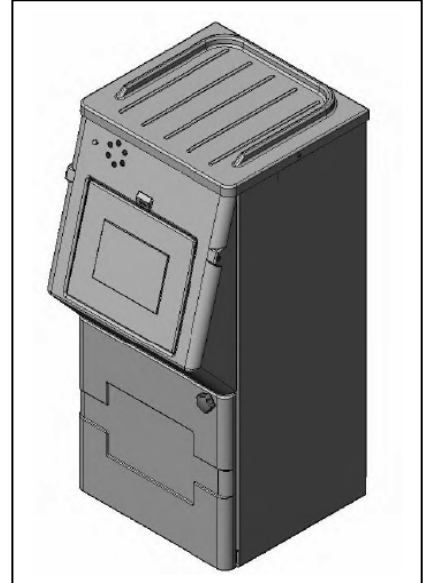
Features:

- Automatic Door Opening Sensor (Adjustable)
- Optional Message System, (7 Pre-Programmed, Rotating)
- Automatic Compaction
- Disposable Compaction Plate Cover (easy cleanup)
- Easy Clean and Scratch Resistant Finishes
- Cycle time of 8 seconds.

Each Unit to Include:

- Unit Provided in Choice of 2 Finishes
- Liquid Retention Base Cube Telescopic Handle
- Cube base on wheels, no trash transfer
- Cube Sleeve easily removable
- ** Installation and training is available

Electrical to be supplied by Customer. (115V-10AMP)



Purchase:

\$ 5495.00 plus tax.

* Warranty – One year parts and labor.

* A 25% deposit is required at time of purchase and balance due on delivery.

Rental: (60 Month)

5 Year (60 Month).....\$125.00 per month plus tax

* Warranty – One year parts and labor.

Lease To Own also available, please call for details.

Volume Discounts Are Available on 10 + Units. (10%)

Additional Operating Costs:

Cube liners: 2mil thick, clear or black roll of one hundred \$75.00 + taxes and delivery.

Now Available in 100% Earth Friendly Degradable format.

Compaction Plate Bonnet, Disposable Easy Clean Up Covers, \$4.00 Each. (Washable)

** Freight to site is extra. Onsite training is available in certain areas, please call for details.

**Errors and omissions accepted*

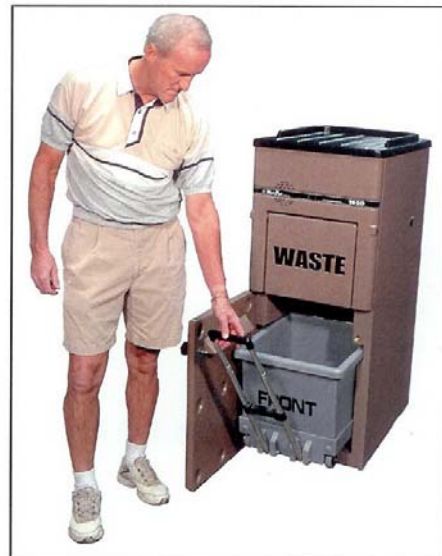
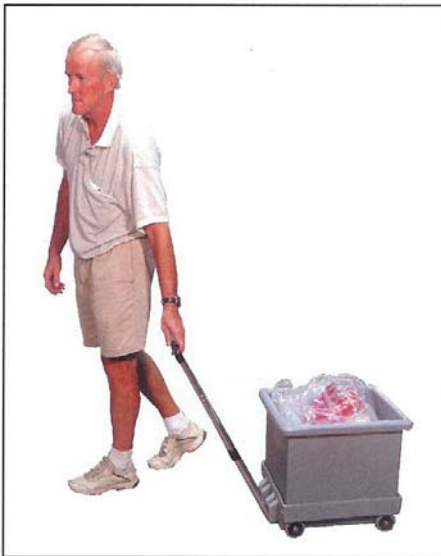
**Subject to Credit Approval*

3.1 Emptying the Unit



To empty the TCG- DA1000, open the main door.
Using the expandable handle on the cart, pull it from the unit.
Pull the sides of the bag up and secure with a twist tie (not provided) or by tying a knot in the bag.

If so desired, use the cart to transport the bagged waste to the dumpster. Remove the sleeve and dispose of the waste. Replace the sleeve, making sure the sleeve is positioned where it says FRONT.



Simple, Easy, Neat & Clean!!



Compaction Plate is Easily Accessed for Cleaning

Compaction Plate Bonnet (Cover) Insures a Clean Compaction Pack Head

Our Newest Model for Indoor and Outdoor Use is now available

- Improved design.
- Up to a 10 to 1 compaction ratio.
- Built to last and easy to clean.
- True compaction NOT a tamper plate.
- Finance or purchase.

OPTIONS:

- Domed or tray lid.
- Indoor or outdoor.
- Voice or no voice.
- Front or back cart removal.
- Custom graphics.
- Eliminates unsightly waste overflows during peak dining times.
- Improves employee efficiency via fewer trash removals.
- Saves money via:
 - Reduced contract hauling.
 - Reduced theft.
 - Labor reduction.
- Improves safety with fewer trips to the dumpster.
- Promotes sanitary and convenient use via "No Touch" door opening sensor.



SPECIFICATIONS:

Compactor: 51" H x 22.25" W x 21.25" D
Removal Door: 22.5" H x 22.5" W
Deposit Door: 13.5" H x 16" W
Bag Size: 16" W x 16" D x 42" T
Weight: 200 Pounds
Compacted Cube Weight: Up to 50 pounds
Electrical: 110/220 volts | 60 hertz | 10 amps
Compaction cycle: 7 seconds



The Best Service Guaranteed

24 Hour, 7 Days a Week. Service Line
905-334-0446

The Best Service Guaranteed.

As North America's leading company for compaction equipment, you can count on The Compactor Guy. We deliver the level of service you expect and deserve; Plus, we back it up with the first real service guarantee in the compaction business. Over the past few years we have streamlined our service procedures and added new technologies "Rent without Worry" is the result of these innovations. As a result, we deliver one-on-one local customer attention and service and 100% customer satisfaction Guaranteed.

Our Service Guarantee Really Works For You.

***Service right from the start. Guaranteed.**

We guarantee you'll get the right equipment on time and in the right place.

***Within 6 hours on site visit**

Normally we are on site within 6 hours of your call during business hours.

***Individualized Service. Guaranteed.**

We recognize that every business is different. If there's something else that is important to you, let us know and we will work with you to **INCLUDE SPECIALIZED SERVICES IN YOUR SERVICE GUARANTEE.**

Certain Conditions apply, Call for details.



RJ-30 High-Density Compactor Extruder

Marathon's RJ-30 features a curved tube and hydraulic choker that discharges densely compacted blocks of refuse into almost any size and type of receiving container. Because of its unique "S" shaped tube, the RJ-30 achieves higher compaction ratios. It is perfect for through-the-wall applications.

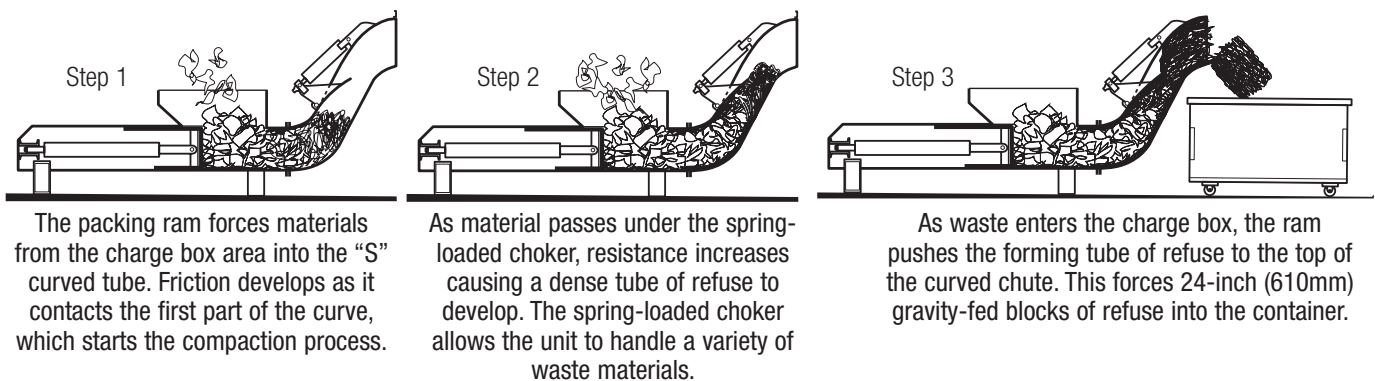
RJ-30 Compactor Extruder

Standard Benefits

- The RJ-30 compacts material in the compactor and not in the container, making unloading fast and easy. The container is not attached to the unit, which saves time and eliminates spillage.
- The body and ram are constructed of heavy steel plate.
- The smooth operating hydraulic power unit is available mounted on the compactor or separate.
- The RJ-30 can be used in a variety of applications, such as deliquifying and recovery of material from outdated beverage containers, oil filters, rejected oil cans, and dairy products.
- Ideal for multi-story apartment buildings where trash is fed by a chute system.
- Optional photoelectric cycle control senses when trash is in the hopper and alerts the unit to cycle automatically.



How the RJ-30 extruder works



**Environmental
Solutions Group**

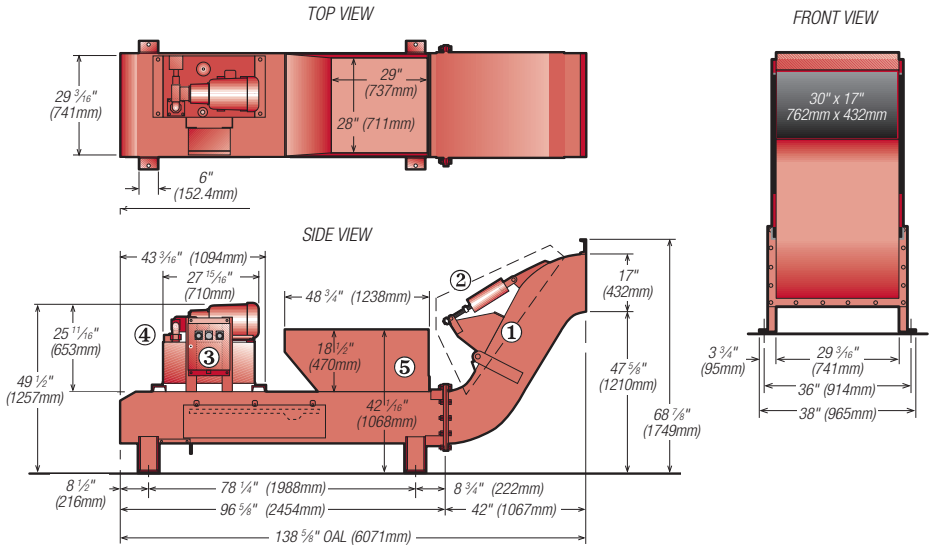
A DOVER COMPANY

STATIONARY COMPACTORS

RJ-30 Compactor Extruder

Dimensions and Specifications

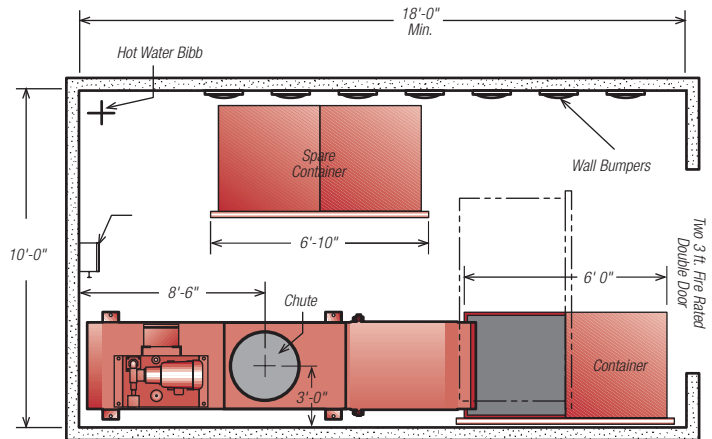
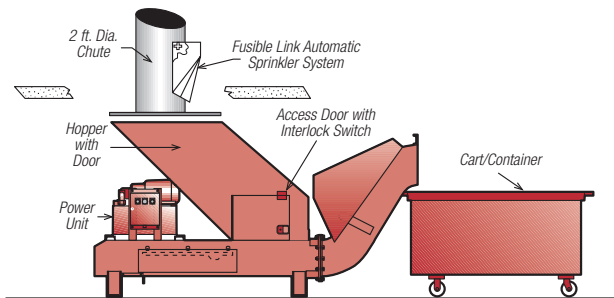
Specifications		
Charge Box Capacity:		
Mfr. Rating	0.38 cu. yd.	0.29 m³
NWRA Rating	0.27 cu. yd.	0.21 m³
Clear Top Opening	30.5"L x 28"W	775mm x 71mm
Performance Characteristics		
Cycle Time	33 sec.	
Normal Force	46,200 lbs.	206 kN
Maximum Force	57,700 lbs.	257 kN
Normal Ram Face Pressure	128.3 psi	885 kPa
Maximum Ram Face Pressure	160.3 psi	1105 kPa
Weight	3,300 lbs.	1497 kg
Electrical Equipment		
Electric Motor 3/60/208/230/460	15 HP	11.2 kW
Electric Control Voltage	120 VAC	
UL® and cUL® Listed		
NEMA 3-type, all circuits fused/standard controls: Keylock start/stop/reverse.		
Mounted in face of electrical panel box.		
Hydraulic Equipment		
Hydraulic Pump Capacity	18.5 gpm	70 L/min.
Normal System Pressure	1,200 psi	83 bar
Maximum System Pressure	1,500 psi	103 bar
Hydraulic Cylinders (2) - Bore	7"	178mm
Hydraulic Cylinders (2) - Rod	4"	102mm



Unit Elements

1	Choker
2	Choker Cover
3	Control Box
4	Power Unit
5	Hopper

Please refer MarathonEquipment.com for the online brochure with the most up-to-date information.



RAMJET
Stationary and self-contained compactors.

Compactor Rental and Leasing Programs Available

For detailed specifications, recommendations, or free economic studies comparing various systems, contact Marathon Customer Care at **1-800-633-8974**.

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www.marathonequipment.com
NJPA Contract #060612-ESG



www.doveresg.com



Pictures in this literature are illustrative only. Specifications are subject to change without notice in order to accommodate improvements to the equipment. Complies with ANSI standard Z245.2, all applicable OSHA regulations, and certified under WASTEC's Stationary Compactor Certification Program. Products must be used with safe practice and in accordance with all applicable regulations and standards.

ANEXO EAP'S



- 1- EAP's ventajas - inconvenientes
- 2 – Músculos artificiales usando polímeros electroactivos
- 3 – Aplicaciones polímeros electroactivos
- 4 – Principios físicos y perspectivas navales. Tablas propiedades.
- 5 – A micro-robot fish with embedded SMA wire

EAP as Artificial Muscles – Progress and Challenges

Yoseph Bar-Cohen

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ABSTRACT

During the last decade and a half new polymers have emerged that respond to electrical stimulation with a significant shape or size change. This capability of electroactive polymer (EAP) materials is attracting the attention of engineers and scientists from many different disciplines. Practitioners in biomimetics are particularly excited about these materials since the artificial muscle aspect of EAPs can be applied to mimic the movements of animals and insects. In the foreseeable future, robotic mechanisms actuated by EAP will enable engineers to create devices previously imaginable only in science fiction. Last year, significant accomplishments were reported include the emergence of the first commercial product and the possibility that an arm can be made with EAP actuators having the potential of winning a wrestling match with human. As such major accomplishments continue to be reported it is interesting to review the progress and provide a prospective regarding the development since the first EAPAD conference in 1999. This manuscript covers the progress in the field of EAP and the challenges that are being addressed.

Keywords: EAP, Artificial Muscles, Armwrestling, actuators, biomimetics

1. INTRODUCTION

The emergence of polymers that respond to electrical stimulation with a significant shape or size change has added greatly to the list of desirable properties of polymers [Bar-Cohen, 2001 and 2004]. The large strain response of EAP materials is increasingly attracting the attention of engineers and scientists from many different disciplines who are seeking novel applications. Since EAP materials operate similar to biological muscles, they have earned the popular name “artificial muscles.” Experts in biomimetics are particularly excited about these materials since they can be applied to mimic the movements of biological creatures [Bar-Cohen and Breazeal, 2003; and Bar-Cohen, 2004a]. Using this capability, EAP actuated robotic mechanisms are enabling engineers to create devices that were previously only imaginable in science fiction. One such commercial product has already emerged in Dec. 2002 is a form of a Fish-Robot (Eamex, Japan). An example of this Fish-Robot is shown in Figure 1. It swims without batteries or a motor and it uses EAP materials that simply bend upon stimulation. For power it uses inductive coils that are energized from the top and bottom of the fish tank. This fish represents a major milestone for the field, as it is the first reported commercial product to use electroactive polymer actuators.

For several decades, it has been known that certain types of polymers can change shape in response to electrical stimulation. Initially, these EAP materials produced a relatively small strain. Since the beginning of the 1990s, a growing number of new EAP materials are emerging with a large strain response to electrical stimulation [Bar-Cohen, 2001 and 2004]. The materials that have emerged were divided by the author into two major groups, including ionic and electronic EAP, and examples of the response of these materials are shown in Figs. 2 and 3, respectively. In Figure 2, a starfish-shaped IPMC (ionomeric polymer-metal composites) is shown to bend significantly. The direction of bending depends on the voltage polarity. In Figure 3, a dielectric EAP is shown with a circular carbon grease electrode area that is activated by an electric field to generate expansion. The expanded elastomer film contracts to the original shape when the electric voltage is turned off. This capability to generate a large strain cannot be matched by alternative active materials such as piezoelectric ceramics and shape memory alloys.

In 1999, in an effort to promote worldwide development towards the realization of the potential of EAP materials the author posed an armwrestling challenge. A graphic rendering of this challenge is illustrated in Figure 4. In posing this challenge, the author sought to see an EAP activated robotic arm win against human in a wrestling match to establish a baseline for the implementation of the advances in the development of these materials. Success in wrestling against human will enable capabilities that are currently considered impossible. It would allow applying EAP materials to improve many aspects of our life where some of the possibilities include effective implants and prosthetics, active clothing, realistic biologically inspired robots as well as fabricating products with unmatched capabilities and dexterity. Recent advances in understanding the behavior of EAP materials and the improvement of their efficiency led to the point where the possibility of EAP actuated arm can win such wrestling match may become feasible in the coming years. The most notable milestone is the recent announcement of scientists from SRI

International, USA, stating that they believe they can build such a robotic arm. To plan the first international arm-wrestling competition efforts are currently underway to consider holding the competition as part of one of the SPIE's Annual International EAPAD (EAP Actuators and Devices) Conferences in San Diego, California, USA.



FIGURE 1: The first commercial EAP product - a fish robot (courtesy of Eamex, Japan)

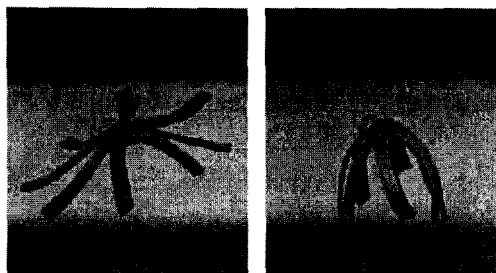


FIGURE 2: IPMC multi-finger starfish (courtesy of K. Oguro, Osaka National Research Institute, Osaka, Japan).

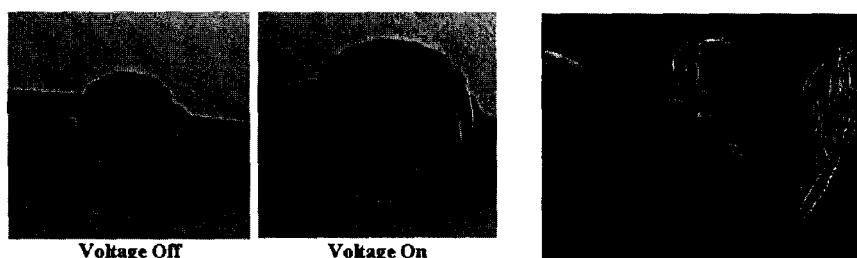


FIGURE 3: Dielectric actuator demonstrated to expand and relax (courtesy of R. Kornbluh and R. Pelrine, SRI International, USA).

FIGURE 4: Grand challenge for the development of EAP actuated robotics.

In recognition of the need for international cooperation among the developers, users, and potential sponsors, the author organized the first EAP conference on March 1–2, 1999, through The International Society for Optical Engineering (SPIE) as part of the Smart Structures and Materials Symposium [Bar-Cohen, 1999]. This conference was held in Newport Beach, California, USA, and was the largest ever on this subject, marking an important milestone. This conference turned the spotlight onto these emerging materials and their potential. Following this success, a Materials Research Society (MRS) conference was initiated to address fundamental issues related to the material science of EAP [Zhang et al., 1999]. In recent years, there has been increasing number of organizations and technical societies who are organizing workshops, meetings and conferences with sessions on EAP. The SPIE's EAPAD conferences are now organized annually and have been steadily growing in number of presentations and attendees. In addition to the conferences, there is a website called the WorldWide EAP (WW-EAP) Webhub that archives related information and links to homepages of EAP research and development facilities worldwide [<http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-web.html>]. Since June 1999, the semi-annual WW-EAP Newsletter has been published with short synopses from authors worldwide providing a snapshot of their advances. This Newsletter is published electronically and its issues are accessible via the above mentioned WW-EAP webhub [<http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html>]. Further, the author edited a reference book on EAP that has been published in 2001 [Bar-Cohen, 2001] with its 2nd edition is expected to be published before the 2004 EAPAD Conference [Bar-Cohen, 2004]. This book provides a comprehensive documented reference, technology user's guide, and tutorial resource, with a vision for the future direction of this field. It covers the field of EAP from all its key aspects, i.e., its full infrastructure, including the available materials, analytical models, processing techniques, and characterization methods.

2. POLYMERS THAT CAN BE STIMULATED TO CHANGE SHAPE OR SIZE

To provide a complete picture one cannot ignore the fact that there are many types of polymers with properties that can be changed by an external stimulation. Some of these polymers exhibit volume or shape change in response to various forms of stimulation. These changes usually result from the perturbation of the balance between repulsive intermolecular forces that act to expand the polymer network, and attraction forces that act to shrink it. Repulsive forces are usually electrostatic or hydrophobic in nature, whereas attraction is mediated by hydrogen bonding or van der Waals interactions. The competition between these counteracting forces, and hence the volume or shape change, can thus be controlled by subtle changes in parameters such as solvent or gel composition, temperature, pH, light,

etc. Activation mechanisms that are not electrical include chemical [Kuhn et al., 1950; and Otero et al., 1995], thermal [Tobushi et al., 1992; and Li et al., 1999], pneumatic [Chou and Hannaford, 1996], optical [van der Veen and Prins, 1971], and magnetic [Zrinyi et al., 1997].

Polymers that are stimulated chemically were discovered more than half a century ago when collagen filaments were demonstrated to reversibly contract or expand when dipped in acid or alkali aqueous solutions, respectively [Katchalsky, 1949]. Even though relatively little has since been done to commercially exploit such “chemo-mechanical” actuators, this early work pioneered the development of synthetic polymers that mimic biological muscles [Steinberg et al., 1966]. However, the convenience and the practicality of electrical stimulation and the recent technical progress have led to a growing interest in EAP materials. Following the 1969 observation of a substantial piezoelectric activity in Poly(vinylidene fluoride) (PVF2) [Bar-Cohen et al., 1996; and Zhang et al., 1998], investigators started to examine other polymer systems, and a series of effective materials have emerged. The largest progress in EAP materials development has occurred in the last fifteen years where effective materials that can induce strains of about 300% have emerged [Peltine et al. 1998].

3. THE EAP TECHNOLOGY INFRASTRUCTURE

As polymers, EAP materials can be easily formed in various shapes, their properties can be engineered, and they can potentially be integrated with micro-sensors to produce smart actuators. Producing practical actuators and mechanisms that are based on EAP requires attention to the critical aspects of these materials. This requires sufficient understanding of the material behavior, ability to optimize the material properties and performance, establish robust actuators with well characterized properties, as well as the development of effective control and design tools. These aspects were identified by the author as the EAP technology infrastructure (see Figure 5) and it defined the roadmap for the technology maturity [Bar-Cohen, 2001]. This effort to develop the infrastructure is multidisciplinary and requires international collaboration.

3.1 Electroactive polymers (EAP) materials

Polymers that exhibit shape change in response to electrical stimulation can be divided into two distinct groups: electronic (driven by electric field or Coulomb forces) and ionic (involving mobility or diffusion of ions). The electronic EAP materials (electrostrictive, electrostatic, piezoelectric, and ferroelectric) require high activation fields ($>10 \text{ V}/\mu\text{m}$) close to the breakdown level. However, they can be made to hold the induced displacement under activation of a dc voltage, allowing them to be considered for robotic applications. Also, these materials have a faster response and they can be operated in air with no major constraints. In contrast, ionic EAP materials (gels, polymer-metal composites, conductive polymers, and carbon nanotubes) require drive voltages as low as 1–5 V. However, there is a need to maintain their wetness, and except for conductive polymers it is difficult to sustain dc-induced displacements. For ionic EAP that are involved with water content, the use of voltages above 1.23 V leads to hydrolysis that damages the material irreversibly. Generally, the produced displacement in both the electronic and ionic EAP can be designed geometrically to bend, stretch, or contract. Any of the existing EAP materials can be made to bend with a significant curving response, offering actuators with an easy-to-see reaction and an appealing response. However, bending actuators have relatively limited applications for mechanically demanding tasks due to the low force or torque that can be induced. The various EAP materials have advantages and disadvantages (see Table 1) that determine both their applicability and practical use.

3.2 EAP characterization

Accurate and detailed information about the properties of EAP materials is critical to potential designers who are considering the construction of related mechanisms or devices. In order to assess the competitive capability of EAPs, there is a need for a performance matrix that consists of comparative performance data. Such a matrix needs to show the properties of EAP materials as compared to other classes of actuators, including piezoelectric ceramic, shape memory alloys, hydraulic actuators, and conventional motors. Studies are currently underway to define a unified matrix and establish effective test capabilities with emphasis on the macroscale structures [Bar-Cohen, 2001 and 2004]. Key parameters are identified and test methods are being developed to allow measurements with minimum effect on the EAP material. While the electromechanical properties of longitudinal electronic-type EAP materials can be addressed with some of the conventional test methods, ionic-type EAPs, such as IPMC, are posing technical challenges. The response of these materials suffers complexities that are associated with the mobility of the cation on the microscopic level, the strong dependence on the moisture content, and hysteretic behavior. The use of a video camera and image processing software offers a capability to study the deformation of IPMC strips under various mechanical loads. Simultaneously, the electrical properties and the response to electrical activation can be measured. Nonlinear behavior has been clearly identified in both the mechanical and electrical properties and efforts are underway to model this behavior [Bar-Cohen, 2001 and 2004].

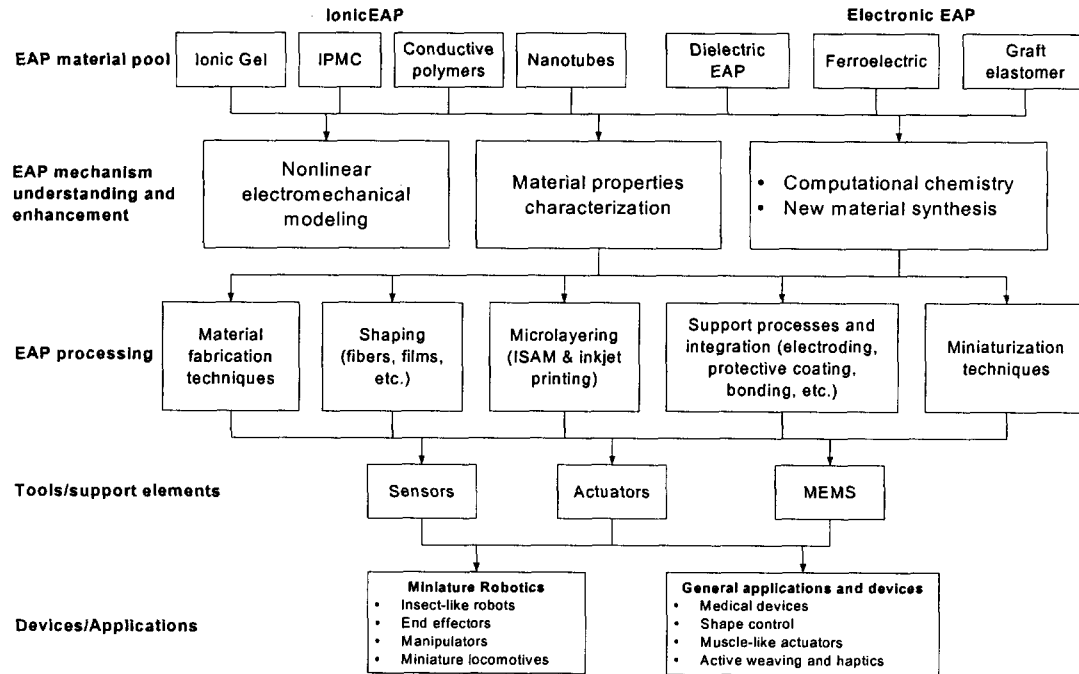


FIGURE 5: EAP infrastructure and areas needing attention.

TABLE 1: Summary of the advantages and disadvantages of the two major EAP groups.

EAP type	Advantages	Disadvantages
Electronic EAP	• Can operate in room conditions for a long time • Rapid response (msec levels) • Can hold strain under dc activation • Induces relatively large actuation forces	• Requires high voltages (~150 MV/m). Recent development allowed for (~20 MV/m) • Glass transition temperature is inadequate for low-temperature actuation tasks and, in the case of Ferroelectric EAP, high temperature applications are limited by the Curie temperature • Due to associated electrostriction effect, a monopolar actuation is produced independent of the voltage polarity.
Ionic EAP	• Produces large bending displacements • Requires low voltage • Natural bi-directional actuation that depends on the voltage polarity.	• Except for CPs and NTs, ionic EAPs do not hold strain under dc voltage • Slow response (fraction of a second) • Bending EAPs induce a relatively low actuation force • Except for CPs, it is difficult to produce a consistent material • In aqueous systems, EAP suffer electrolysis at >1.23 V • To operate in air requires attention to the electrolyte. • Low electromechanical coupling efficiency.

3.3 Expected applications

In recent years, there has been significant progress toward making practical EAP actuators, and commercial products are starting to emerge including the fish-robot that was reported earlier. A growing number of organizations are now exploring potential applications for EAP materials and cooperation across many disciplines are helping to overcome some of the challenges. Some of the mechanisms and devices that are being considered are related to aerospace, automotive, medical, robotics, entertainment, toys, clothing, haptic and tactile interfaces, noise control, transducers, power generators and smart structures.

The potential capability of EAPs to emulate muscles may enable robotic capabilities that are in the realm of science fiction when relying on existing actuation materials [Bar-Cohen, 2001& 2004; Bar-Cohen and Breazeal, 2003; Kornbluh et al., 1995]. The large displacement that can be obtained using low mass, low power, and, in some of the EAPs, low voltage, makes them attractive for attempting to produce biologically inspired robots. EAP materials are being sought as a substitute for conventional actuators, possibly eliminating the need for motors, gears,

bearings, screws, etc. [Bar-Cohen et al., 1999b; Fischer et al., 1999a]. Combining the bending and longitudinal strain capabilities of EAP actuators, a miniature robotic arm was designed and constructed at JPL. The gripper consists of four IPMC finger strips with hooks at the bottom emulating fingernails. Experiments with this robotic arm raised concerns regarding the ability to control the kinematics of robotic components that are made of dielectric EAP and of IPMC since these actuators are flexible and do not provide accurate positioning. Upon activation, the arm exhibits low-frequency vibration with a relatively low damping. The inherent vibration-damping characteristics of polymers are not sufficient to suppress this low frequency vibration. Besides effective control algorithms, sensor feedback is expected to be critical to addressing the issue of precision positioning of EAP activated devices.

The growing availability of EAP materials that exhibit high actuation displacements and forces is opening new avenues to bioengineering in terms of medical devices and assistance to humans in overcoming different forms of disability. Areas that are being considered include an angioplasty steering mechanism, and rehabilitation robotics. For the latter, exoskeleton structures are being considered in support of rehabilitation or to augment the mobility and functionalities of patients with weak muscles. One important question, which has been asked by new users or researchers/engineers who are coming to this field, is: "where can I get these materials?" This issue of unavailability of commercial EAP materials is dampening the rate of progress in the field of EAP. To help potential users, the author has established a website to provide "recipes" describing how to make the various EAPs. The address of this website is: <http://ndcaa.jpl.nasa.gov/nasa-nde/lommas/cap/EAP-recipe.htm>. To help further, the author compiled inputs from companies that make EAP materials, prototype devices or provide EAP related processes and services. The inputs were compiled into a handy table that is posted on one of the links of the WW-EAP webhub: <http://ndcaa.jpl.nasa.gov/nasa-nde/lommas/cap/EAP-material-n-products.htm>.

4. PLATFORMS FOR DEMONSTRATION OF EAP

Developing biomimetic intelligent robots involves many disciplines including materials, actuators, sensors, structures, functionality, control, intelligence and autonomous operations [Bar-Cohen and Breazeal, 2003]. Mimicking nature has immensely expanded the collection and functionality of robots. As technology evolves, great numbers of biologically inspired robots that emulate biological creatures are expected to emerge and find applications in our daily life. Even a simple task of staying stable while being pushed is complex for a robot to perform and will require significant progress in many technology areas.

Beside the armwrestling challenge, to promote the development of human-like robots that are actuated by artificial muscles, two platforms were developed and made available to the author at his lab at JPL to support of the worldwide development of EAP. These platforms include an Android head that can make facial expressions and a robotic hand (Figure 6). The head can move the eyes and the lips, whereas the hand allows moving the index finger. At present, conventional electric motors are used to produce the required movement and thus leading to the desired facial expressions of the Android. Once effective EAP materials are developed, they will be modeled into the control system in terms of surface shape modifications and control instructions for the creation of controlled expressions. The robotic hand is equipped with wire-based tendons and has sensors for the operation of the various joints mimicking human hand. This robotic hand is also driven by conventional motors allowing the up and down movement of the index finger of this hand. As the android head, this hand is also used as a baseline for milestone comparison with the performance of emerging EAP actuators. Artificial muscles will substitute the motors when such EAP materials are developed to serve as effective actuators.

FIGURE 6: An android head and a robotic hand that are serving as biomimetic platforms for the development of artificial muscles

ACKNOWLEDGEMENT: This photo was made at JPL where the head was sculptured and instrumented by D. Hanson, University of Texas, Dallas. The hand was made by G. Whiteley, Sheffield Hallam U., UK.



5. FUTURE EXPECTATIONS

Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where EAP materials would not need to compete with existing technologies. The large strain response of EAP to electrical stimulation is nonlinear and requires adequate analytical tools for the design and control of related devices. Efforts are currently being made to model this nonlinear electromechanical behavior and

to develop experimental techniques of material properties measurements and characterization. These efforts are leading to better understanding of the origin of the electroactivity in various EAP materials, allowing improvement of their performance, and offering effective design tools for simulation of the performance of related devices. Methods of producing EAP fibers and films are being studied to effectively operate EAP materials as actuators and sensors and to improve their robustness.

The increased resources, the growing number of investigators conducting research related to EAP, and the improved collaboration among developers, users, and sponsors are leading to rapid advancements in this field. At the rate of development that is being reported in recent international EAP conferences, it is believed that the authors' armwrestling challenge will be met in few years rather than in many decades from now. Progress toward this goal will lead to great benefits, particularly in the medical area, where EAP materials may be used to replace damaged human muscles, actuate prosthetics and potentially lead to "bionic humans." A remarkable contribution of the EAP field would be to one day seeing a disabled person jogging to the grocery store using this technology.

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Artificial Muscles using Electroactive Polymers (EAP): Capabilities, Challenges and Potential

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For decades, EAP received relatively little attention due to their limited actuation capability. However, in the last fifteen years a series of Electroactive Polymers (EAP) materials have emerged that produce a significant shape or size change in response to electrical stimulation. These materials have the closest functional similarity to biological muscles enabling to engineer novel capabilities that were impossible to do up until recently. Efforts are underway to address the many challenges that are hampering the practical application of these materials and recent progress already led to dramatic capability improvements. Various novel mechanisms and devices were demonstrated including robot fish, catheter steering element, robotic arms, miniature gripper, loudspeaker, active diaphragm, Braille display, and dust-wiper. For developers of future medical devices these materials are offering numerous advantages for their flexibility, fracture toughness, and controllability, as well as low mass and low power requirements. This paper provides a review of the current status, the challenges and potential near future applications of these materials.

Keywords: Artificial Muscles, Electroactive Polymers, EAP, Biomimetics, Polymer Actuators, Robotics

Background

Natural muscles are one of the most important actuators in biological systems that are larger than a bacterium. The fact that, with a very small difference between species, muscles are fundamentally driven by the same mechanism in all animals suggests that they are highly optimized. Electroactive polymers (EAP), which emerged in the last fifteen years exhibiting large strain in response to electrical stimulation, are human made actuators that most closely emulate muscles. For this response, EAP have earned the moniker “artificial muscles” [1]. The impressive advances in improving their actuation strain capability are attracting the attention of engineers and scientists from many different disciplines. They are particularly attractive to biomimetic experts since they can be used to mimic the movements of humans, animals and insects for making biologically inspired mechanisms, devices and robots [2]. Increasingly, engineers are able to develop EAP actuated mechanisms that were previously considered unimaginable.

For many decades, it has been known that certain types of polymers can change shape in response to electrical stimulation [3-4]. Initially, these EAP materials were capable of producing only a relatively small strain. However, since the beginning of the 1990s, new EAP materials

have emerged that exhibit large strains and they led to a great paradigm change with regards to the capability of electroactive polymers and their potential [1]. Generally, EAP materials can generate strains that are as high as two orders of magnitude greater than the striction-limited, rigid and fragile piezoelectric ceramics. Further, EAP materials are superior to shape memory alloys (SMA) in higher response speed, lower density, and greater resilience. They can be used to make mechanical devices without the need for traditional components like gears, and bearings, which are responsible for their high costs, weight and premature failures. The current limitations of EAP materials that include low actuation force, mechanical energy density and robustness are constraining the practical application but improvements in the field are expected to overcome these limitations.

In 1999, in recognition of the need for international cooperation among the developers, users, and potential sponsors, the author initiated a related annual SPIE conference as part of the Smart Structures and Materials Symposium [5]. This conference was held in Newport Beach, California, USA, and was the largest ever on this subject, marking an important milestone and turning the spotlight onto these emerging materials and their potential. The SPIE EAP Actuators and Devices (EAPAD) conferences are now organized annually and have been steadily growing in number of presentations and attendees. Also, the author is issuing electronically the semi-annual WorldWide ElectroActive Polymers (WW-EAP) Newsletter covering the latest news and advances [<http://ndea.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html>], and he is managing a website that archives related information that includes links to homepages of EAP research and development facilities worldwide [<http://eap.jpl.nasa.gov>]. In the past few years, in addition to the SPIE conferences, several other conferences and special sessions within conferences focusing on electroactive polymer actuators have also taken place.

Electroactive Polymers (EAP)

There are many EAP materials [1]. In order to make a clear distinction between their activation mechanisms, the author divided them into two major groups including: ionic (involving mobility or diffusion of ions) and electronic (driven by electric field or Maxwell forces) [1 & 6]. The currently available leading EAP materials are listed in Table 1 and a summary of the advantaged and disadvantages of these two groups of materials are listed in Table 2. The electronic polymers (electrostrictive, electrostatic, piezoelectric, and ferroelectric) can be made to hold the induced displacement under activation of a DC voltage, allowing them to be considered for robotic applications. Also, these materials have a greater mechanical energy density and they can be operated in air with no major constraints. However, they require a high activation field ($>100\text{-V}/\mu\text{m}$) close to the breakdown level. In contrast, ionic EAP materials (gels, polymer-metal composites, conductive polymers, and carbon nanotubes.) are driven by diffusion of ions and they require an electrolyte for the actuation mechanism. Their major advantage is the requirement for drive voltages as low as 1-2 Volts. However, there is a need to maintain their wetness, and except for conductive polymers and carbon nanotubes, it is difficult to sustain DC-induced displacements. The produced displacement of both the electronic and ionic EAP can be geometrically designed to bend, stretch or contract. Any of the existing EAP materials can be made to bend with a significant curving response, offering actuators with an easy to see reaction and an appealing response. However, bending actuators have relatively limited applications due to the low force or torque that can be induced.

TABLE 1: List of the leading EAP materials

Electronic EAP	Ionic EAP
▪ Dielectric elastomer EAP ▪ Electrostrictive Graft Elastomers ▪ Electrostrictive Paper ▪ Electro-Viscoelastic Elastomers ▪ Ferroelectric Polymers ▪ Liquid Crystal Elastomers (LCE)	▪ Carbon Nanotubes (CNT) ▪ Conductive Polymers (CP) ▪ ElectroRheological Fluids (ERF) ▪ Ionic Polymer Gels (IPG) ▪ Ionic Polymer Metallic Composite (IPMC)

TABLE 2: A summary of the advantages and disadvantages of the two basic EAP groups

EAP type	Advantages	Disadvantages
Ionic EAP	• Natural bi-directional actuation that depends on the voltage polarity. • Some ionic EAP like conducting polymers have a unique capability of bi-stability • Requires low voltage	• Requires using an electrolyte • Electrolysis occurs in aqueous systems at >1.23 V • Require encapsulation or protective layer in order to operate in open air conditions • Low electromechanical coupling efficiency. • Except for CPs and NTs, ionic EAPs do not hold strain under dc voltage • Slow response (fraction of a second) • Bending EAPs induce a relatively low actuation force • High currents require rare earth electrodes such as gold or platinum • Except for CPs, it is difficult to produce a consistent material (particularly IPMC)
Electronic EAP	• Exhibits high mechanical energy density. • Induces relatively large actuation forces • Can operate for a long time in room conditions • Exhibit rapid response (mSec) • Can hold strain under DC activation	• Independent of the voltage polarity, it produces mostly monopolar actuation due to associated electrostriction effect. • Requires high voltages (~ 100 MV/m). Recent development allowed for a fraction of the field in the Ferroelectric EAP

EAP materials characterization

Construction of mechanisms or devices that are actuated by EAP materials requires accurate and detailed information about the properties of the materials that are used [7]. In order to assess the competitive capability of EAPs, there is a need for a performance matrix that consists of comparative performance data. Such a matrix needs to show the properties of EAP materials as compared to other classes of actuators, including piezoelectric ceramic, shape memory alloys, hydraulic actuators, and conventional motors. Studies are underway to define a unified matrix

and establish effective test capabilities [7]. Test methods are being developed to allow measurements with minimum effect on the EAP material. While the electromechanical properties of electronic-type EAP materials can be addressed with some of the conventional test methods [6 and 7], which are used for example to test piezoelectric materials, the ionic-type EAPs (such as IPMC) are posing technical challenges. The response of these materials suffers complexities that are associated with the mobility of the cation on the microscopic level, strong dependence on the moisture content, and hysteretic behavior. The use of a video camera and image processing software offers an effective capability to study the deformation of IPMC strips under various mechanical loads. Simultaneously, the electrical properties and the response to electrical activation can be measured. Nonlinear behavior has been clearly identified in both the mechanical and electrical properties and efforts were made to model this behavior [6 and 7].

Applications of EAP

As polymers, EAP materials have a lot of attractive properties that are superior to other actuation materials. EAP can be easily formed in various shapes, their properties can be engineered and they can potentially be integrated with miniature sensors to produce smart actuators. Unfortunately, the existing EAP materials are still exhibiting low conversion efficiency, are not robust, and there are no standard commercial materials available for consideration in practical applications. In order to take these materials from the development phase to application as effective actuators, the field infrastructure is being established address the science, engineering, and manufacturing [1] issues as well as the commercial availability of these materials for wider use.

In recent years, there has been significant progress in the field of EAP toward making practical actuators, and commercial products are starting to emerge. At the end of 2002, the first milestone product was announced by Eamax, Japan, and it is in the form of a fish robot. Moreover, many organizations are exploring potential applications for EAP materials for such areas as medical, robotics, exoskeletons, articulation mechanisms, aerospace, automotive, entertainment, animation, toys, clothing, haptic and tactile interfaces, noise control, transducers, power generators and smart structures. Some of the applications that are considered include:

Medical applications and potential artificial organs

Using EAP materials as actuators of artificial organs and limbs is involved with significant challenges including functional compatibility, rejection avoidance, and ability to meet the stringent requirements that are associated with the use of these materials on or in humans. At present, the electronic EAP materials seem to be the most applicable since they generate the largest actuation forces and they have the highest robustness. However, the required voltages that can be as high as several thousands of voltage pose potential hazard that must be addressed. Even though the electric current is relatively low, the use of high voltages can cause blood clots or injury due to potential voltage breakdown and shorting to the body. On the other hand, the ionic EAP group is chemically sensitive requiring effective sealing for protection of the internal organs and avoiding contamination of the ionic content, which reduces the performance efficiency. Also, it is difficult to maintain their static position, particularly for the IPMC, because of the fact that these materials involve chemical reaction and even DC voltage causes a reaction.

Interfacing between human and machine to complement or substitute our senses can enable important capabilities for medical applications. A number of such interfaces were investigated or have been considered and the most significance work is in area of interfacing machines and the human brain. A development by scientists at Duke University [8-9] as well as Caltech, MIT, Brown University, and many other research institutes enabled this possibility where electrodes were connected to the brain of a monkey, and, using brain waves, the monkey operated a robotic arm. If EAP actuated robotic arms are developed with sufficient strength and dexterity to function as effective prosthetics then this development by neurologists would help disabled people greatly. Using such interfacing capability to control prosthetics would require feedback to allow the human user to “feel” the artificial limbs. The required feedback can be provided with the aid of tactile sensors, haptic devices, and other interfacing mechanisms. Besides providing feedback, sensors will be needed to allow the users to protect the prosthetics from potential damage from heat, pressure, impact, and others just as we do with our biological limbs. The development of EAP materials that can provide tactile sensing is currently under way as described in [1]. Other areas of medicine that are benefiting from the development in EAP include robotics as discussed in the next section.

Biomimetic robots

Engineering an artificial limb, face and other parts of the body that appear and functions as realistic as the biological organs is a significant challenge due to the physical and technological constraints and shortcomings of the available technology. The use of effective artificial muscles, artificial intelligence and other biomimetic technologies are expected to make the possibility of realistically looking and behaving organs more practical engineering models [2]. Further, using this technology would allow making robots that are more accurate copies of the original creatures. The capability to produce EAP in various shapes and configurations can be exploited using such methods as stereolithography and ink-jet processing techniques [10]. Potentially, a polymer can be ejected drop-by-drop onto various substrates. Such rapid prototyping processing methods may lead to mass-produced robots in full 3D details including the actuators allowing quick transition from concept to full production [1].

To mimic a biological hand using simple elements, the author and his coinvestigators constructed a miniature robotic arm that was lifted by a rolled dielectric elastomer EAP as a linear actuator and four IPMC-based fingers as a bending actuator [1]. The linear actuator was used to raise and drop a graphite/epoxy rod that served as a simplistic representation of a robotic arm. As shown in Figure 1, this gripper grabs rocks very similar to the human hand.

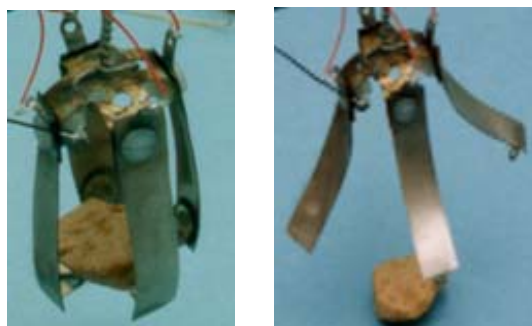


FIGURE 1: 4-finger EAP gripper lifting a rock.

Using EAP actuators, biologically inspired robots may be developed with capabilities that are far superior to natural creatures since they are not constrained by evolution and survival needs. These robots can be used in such configurations as octopus to perform multiple tasks simultaneously or operate as worms to travel thru the human body and perform various surgical procedures that can be performed either autonomously or wirelessly controlled. Important addition to this capability can be the application of tele-presence combined with virtual reality using haptic interfacing. The use of electrorheological fluids was proposed for the development of haptic interfaces [11]. Using such an interface for a simulator aided by virtual reality can potentially benefit medical therapy in space and at distant human habitats. The probability that a medical urgent care procedure will need to be performed in space is expected to increase with the growth in duration and distance of manned missions. A major obstacle may arise as a result of the unavailability of on-board medical staff capable of handling every possible medical procedure that may be required. To conduct emergency treatments and deal with unpredictable health problems the medical crews will require adequate tools and capability to practice the necessary procedure to minimize risk to the astronauts. With the aid of all-in-one-type surgical tools and a simulation system, astronauts with medical background would be able to practice the needed procedures and later physically perform the specific procedures. Medical staff in-space may be able to sharpen their professional skills by practicing existing and downloaded new procedures. Generally, such a capability can also serve people who live in rural and other remote sites with no readily available full medical care capability. As an education tool employing virtual reality, training paradigms can be changed while supporting the trend in medical schools towards replacing cadaveric specimens with computerized models of human anatomy.

Recent milestone for the Field

The field of EAP has been advancing rapidly in the last few years and major milestones were made including:

- a. In Dec. 2002, the first commercial product has emerged having the form of a Fish-Robot (Eamex, Japan). An example of this Fish-Robot can be seen on [<http://eap.jpl.nasa.gov>] where there is also a link to a video showing Fish-Robots swimming in a fish tank. It swims without batteries or a motor and it uses EAP materials that simply bend upon stimulation. For power it uses inductive coils that are energized from the top and bottom of the fish tank.
- b. On March 7, 2005, the first arm wrestling contest took place between a human opponent and three robotic arms driven by EAP actuators. This content was in response to the 1999 challenge posed to the worldwide engineers by the author in an effort to promote worldwide development for the realization of the potential of EAP materials [1]. A graphic rendering of this challenge that was posed by the author is illustrated in Figure 2. Success in developing such a winning arm will lead to many important applications including the possible use of EAP to replace damaged human's muscles, i.e., making "bionic human." It will also enable biomimetic capabilities that are currently considered impossible. It would allow applying EAP materials to improve many aspects of our life where some of the possibilities include smart implants and prosthetics (also known as cyborgs), active clothing [12], realistic biologically-inspired robots [2] as well as fabricating products with unmatched capabilities.

The intent of posing this challenge was to use the human arm as a baseline for the implementation of the advances in the development of EAP materials. During the contest, which has been a significant event for the field, a 17-years old female student wrestled with three robotic arms driven by EAP. These arms were made by Environmental Robots Incorporated (ERI), New Mexico; Swiss Federal Laboratories for Materials Testing and Research, EMPA, Dübendorf, Switzerland; and three senior students from the Engineering Science and Mechanics Dept., Virginia Tech. The arms and the results were as follows:

FIGURE 2: An artistic interpretation of the Grand Challenge for the development of EAP actuated robotics.



1. The arm held for 26-second against the student. This wrestling arm (see Figure 3) had the size of an average human arm and it was made of polypropylene and Derlin. This arm was driven by two groups of artificial muscle. One group consisted of dielectric elastomeric resilient type that was used to maintain an equilibrium force and the second was composed of ionic polymer metal composites (IPMC) type strips that flex to increase or decrease the main resilient force.

FIGURE 3: The ERI arm wrestling with the 17-year old human opponent, Panna Felsen. This arm has the size of an average human arm and it held for 26-seconds against Panna.



2. The Swiss arm (Figure 4) was able to resist for 4-seconds before losing. This arm was driven by the dielectric elastomer EAP type using multi-layered scrolled actuators that were organized in 4 groups. A photo of one of the group lifting two 5-gallon water containers (about 20-kg) is shown in Figure 5. These actuators were operated similar to

human muscles, where two of these groups acted as protagonists and the other two operated as antagonists. The arm had an outer shell made of fiberglass that was used as a shield for the electric section. The arm structure was made of composite sandwich consisting of fiberglass and carbon fibers.

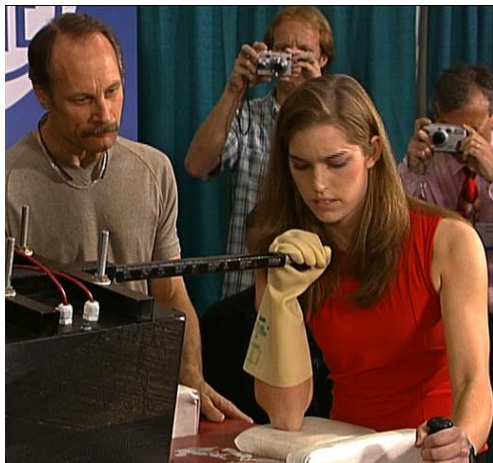


FIGURE 4: The Swiss company, EMPA, arm is shown wrestling with the student. The rubber glove that the Panna is using provided her electrical insulation for protection.



FIGURE 5: One of the groups of EMPA's EAP actuators is shown lifting two 5-gallon water containers.

3. The VT arm (Figure 6) managed to hold for 3-seconds. The EAP actuator of this arm was constructed of polyacrylonitrile (PAN) gel fiber batches. This EAP material was shown experimentally to produce close to 200% linear strain and pulling strength that is higher than human muscles [13]. To encase the fibers and chemicals that make up their EAP actuator, they designed an electrochemical cell. For the skeleton of the arm they used a structure that is made of composite material and, for support, this structure was connected to an aluminum base.

FIGURE 6: The VT students' arm wrestling with the student. Panna needed the goggles for eye protection from the chemicals that were used for their EAP material.



This contest helped in pursuing the goals of the challenge, namely:

1. Promote advances towards making EAP actuators that are superior to the performance of human muscles

2. Increase the worldwide visibility and recognition of EAP materials
3. Attract interest among potential sponsors and users
4. Lead to general public awareness since it is hoped that they will be the end users and beneficiaries in many areas including medical, commercial, etc.

Expert Opinion: Needs and Opportunities

For many years, electroactive polymers (EAP) received relatively little attention due to their limited actuation capability and the small number of available materials. In the past fifteen years, a series of new EAP materials have emerged that exhibit large displacement in response to electrical stimulation. This capability of these new materials is making EAP materials attractive as actuators for their operational similarity to biological muscles, particularly their resilience, damage tolerance, and ability to induce large actuation strains (stretching, contracting or bending). The application of these materials as actuators to drive various manipulation, mobility, and robotic devices involves multi-disciplines including materials, chemistry, electromechanics, computers, and electronics. Even though the force of actuation of existing EAP materials and their robustness require further improvement, there has already been a series of reported successes in the development of EAP-actuated mechanisms. Successful devices that have been reported include a fish-robot (described earlier), audio speakers, catheter-steering element [14], miniature manipulator and miniature gripper, active diaphragm, and dust wiper. The field of EAP has enormous potential in many application areas, and, judging from the range of inquiries that the author has received since his start in this field in 1995, it seems that almost any aspect of our lives can potentially be impacted. Some of the considered applications are still far from being practical, and it is important to tailor the requirements to the level that current materials can address. Using EAP to replace existing actuators may be a difficult challenge and therefore it is highly desirable to identify a niche application where EAP materials would not need to compete with existing technologies.

The development of an effective infrastructure for the EAP field is critical to the commercial availability of robust actuators and their use in practical applications. The challenges are enormous, but the recent trend of international cooperation, the greater visibility of the field, and the increased funding of related research offer great hope for the future of these exciting new materials. The arm-wrestling challenge of a match between an EAP-actuated robot and a human opponent highlights the potential of EAP. Progress toward overcoming this challenge will lead to great benefits to mankind. The author believes that an emergence of a niche application that addresses a critical need will significantly accelerate the transition of EAP from novelty to actuators of choice. In niche cases, these materials will be used in spite of their current limitations, taking advantage of their uniqueness.

The use of robotics contributed significantly to reduction in mortality after surgery, faster recovery and minimized complications. An example of the existing robotics is the de Vinci surgical system that is becoming a standard tool in increasing number of hospitals worldwide. Unfortunately, the current systems are quite large and do not allow for delicate surgical procedures as required, for example, in the brain. One may consider a minimally-invasive robotic arm as a surgical tool that has an octopus-configuration with multiple degrees of freedom tentacles equipped with various tools. In developing such a technology one may use beside EAP as actuators also take advantage of the capability of ElectroRheological Fluids (ERF) to become

highly viscous when subjected to electrical excitation. This property can allow controlling the rigidity of flexible robotic arms and also operate as haptic interface [1 and 11]. A graphic illustration of such a futuristic concept is shown in Figure 7 and it is biologically-inspired using the octopus tentacle structure offering capabilities that are impossible today [1, 2 and 15].

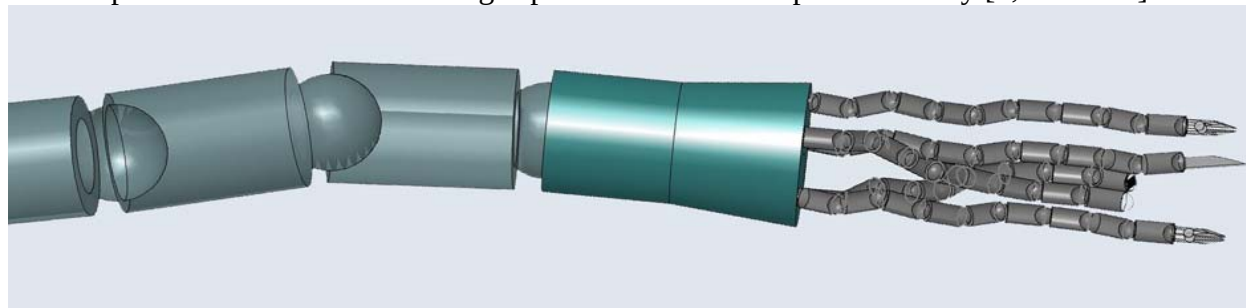


FIGURE 7: A graphic view of an octopus-configured catheter for surgical applications.

The required EAP actuators can be based on the Multifunctional Electroelastomer Roll (MER) Actuators that were developed by SRI International [16]. This actuator has a cylindrical shape and it is made of dielectric elastomers that have been demonstrated to produce 380% actuation strain. Such actuators have already exhibited high strain and moderate stress (up to 8 MPa). The response speed varies in a wide range from 1 Hz to as high as 20 kHz, depending on the type of materials and the amount of strain. One-degree-of-freedom (1-DOF), 2-DOF, and 3-DOF spring rolls have been demonstrated wherein the compliant electrodes are not patterned, are patterned on two, and are patterned on four circumferential spans, respectively.

Space applications are among the most demanding in terms of the harshness of the operating conditions, requiring a high level of robustness and durability. Making biomimetic capability using EAP material will potentially allow NASA to conduct missions in other planets using robots that emulate human operation ahead of a landing of human. For an emerging technology, the requirements and challenges associated with making hardware for space flight are very difficult to overcome. However, since such applications usually involve producing only small batches, they can provide an important avenue for introducing and experimenting with new actuators and devices. This is in contrast to commercial applications, for which issues of mass production, consumer demand and cost per unit can be critical to the transfer of technology to practical use. Some of the challenges that are facing the users of EAP materials in expanding their potential applications to space include their capability to respond at low or high temperatures. Space applications are of great need for materials that can operate down to single digit degrees of Kelvin or as high temperatures in the hundreds of Celsius as on Venus. Another challenge to EAP is the development of large scale EAP in the form of films, fibers and others. The required dimensions can be as large as several meters or kilometers and in such dimensions they can be used to produce large gossamer structures such as antennas, solar sails, and various large optical components.

In order to exploit the highest benefits from EAP, multidisciplinary international cooperative efforts need to grow further among scientists, engineers, and other experts (e.g., medical doctors, etc.). Experts in chemistry, materials science, electro-mechanics/robotics, computer science, electronics, etc., need to advance the understanding of the material behavior, as well as develop EAP materials with enhanced performance, processing techniques and applications. Effective

feedback sensors and control algorithms are needed to address the unique and challenging aspects of EAP actuators. If electrically-driven artificial muscles can be implanted into a human body, this technology can make a tremendously positive impact on many human lives.

Five-years View

The field of EAP is far from mature but advances in the various elements of the field infrastructure are expected to lead to a growing number of applications in the coming years. The development of three EAP actuated robotic arms that wrestled on March 7, 2005 with the human opponent, 17-year old female student, is a major milestone for the field. Even though the student won against the three arms the competition helped increasing the visibility of the field worldwide and the recognition of its potential. The longest to hold against the student has been the arm from ERI and it lasted for 26-seconds. To get a prospective to this major milestone for the field of EAP one may want to be aware that the first flight of the Wright brothers before over hundred years lasted only 12-seconds. While there is more needed work in order to reach the level of wining against human it is inevitable that this would happen just like the check game between the champion and the Big Blue IBM computer. Initially, the challenge is to win a wrestling match against a human (any human) using a simple shape arm with minimum functionality. However, the ultimate goal is to win against the strongest human using as close as possible as resemblance of the shape and performance of the human arm. Once such a robotic arm wins against human, it would become clear that EAP performance has reached the level that devices can be designed and produced with the many physical functions of humans with superior capability. Such a success is one of the ultimate goals of the field of biomimetics.

EAP materials that produce high actuation displacement and force are opening new avenues to bioengineering in terms of medical devices for diagnosis, treatment and assistive devices for disabled. Applications that are currently being considered include catheter steering mechanism [12], vein connectors for repair after surgery [<http://www.micromuscle.com/1024.htm> and 17], smart prosthetics [18], Braille displays [1 and 19] and others. Recent research at the Sungkyunkwan University, Korea, has led to the development of a series of mechanisms and devices that use dielectric elastomer EAP [20]. These devices include a smart pill, which is made as a tube-like structure that performs inchworm motion for traversing thru gastrointestinal track. A flexible skin of the smart pill was fabricated using a 3-D molding technique. Using dielectric EAP, these researchers in Korea are also developing Braille display for visually impaired and it is designed to be compatible with existing Braille devices. The performance of the Braille device is currently under evaluation, where blind patients are given display patterns of letters and symbols and they are asked to recognize them. The use of dielectric elastomer EAP for Braille display has also been a subject of study at SRI [16] where a simple mechanism was constructed taking advantage of the large strains and high energy density of this EAP material.

In summary it is difficult to predict what exactly will happen in the next five years but one can assume some level of success in the current exploration of applications worldwide. This include drug release mechanisms using smart peels with a shell that shrinks or expands as needed for the controlled release, catheter steering system that allows reaching various areas of the blood system as desired, active Braille displays that can possibly used as an aid in converting video images of the street helping the blind walking independently, and possibly assistive exoskeleton devices that are biologically inspired.

Key Issues

Most conventional mechanisms are driven by actuators requiring gears, bearings, and other complex components that are costly and prone to failure. Emulating biological muscles can enable various novel manipulation capabilities that are impossible today. Electroactive polymers (EAP) have emerged with the capability to mimic muscles to actuate biologically inspired mechanisms. EAP are resilient, fracture tolerant, noiseless actuators that can be made miniature, low mass, inexpensive and consume low power. EAP can potentially be used to construct 3-D systems, such as robotics, which can only be imagined as science fiction using such capabilities as inkjet printing. However, these materials are still limited by various challenges.

- No established database or standard test procedures
- Low actuation force, mechanical energy density and conversion efficiency
- Notch applications are needed where the specifications are within the EAP capability range
- The electronic EAP are limited by the need for quite high voltage while the ionic type is sensitive to contamination, and suffers electrolysis when subjected to voltages above 1.23V.
- Robustness – there are lifetime and reliability issues
- Scalability – it is not obvious how to make very large or very small EAP
- Competitiveness – there is a need for niche applications where it would not need to compete with existing technology.

Acknowledgement

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2. **Books and proceedings** <http://ndeaa.jpl.nasa.gov/nasa-nde/yosi/yosi-books.htm>
3. **WW-EAP Newsletter -** <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/WW-EAP-Newsletter.html>
4. **Armrestling Challenge -** <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-armrestling.htm>
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7. **How to make EAP:** <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/eap/EAP-recipe.htm>
8. **Biomimetics: Biologically-Inspired Technologies** <http://ndeaa.jpl.nasa.gov/nasa-nde/biomimetics/bm-hub.htm>
9. **Selected EAP videos** <http://ndeaa.jpl.nasa.gov/nasa-nde/lommas/EAP-video/EAP-videos.html>
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**VIGILANCIA TECNOLÓGICA
“MÚSCULOS ARTIFICIALES”**

APLICACIONES POLÍMEROS ELECTROACTIVOS

Prospección en el Diseño
Curso 2014-2015

Germán Bielsa Pérez
Cristina Meléndez Sancho

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INTRODUCCIÓN

El siguiente informe contiene la información relativa al apartado de aplicaciones de los Polímeros Electroactivos como actuadores, que forma parte del trabajo de vigilancia tecnológica y minería de datos sobre músculos artificiales.

En él se recogen las distintas aplicaciones o características de los distintos tipos de Polímero Electroactivos a investigar, la metodología empleada para la realización de la búsqueda de información y las conclusiones obtenidas tras el análisis y síntesis de la información.

DESARROLLO DEL EJERCICIO

Para la realización de este ejercicio se siguieron las fases del trabajo planteadas en el brief del ejercicio adaptadas a nuestras necesidades.

En primer lugar se definieron nuestras necesidades de información, que incluyen la información que necesitamos saber o los objetivos de información a conseguir que queremos para poder obtener conclusiones útiles. Se indicaron a su vez las fuentes de información que se iban a utilizar para la búsqueda de esta información y como debíamos buscar la información en las distintas fuentes.

Toda esta planificación inicial se expuso en clase para comprobar que habíamos estructurado de forma correcta la búsqueda de información y acordar con los compañeros los límites de cada trabajo y definir qué información tenía que buscar cada grupo, para aquellas partes que podían solaparse.

A partir de aquí se separó el trabajo en dos, para que cada miembro de la pareja buscara un tipo de polímero, pero con los mismos criterios de búsqueda. Se buscó en las diferentes fuentes propuestas, seleccionando solo aquella información que nos resultaba de utilidad, indicando en todo momento su referencia.

Las dos partes se pusieron en común y se estructuraron para generar un contenido lo más homogéneo posible dentro de cada tipo de polímero electroactivo.

Finalmente se realizó una última sesión de búsqueda en común para comprobar que abarcábamos la mayor cantidad de aplicaciones posibles.

Toda la fase de información se documentó realizando diversas capturas de pantalla, para mostrar cómo se realizaban las búsquedas.

Por último se redactaron las conclusiones obtenidas del trabajo y se maqueto toda la información en un dossier.

QUÉ QUEREMOS SABER - NECESIDADES DE INFORMACIÓN

Tipos de PEA

Donde y para qué se están utilizando los PEA

Qué características de cada tipo de PEA lo hace útil en su aplicación / Las prestaciones de los diferentes PEA

Posibles aplicaciones en un futuro

DÓNDE LO ENCONTRAREMOS - FUENTES DE INFORMACIÓN

LIBROS

Google Books (Texto e Imagen): Buscador dentro de una base de libros, que permite previsualizar ciertas partes de cada libro.

Aunque los libros no se pueden leer de forma completa muchos pueden ser útiles para ver los tipos de PEAs existentes o cómo están organizados.

ARTÍCULOS CIENTÍFICOS

Alcorze (Texto e Imagen): Herramienta con acceso a la mayoría de los recursos de información en la colección de la BUZ, tanto de fuentes internas como externas, en formato impreso o electrónico.

Esta es la fuente principal de información, puesto que proviene de fuentes fiables y contrastadas con toda la información necesaria.

Google academics (Texto): Google Académico te permite buscar bibliografía especializada de una manera sencilla. Podrás realizar búsquedas en tesis, artículos de editoriales académicas, sociedades profesionales, universidades y otras organizaciones académicas.

A pesar de buscar la información en fuentes académicas, muchas de ellas no se encuentran disponibles para su visualización online del texto entero, aunque pueden servir de referencia para buscar en Alcorze.

PÁGINAS WEB

Google (Texto, Imagen y Vídeo): El motor de búsqueda más utilizado en la web, que permite buscar texto dentro de las páginas web que tenga indexadas.

Este es el primer objetivo de búsqueda puesto que nos da una visión general de la información disponible en Internet y permite buscar en todas las páginas web disponibles. Hay que tener cuidado con la información encontrada.

YouTube (Vídeo): Es el portal de vídeos más popular y usado de Internet.

Permite ver de forma visual el funcionamiento y aplicaciones de los polímeros e incluso aportar información valiosa sobre estos.

Google imágenes (Imagen): *Es un buscador especializado en imágenes en aquellas páginas que contienen información sobre la búsqueda realizada.*

Fuente imprescindible para ilustrar las diversas aplicaciones y la forma de utilizarlos.

Wikipedia (Texto e Imagen): *Es una enciclopedia Online y colaborativa, que contiene multitud de artículos redactados y corregidos por la comunidad.*

Actualmente la página web para buscar información número 1 de referencia. Aquí se puede consultar información genérica sobre los tipos de PEAs con referencias a artículos científicos.

AUTORES

Yoseph Bar-Cohen (Texto): *Físico especializado en polímeros electroactivos, sus esfuerzos le llevaron a organizar la conferencia anual sobre polímeros electroactivos y escribir multitud de artículos y libros sobre estos temas, los cuales han sido ampliamente citados por investigadores posteriores.*

Sus artículos van a ser una fuente valiosa de información dado su conocimiento genérico de estos materiales y por ser el mayor experto en este tema.

Toribio Fernández Otero (Texto): *Científico español y referente mundial en investigación sobre polímeros conductores y sus aplicaciones electroquímicas en músculos artificiales, ventanas inteligentes, membranas adaptables o interfases nerviosas.*

Es uno de los mayores expertos en estos materiales y en español, lo que es una ventaja añadida.

CÓMO LO HEMOS ENCONTRADO - CRITERIOS DE BÚSQUEDA



Directo a la información

Buscando: AlcorZe

Palabra clave

[Opciones de búsqueda](#) [Búsqueda básica](#) [Búsqueda avanzada](#) [Historial de búsqueda](#)

No se encontraron resultados.

Tras comprobar que la búsqueda en español en Alcorze no devolvía ningún resultado, se realizó la búsqueda en inglés

AlcorZe Buscando: AlcorZe

Palabra clave

[Búsqueda básica](#) [Búsqueda avanzada](#) [Historial de búsqueda](#)

Resultados de la búsqueda: 1 a 20 de 6,316

1. **Optimal control of electrorheological fluids through the action of**

By: De Los Reyes, J.C.; Yousept, I. Computational Optimization and Applications, In f Kluwer Academic Publishers DOI: 10.1007/s10589-014-9705-5, Base de datos: Sco

Materias: Control in coefficients; Electrorheological fluids; Electrostatic potential; Op

Publicación académica [Pedir al Servicio de Obtención de Documentos](#)

2. **Non-contact piezoelectric rotary motor modulated by giant electrorheological**

La búsqueda en inglés aportó más resultados, algunos irrelevantes para el trabajo, por lo que se redujo el número de resultados indicando que solo nos interesaban aquellos que hablaran sobre aplicaciones y los que estuviesen disponibles para leer online

AlcorZe Buscando: AlcorZe

Palabra clave

[Búsqueda básica](#) [Búsqueda avanzada](#) [Historial de búsqueda](#)

Resultados de la búsqueda: 1 a 20 de 564

1. **Optically transparent electrorheological fluid with urea-modified silica haptic display application**

By: Liu, Y.D.; Lee, B.M.; Kim, J.E.; Choi, H.J.; Park, T.-S.; Booh, S.W. Journal of Colloid and Interface Science DOI: 10.1016/j.jcis.2013.05.012, Base de datos: Scopus®

Materias: Display; Electrorheological fluid; Haptic; Silica; Transparent; Urea; Yield stress

Cantidad de veces que se cita en Scopus®: (2)

☒ Texto completo UZ

2. **Electrorheological Fluids: Mechanisms, Dynamics, and Microfluidics**

By: Sheng, Ping; Wen, Weijia. Annual Review of Fluid Mechanics. Jan2012, Vol. 44, p143-171 DOI: 10.1016/j.annrvm.2012.01.004

Materias: ELECTORHEOLOGICAL fluids; FLUID mechanics; FLUID dynamics; HYDROSTATICS



Directo a la información

Buscando: AlcorZe

Palabra clave

Opciones de búsqueda [Búsqueda básica](#) [Búsqueda avanzada](#) [Historial de búsqueda](#)

No se encontraron resultados.

Para la gran mayoría de casos se repitieron las búsquedas nulas en español. Aunque las búsquedas en inglés sí que aportaban buenos resultados

Buscando: AlcorZe

Palabra clave

[Búsqueda básica](#) [Búsqueda avanzada](#) [Historial de búsqueda](#)

Resultados de la búsqueda: 1 a 20 de 442 Rele

1. **Mechanics and actuation properties of bucky gel-based electroact**
By: Ceseracciu, L.; Barone, A.C.; Biso, M.; Ansaldo, A.; Ricci, D.; Futaba, D.N.; Hata, K. 156(2):949-953 Language: English. DOI: 10.1016/j.snb.2011.03.012. Base de datos:
Materias: Carbon nanotubes; Composite material; Electrochemical actuators
Publicación académica [Texto completo UZ](#) [Ver revista en el catálogo](#) [Exportación a Refw](#)

2. **Improving electroactive polymer actuator by tuning ionic liquid co**
By: Kwon, Kye-Si; Ng, Tse Nga. *Organic Electronics*. Jan2014, Vol. 15 Issue 1, p294-2
Materias: ELECTROACTIVE polymer actuators; IONIC liquids; DISPLACEMENT (Mech colloids; POLYELECTROLYTES
Publicación académica [Texto completo UZ](#) [Ver revista en el catálogo](#) [Exportación a Refw](#)

Depurar los resultados

Búsqueda actual

Buscar todos mis términos:
[gel electroactive polymer](#)

Limitadores
☒ Texto completo (en línea)

Limitar a

☒ Texto completo (en línea)

Si la cantidad de artículos encontrados era muy grande se limitaba la búsqueda a las aplicaciones de aquellos polímeros utilizados como actuadores

Buscando: AlcorZe

Palabra clave

[Búsqueda básica](#) [Búsqueda avanzada](#) [Historial de búsqueda](#)

Resultados de la búsqueda: 1 a 20 de 31 R

1. **Electroactive polymer actuators as artificial muscles: are they applications?**
Carpí, F.; Kornbluh, R.; Sommer-Larsen, P.; Alici, G. *BIOINSPIRATION & BIOMIMET Index*
Materias: METAL COMPOSITES; BIOMIMETIC SENSORS; GEL; TRANSDUCERS; I FIELD; ELECTROSTRICTION; ENGINEERING, MULTIDISCIPLINARY; MATERIALS
Cantidad de veces que se cita en Web of ScienceSM: (10)
[Texto completo UZ](#) [Ver revista en el catálogo](#) [Exportación a Refw](#)

2. **Ionic liquid/polyurethane/PEDOT:PSS composites for electro-acti**
By: Okuzaki, Hidenori; Takagi, Satoshi; Hishiki, Fumiya; Tanigawa, Ryo. *Sensors & DOI: 10.1016/j.snb.2013.12.059*

Depurar los resultados

Búsqueda actual

Buscar todos mis términos:
[gel electroactive polymer actuator application](#)

Limitadores
☒ Texto completo (en línea)

Limitar a

☒ Texto completo (en línea)

Buscando: AlcorZe

Palabra clave: CNT actuator applications

Buscar Crear alerta

Búsqueda básica Búsqueda avanzada Historial de búsqueda

Depurar los resultados

Búsqueda actual

Buscar todos mis términos:

CNT actuators applications

Limitadores

Texto completo (en línea)

Limitar a

Texto completo (en línea)

Resultados de la búsqueda: 1 a 20 de 319

1. Interfacial durability and electrical properties of CNT or ITO/PVDF nan sensor and micro actuator applications

Park, JM; Gu, GY; Wang, ZJ; Kwon, DJ; DeVries, KL. *APPLIED SURFACE SCIENCE*; DE Citation Index

Materiales: Actuator; Sensing; Durability; Wettability; CARBON NANOTUBES; COMPOSIT MATERIALS SCIENCE, COATINGS & FILMS; PHYSICS, APPLIED; PHYSICS, CONDENS

Publicación académica

Texto completo UZ Ver revista en el catálogo Exportación a Refworks

2. 3D porous CNT/MnO₂ composite electrode for high-performance enzy detection and supercapacitor application

By: Guo, C.; Zhang, X.; Huo, H.; Xu, C.; Li, H. *Sensors and Actuators, B: Chemical*, Janu

Los criterios de búsqueda que mejor funcionaron se reutilizaron adaptándolos a cada búsqueda

Buscando: AlcorZe

CNT actuators applications

Seleccione un camp...

Buscar Crear alerta Borrar

NOT sensor

Seleccione un camp...

AND

Seleccione un camp...

Búsqueda básica Búsqueda avanzada Historial de búsqueda

Depurar los resultados

Búsqueda actual

Buscar todos mis términos:

CNT actuators applications

NOT sensor

Limitadores

Texto completo (en línea)

Limitar a

Texto completo (en línea)

Resultados de la búsqueda: 1 a 20 de 48

1. Interfacial durability and acoustical properties of transparent graphene nano pl (vinylidene fluoride) composite actuators

Park, JM; Gu, GY; Wang, ZJ; Kwon, DJ; DeVries, KL. *THIN SOLID FILMS*, JUL 31, 2013; 539; p350-p31

Materiales: Actuator; Sensing; Durability; Wettability; TRANSDUCERS; PERFORMANCE; MATERIALS SCIENCE, COATINGS & FILMS; PHYSICS, APPLIED; PHYSICS, CONDENSED MATTER

Publicación académica

Texto completo UZ Ver revista en el catálogo Exportación a Refworks

2. Nanocarbon based ionic actuators—a review.

By: Kosidlo, U.; Omastová, M.; Micsuk, M.; Čirić-Marjanović, G.; Randriamahazaka, H.; Wallmersperger, T. *Smart Materials & Structures*, Oct2013, Vol. 22 Issue 10, p104022-104051, 30p. Publisher: IOP Publ

En algunas ocasiones se utilizaban criterios para discriminar artículos cuyo contenido no era relevante o de interés para el trabajo

Google

cnt actuator application

Web Imágenes Shopping Videos Noticias Más Herramientas de búsqueda

Aproximadamente 219.000 resultados (0,28 segundos)

Artículos académicos para cnt actuator application

... elastomers as next generation polymeric actuators - Smartkar - Citado por 175

Polymer artificial muscles - Mirfakhrai - Citado por 282

... carbon nanotubes: New electromechanical actuators - Courty - Citado por 128

También se realizaron búsquedas en google, teniendo siempre precaución en que la información encontrada estuviese contrastada y aprovechando las búsquedas en Academics

Se comprobaban distintas formas de búsqueda para comprobar cual reflejaba resultados más relevantes

The first screenshot shows a search for 'IPMC' with 1,432 results. The second screenshot shows a search for 'IPMC actuador' with 677 results. The third screenshot shows a search for 'IPMC actuador application' with 56 results. In the third screenshot, the 'Búsqueda actual' sidebar is visible, showing the search terms 'IPMC actuador application' and 'Limitadores: Texto completo (en línea)', 'Materia: actuators'. A red circle highlights the 'Búsqueda actual' sidebar. The results list shows two items: 1. 'An IPMC-enabled bio-inspired bending/twisting fin for underwater' and 2. 'Recent advances in ionic polymer-metal composite actuators and applications'.

AlcorZe Buscando: AlcorZe
Palabra clave: IPMC Buscar Crear alerta
Búsqueda básica Búsqueda avanzada Historial de búsqueda

Depurar los resultados Resultados de la búsqueda: 1 a 20 de 1,432

AlcorZe Buscando: AlcorZe
Palabra clave: IPMC actuador Buscar Crear alerta
Búsqueda básica Búsqueda avanzada Historial de búsqueda

Depurar los resultados Resultados de la búsqueda: 1 a 20 de 677

AlcorZe Buscando: AlcorZe
Palabra clave: IPMC actuador application Buscar Crear alerta
Búsqueda básica Búsqueda avanzada Historial de búsqueda

Depurar los resultados Resultados de la búsqueda: 1 a 20 de 56

Búsqueda actual
Buscar todos mis términos:
IPMC actuador application
Limitadores
Texto completo (en línea) x
Materia
actuators x

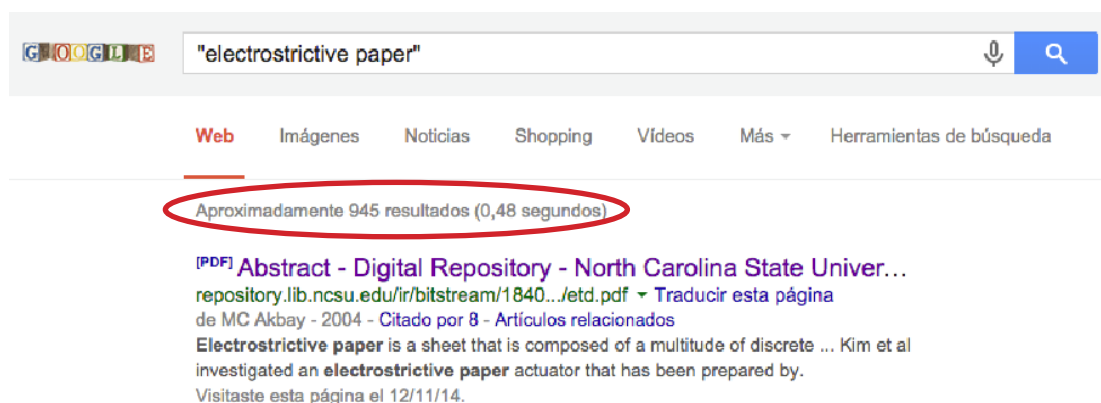
1. An IPMC-enabled bio-inspired bending/twisting fin for underwater
Palmre, V; Hubbard, JJ; Fleming, M; Pugal, D; Kim, S; Kim, KJ; Leang, KK. SMART Base de datos: Science Citation Index
Materias: POLYMER-METAL COMPOSITE; ARTIFICIAL MUSCLES; ACTUATORS; SENSORS; INSTRUMENTS & INSTRUMENTATION; MATERIALS SCIENCE, MULTIDISCIPLINARY
Cantidad de veces que se cita en Web of Science™: (3)
Texto completo UZ Ver revista en el catálogo Exportación a RDS

2. Recent advances in ionic polymer-metal composite actuators and applications.
By: Jo, Choonhee; Pugal, David; Oh, Il-Kwon; Kim, Kwang J.; Asaka, Kinji. Progress in Materials Science

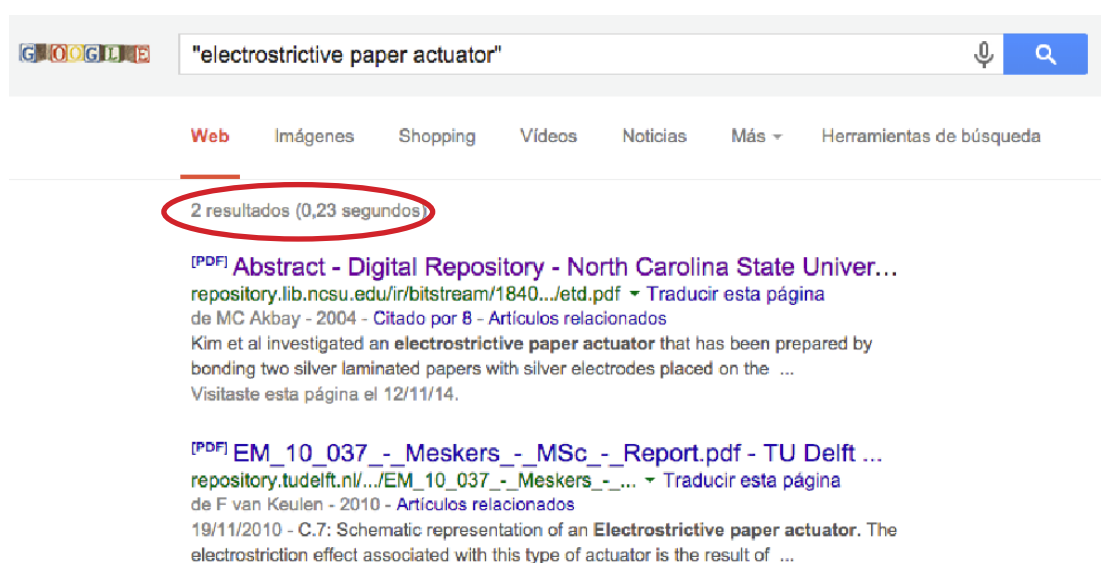
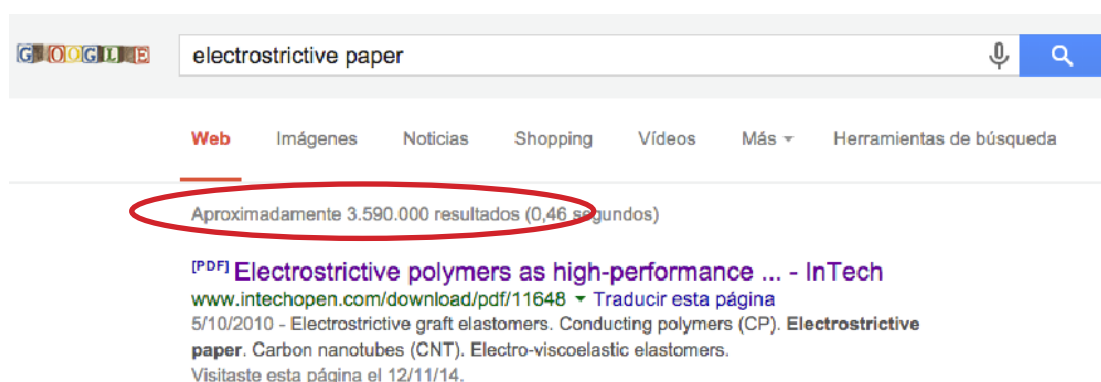
AlcorZe Buscando: AlcorZe
IPMC actuador applications Seleccione un camp... Buscar Crear alerta Borrar
NOT sensors Seleccione un camp...
AND Seleccione un camp... + -
Búsqueda básica Búsqueda avanzada Historial de búsqueda

Depurar los resultados Resultados de la búsqueda: 1 a 20 de 77 Relevancia 0

Algunos resultados al intentar acceder al documento en línea, arrojaban error en el servidor y no se pudieron consultar



A la hora de realizar las búsquedas en google de los distintos tipos de polímeros electroactivos es importante utilizar las comillas para buscar únicamente aquellos documentos que hablan del material exacto



Google  

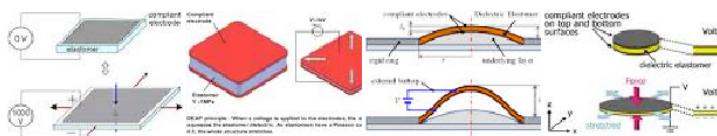
Web Imágenes Vídeos Shopping Noticias Más ▾ Herramientas de búsqueda

Aproximadamente 259.000 resultados (0,27 segundos)

Artículos académicos para dielectric elastomer actuators

Dielectric elastomer actuators - Kofod - Citado por 201
 ... -scale failure modes of **dielectric elastomer actuators** - Plante - Citado por 282
 ... and simulation of **dielectric elastomer actuators** - Wissler - Citado por 147

Imágenes de dielectric elastomer actuators Informar sobre las imágenes



Más imágenes de dielectric elastomer actuators

No es lo mismo buscar aplicaciones que buscar su uso como actuadores, puesto es solo una de sus posibilidades de uso

Google  

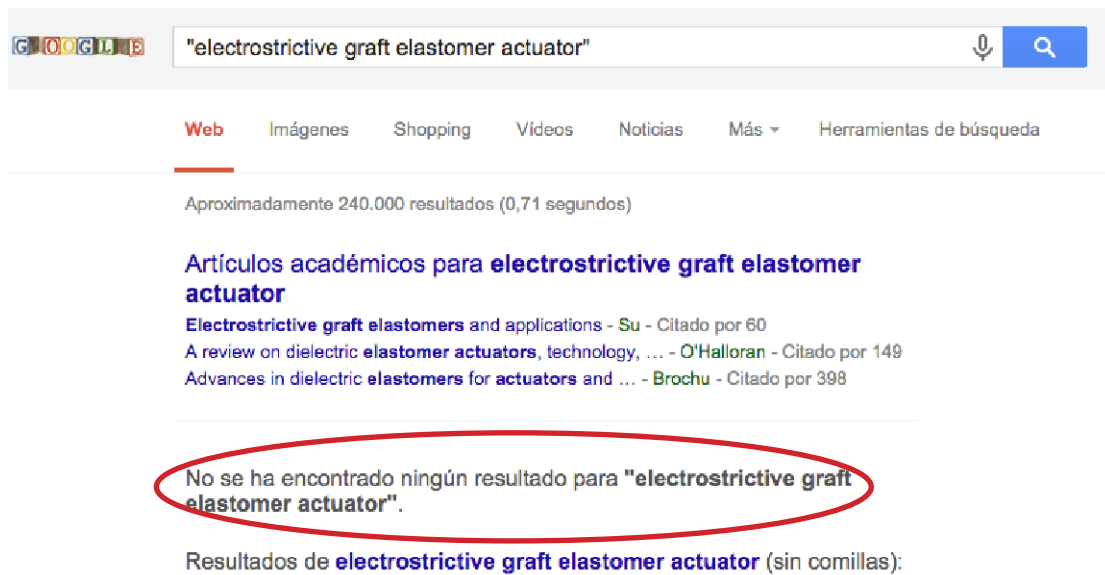
Web Vídeos Imágenes Shopping Noticias Más ▾ Herramientas de búsqueda

Aproximadamente 459.000 resultados (0,39 segundos)

Artículos académicos para dielectric elastomer applications

Dielectric elastomers as electromechanical transducers ... - Carpi - Citado por 376
 Electroelastomers: **applications of dielectric elastomer** ... - Kornbluh - Citado por 180
 Topic 1 Introduction - Bar-Cohen - Citado por 1564

Dielectric elastomers - Wikipedia, the free encyclopedia
en.wikipedia.org/wiki/Dielectric_elastomers ▾ Traducir esta página
 Ir a **Applications** - Applications[edit]. Dielectric elastomers offer multiple potential **applications** with the potential to replace many electromagnetic ...
 Has visitado esta página 2 veces. Fecha de la última visita: 11/11/14.



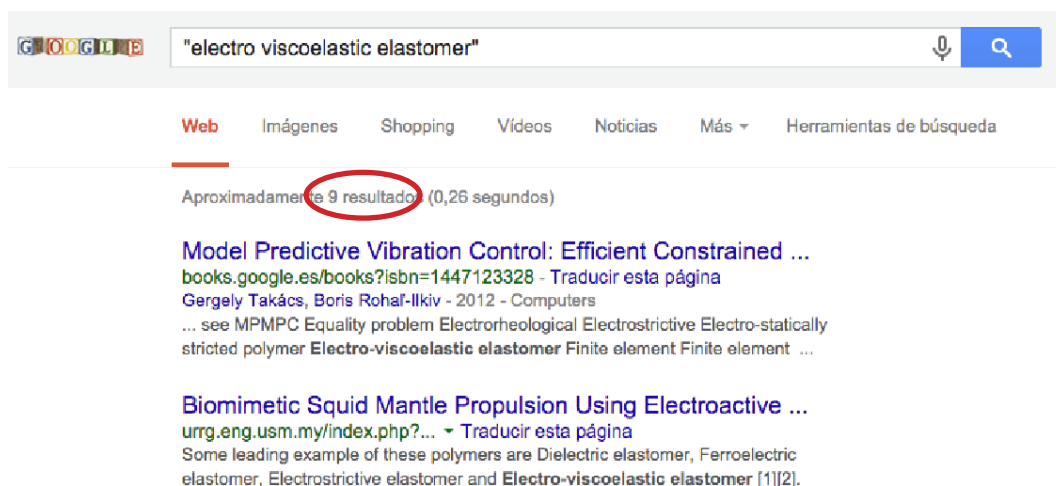
Google search results for "electrostrictive graft elastomer actuator". The search bar shows the query. Below the search bar, the results are categorized by tabs: Web, Imágenes, Shopping, Vídeos, Noticias, Más, and Herramientas de búsqueda. The results show approximately 240,000 results in 0.71 seconds. The first section is titled "Artículos académicos para electrostrictive graft elastomer actuator" and lists three academic articles. Below this, a red oval highlights the message: "No se ha encontrado ningún resultado para 'electrostrictive graft elastomer actuator'". Below the oval, it says "Resultados de electrostrictive graft elastomer actuator (sin comillas):".

También hay que tener cuidado con el uso de comillas pues pueden limitar la búsqueda cuando sobre lo que se busca no hay demasiada información o está dispersa



Google search results for "electro-viscoelastic elastomer actuator". The search bar shows the query. Below the search bar, the results are categorized by tabs: Web, Shopping, Imágenes, Vídeos, Noticias, Más, and Herramientas de búsqueda. The results show approximately 403,000 results in 0.67 seconds. The first section is titled "Artículos académicos para electro-viscoelastic elastomer actuator" and lists three academic articles. Below this, a red oval highlights the message: "No se ha encontrado ningún resultado para 'electro-viscoelastic elastomer actuator'". Below the oval, it says "Resultados de electro-viscoelastic elastomer actuator (sin comillas):".

Muchas de las búsquedas en google aportaban muy pocos resultados, con lo que se pasaba a buscar en artículos científicos desde Alcorze



Google search results for "electro viscoelastic elastomer". The search bar shows the query. Below the search bar, the results are categorized by tabs: Web, Imágenes, Shopping, Vídeos, Noticias, Más, and Herramientas de búsqueda. The results show approximately 9 results in 0.26 seconds. The first section is titled "Model Predictive Vibration Control: Efficient Constrained ..." and lists two articles. Below this, it says "Biomimetic Squid Mantle Propulsion Using Electroactive ...".

Se realizaron además búsquedas entrando por aplicaciones concretas de polímeros electroactivos para asegurarnos de que nada se pasara por alto. Para algunos casos era más práctico buscar una aplicación determinada en lugar de buscar el material que se empleaba para ella



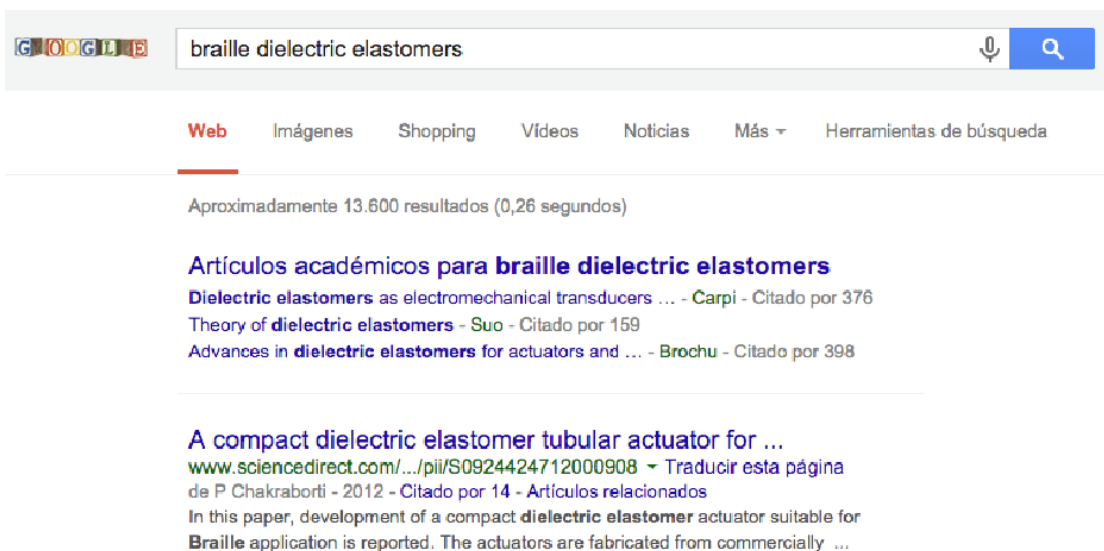
Google search results for "haptic feedback dielectric elastomers".

Aproximadamente 18.900 resultados (0,24 segundos)

Artículos académicos para haptic feedback dielectric elastomers

Dielectric elastomers as electromechanical transducers ... - **Carpi** - Citado por 376
 ... and stretchable electrodes for **dielectric elastomer** ... - **Rosset** - Citado por 51
Dielectric elastomer actuators for **tactile** displays - **Matysek** - Citado por 21

Dielectric Elastomer Actuators for Tactile Displays - IEEE ...
ieeexplore.ieee.org/iel5/4805587/.../04810822.pdf?... Traducir esta página
 de M Matysek - 2009 - Citado por 21 - Artículos relacionados
 KEYWORDS: **dielectric elastomer** actuator, (vibro-)tactile display, self-sensing, tactile
 ... Furthermore, **tactile feedback** improves haptic impression in virtual reality ...



Google search results for "braille dielectric elastomers".

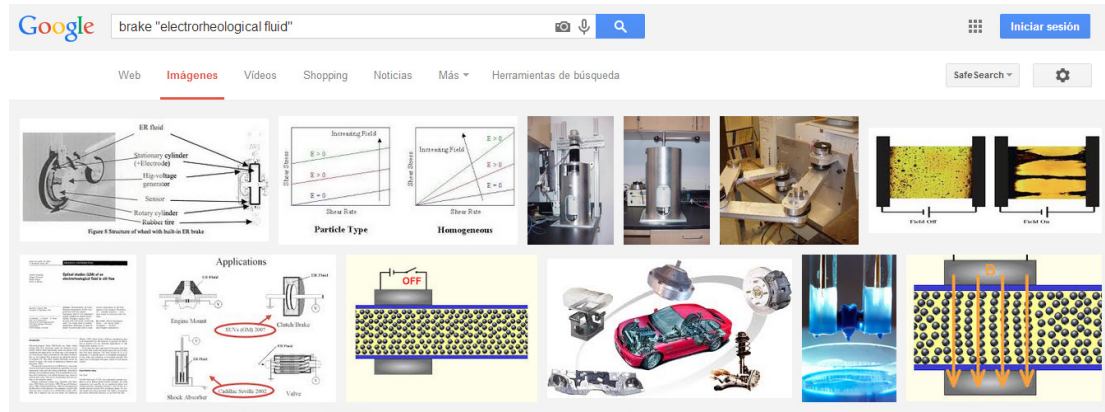
Aproximadamente 13.600 resultados (0,26 segundos)

Artículos académicos para braille dielectric elastomers

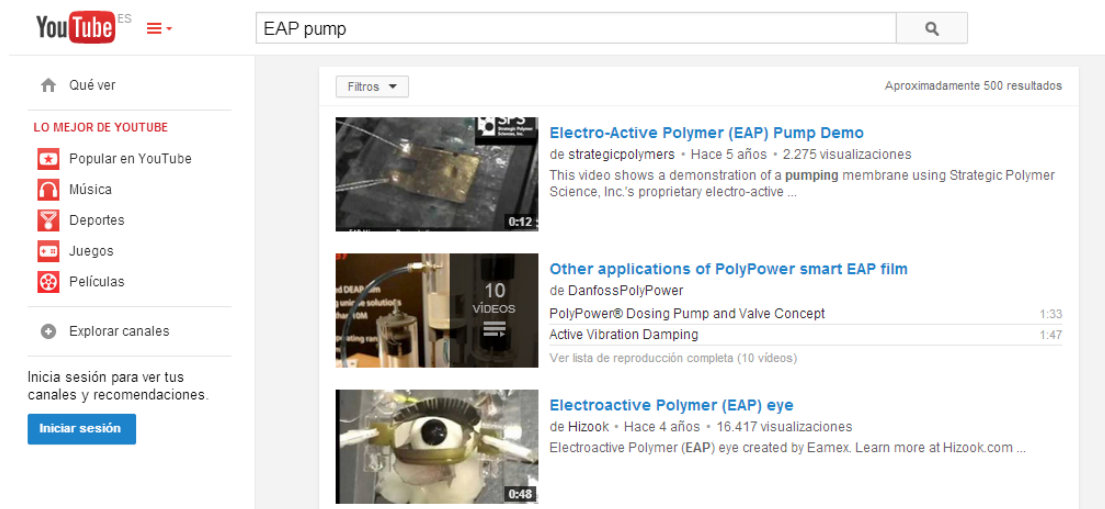
Dielectric elastomers as electromechanical transducers ... - **Carpi** - Citado por 376
 Theory of **dielectric elastomers** - **Suo** - Citado por 159
 Advances in **dielectric elastomers** for actuators and ... - **Brochu** - Citado por 398

A compact dielectric elastomer tubular actuator for ...
www.sciencedirect.com/.../pii/S0924424712000908 Traducir esta página
 de P Chakraborti - 2012 - Citado por 14 - Artículos relacionados
 In this paper, development of a compact **dielectric elastomer** actuator suitable for **Braille** application is reported. The actuators are fabricated from commercially ...

Para ilustrar las aplicaciones encontradas, en caso de que no vinieran imágenes se utilizaban la búsquedas en google imágenes para tener ilustraciones explicativas



También se aprovecharon los vídeos de Youtube, aunque en muchos no se incluía el tipo de PEA utilizado, se podía observar de forma visual el funcionamiento de estos polímeros



TIPOS	CLASIFICACIÓN	VENTAJAS	INCONVENIENTES	APLICACIONES
PEA Eléctricos	Polímeros dieléctricos	Funcionamiento a temperatura ambiente durante tiempos largos	Requiere altos voltajes (200 V/nm)	Dispositivos robóticos como músculos artificiales
	Polímeros ferroeléctricos	Respuesta rápida (ms)	Independiente de la polaridad de la tensión	Dispositivos industriales como válvulas, bombas y amortiguadores
	Elastómeros de cristal líquido	Inducen relativamente grandes fuerzas de accionamiento		Dispositivos electrónicos como altavoces, retroalimentación háptica y muestras de braille
	Elastómeros electrostrictivos de injerto	Pueden aguantar la tensión bajo la activación de la corriente continua		Dispositivos médicos como prótesis y vendajes activos
	Elastómeros electro-viscoelásticos			
	Papel electrostrictivo			
	PEA Iónicos	Geles de polímero iónico	Accionamiento bi-direccional que depende de la polaridad de la tensión	Requieren del uso de un electrolito
Compuestos polímero metálicos ionoméricos		Requieren bajo voltaje	Requieren de encapsulación o capa protectora para operar al aire libre	Microfluidos
Polímeros conductores		Algunos (conductores) tienen una capacidad única de bi-estabilidad	Baja eficiencia de acoplamiento electromecánico	Dispositivos electrónicos como altavoces o retroalimentación háptica
Nanotubos de carbono			Respuesta lenta (fracción de segundo)	Dispositivos industriales como válvulas, bombas, amortiguadores y frenos
Fluidos electroreológicos			El material se dobla con una relativa baja fuerza de actuación	Dispositivos médicos como prótesis y diversos tratamientos para incontinencia, apnea y marcapasos
			Bajo rendimiendo	
		En sistemas acuosos se produce hidrólisis a > 1.23 V		

POLÍMEROS DIELECTRICOS

De entre los requisitos de un material elastómero para su aplicación en polímeros dieléctricos se encuentran la baja rigidez del material, la alta constante dieléctrica y la alta resistencia a la ruptura eléctrica.

Una posibilidad para mejorar la resistencia a la ruptura eléctrica es el estiramiento previo de la película de elastómero mecánicamente. [1]

Poseen propiedades destacadas de elongación, alta densidad de energía elástica, eficiencia y velocidad de respuesta. Son ligeros, económicos y han exhibido un buen desempeño en demostraciones de laboratorio. [2] [3] [4]

Los actuadores de elastómeros dieléctricos muestran aplicaciones prometedoras en robótica y mecatrónica. La configuración de los polímeros dieléctricos para actuadores es la cilíndrico/rollo. Se enrollan dos capas de elastómero dieléctrico formando cilindros compactos. La aplicación de tales actuadores cilíndricos son accionadores para mecanismos robóticos y protésicos, válvulas, bombas y, en general, cuanto requiera un simple movimiento lineal. [1] [5] [6]

Los elastómeros dieléctricos ofrecen múltiples aplicaciones con el potencial de reemplazar a muchos actuadores electromagnéticos, neumáticos y piezoeléctricos.

Se están desarrollando sistemas de mejora de la experiencia táctil en videojuegos y móviles, nuevos elementos que, situados en la pantalla del ordenador ofrecen distintas sensaciones dependiendo de lo que pulsemos, y que en un futuro harán de la comunicación táctil un sistema más completo. [7]

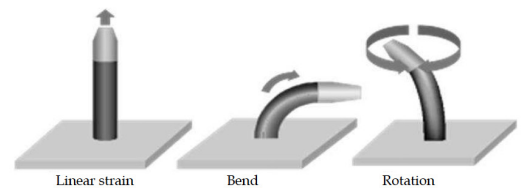
Han desarrollado un sistema de visualización braille a pantalla completa además de nuevas pulseras braille para viajar en tren que indican a los invidentes toda la información necesaria para que puedan viajar de forma independiente. [8] [9]

Con la utilización de músculos artificiales también se podrían controlar lentes de cámaras fotográficas (nueva patente de Apple) y hasta sustituir el músculo afectado del párpado en caso de lesiones. [10] [11] [12]

APLICACIONES

Retroalimentación háptica (a)
Músculos artificiales (b)
Posicionadores ópticos como para enfoque automático, zoom, estabilizador de imagen (c)
Muestras de braille activas (d)
Bombas
Válvulas
Prótesis
Control activo de vibraciones de las estructuras
Altavoces
Ventanas con anulación de ruido
Motores

3 grados de libertad



[Video de demostración óptica](#)

[Video de demostración braille](#)

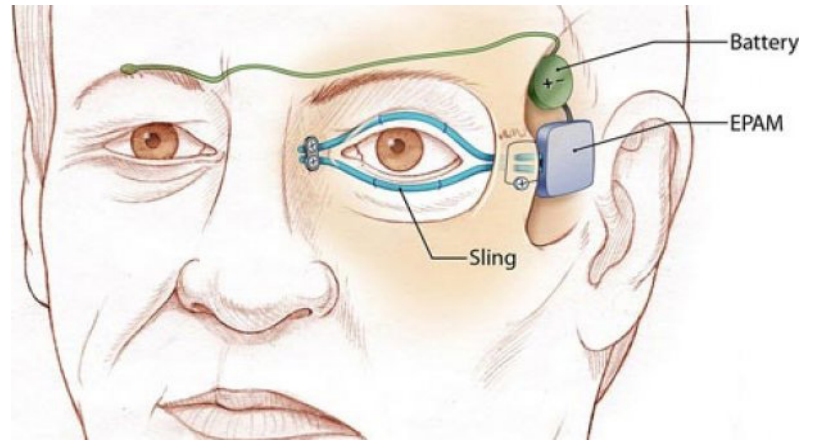
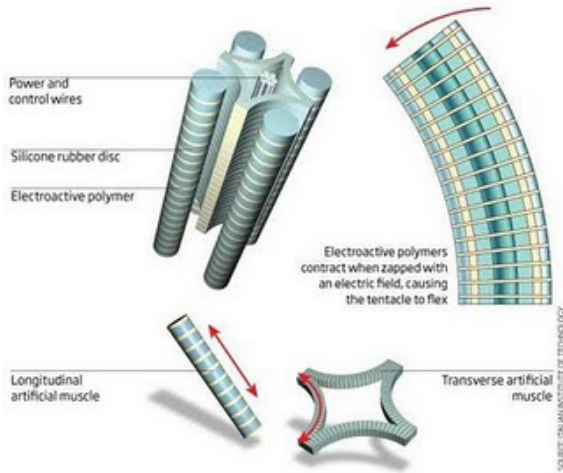
[Video de demostración braille](#)

[Video de demostración motor](#)

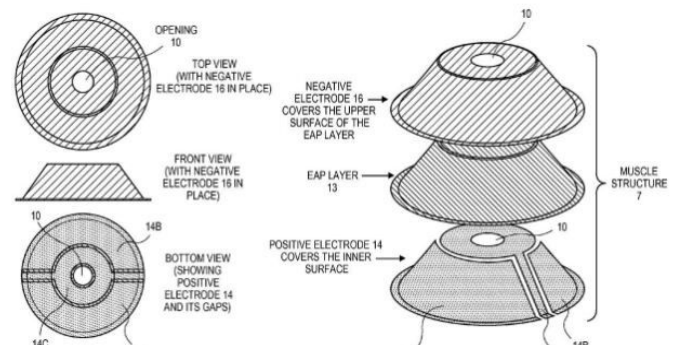
b)

Artificial tentacles

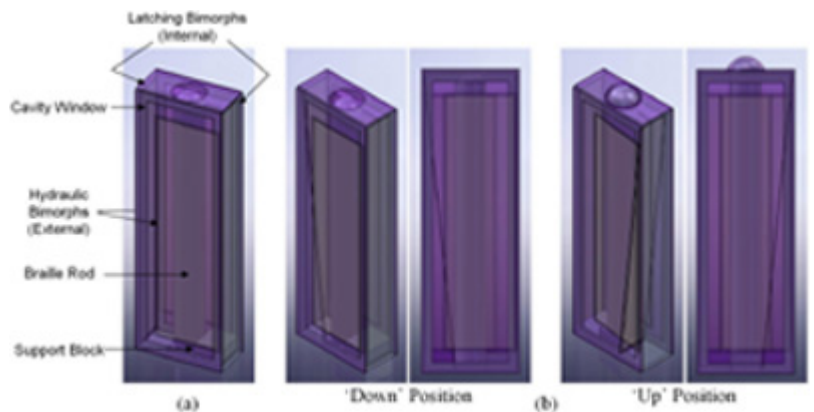
The structure of octopus arms can be reproduced using artificial muscles made of silicone rubber interspersed with electroactive polymers



c)



d)



POLÍMEROS FERROELÉCTRICOS

Los materiales poliméricos ferroeléctricos como el polifluoruro de vinilideno o PVDF y sus copolímeros presentan gran número de aplicaciones industriales.

Los polímeros ferroeléctricos presentan dos propiedades destacables, la piezoelectricidad y la piroelectricidad, que potencian enormemente su aplicabilidad industrial, especialmente para el desarrollo de sensores, pero también para la obtención de actuadores en base al efecto piezoeléctrico inverso (lo que a nosotros nos ocupa)

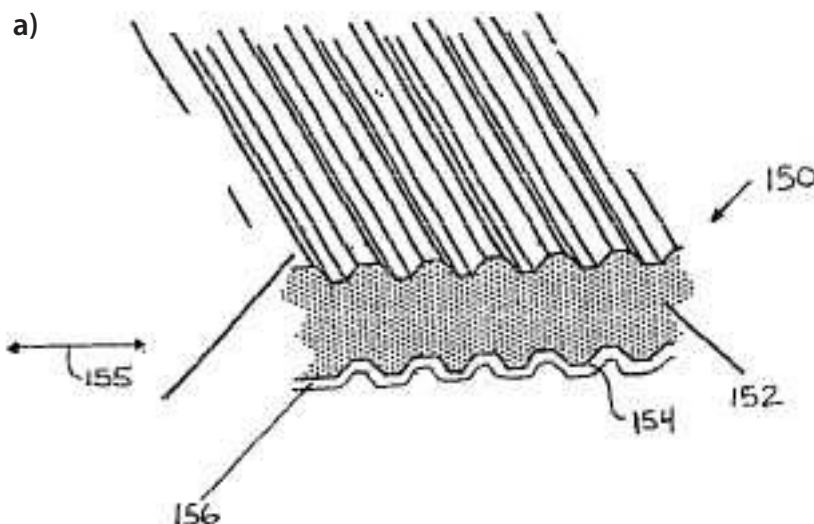
La piezoelectricidad, o polarización como respuesta a tensiones mecánicas, está basada en la deformación bajo carga de estos materiales, que va acompañada de un desplazamiento de cargas que genera polarización en una dirección. Cuando un polímero ferroeléctrico es puesto bajo un campo eléctrico, cambia su forma. [13]

El polifluoruro de vinilideno tiene una alta resistencia eléctrica, buena resistencia a la llama y baja impedancia acústica, permitividades y conductividad térmica. [14] [15]

Los polímeros ferroeléctricos, se utilizan en transductores acústicos (transforman la corriente en vibraciones sonoras) y actuadores electromecánicos debido a su respuesta piezoeléctrica inherente. Se han demostrado de gran potencial, transductores suaves en forma de espumas como altavoces y dispositivos ultrasónicos. [15] [16] [17] [18]

APLICACIONES

Transductores electroacústicos (a)
Altavoces
Dispositivos ultrasónicos
Actuadores electromecánicos



ELASTÓMEROS DE CRISTAL LÍQUIDO (LCE)

Los elastómeros de cristal líquido se alargan en presencia de orden nemático, y reversiblemente se contraen cuando el orden se pierde (normalmente por calentamiento, aunque también por la iluminación o absorción de disolvente).

Se han desarrollado nuevos elastómeros con cristal líquido que imitan la acción de un músculo. Mediante el calentamiento de la película a través de la transición de fase nemática a isotrópica se puede lograr la contracción uniaxial de la película del material. [19] [20]

Se caracterizan por su excelente capacidad de actuación y su elevado grado de deformación mecánica mediante la aplicación de un campo eléctrico (se pueden lograr cambios de hasta 500%)

Sus principales ventajas son la capacidad de actuación mejorada, lo que se traduce en una mejora de su resistencia a la ruptura dieléctrica, y la posibilidad de escalado industrial ya que estos materiales se procesan mediante métodos convencionales de procesamiento de elastómeros.

El Consejo Superior de Investigaciones Científicas (CSIC), ha desarrollado una nueva familia de actuadores basados en una matriz elastomérica en la que se encuentra disperso un cristal líquido en forma de gotas. Estos actuadores responden de modo reversible y controlable ante un estímulo externo llegando en algunos casos a mejorar hasta 10 veces la capacidad de actuación con respecto a la matriz base y vencen limitaciones de voltajes al presentar porcentajes de actuación mejorados aún a bajos voltajes.

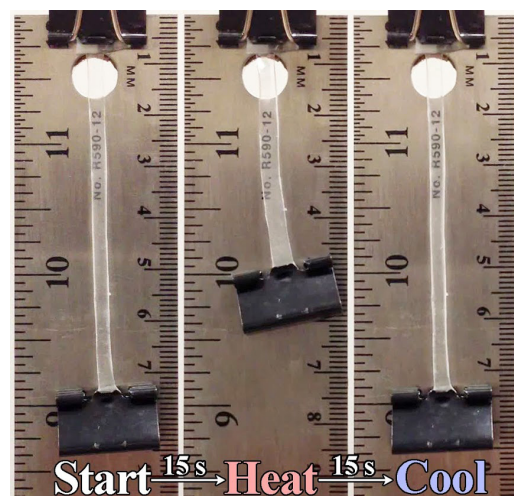
Estos actuadores son idóneos para la fabricación de dispositivos robóticos, electrónicos, industriales y/o componentes biomédicos.

Los elastómeros de cristal líquido pueden ser aplicados en dispositivos industriales tales como microválvulas o brazos articulados; dispositivos electrónicos tales como altavoces ultraplano o posicionadores de lente; componentes biomédicos tales como prótesis o vendajes activos. [21] [22] [23]

APLICACIONES

Dispositivos industriales
Microválvulas
Brazos articulados
Dispositivos electrónicos
Altavoces ultraplano
Posicionadores de lente
Componentes biomédicos
Prótesis
Vendajes activos

[Vídeo de demostración](#)



Ciclo reversible de un actuador LCE moldeado en forma de cúpula aplanándose mediante calentamiento en la transición a la fase isotrópica [24]



ELASTÓMEROS ELECTROESTRICTIVOS DE INJERTO

La combinación de un elastómero electrostrictivo de injerto con un polímero piezoeléctrico permite aplicaciones como actuadores electrostrictivos. Se han fabricado dos tipos de actuadores utilizando los elastómeros electrostrictivos de injerto: un actuador unimorfo y un actuador bimorfo.

El unimorfo se fabrica mediante la adhesión de una capa de la película de elastómero de injerto con electrodos y una capa de la película de elastómero de injerto sin electrodo. El adhesivo utilizado es resina epoxi endurecible a temperatura ambiente.

Las imágenes a) y b) muestran el actuador unimorfo en estado no excitado y excitado, respectivamente. El actuador unimorfo dobla en una dirección.

La imagen c) muestra el actuador bimorfo, que se puede doblar en ambas direcciones controladas por la fuente de alimentación.

Estos elastómeros ofrecen una combinación única de deseables propiedades prometedoras incluyendo: peso ligero, gran tensión inducida por el campo eléctrico, alto rendimiento, excelente procesabilidad y gran deformación ante el campo eléctrico inducido. Se pueden optimizar las propiedades electromecánicas del elastómero de injerto por diseño molecular, ajuste de la composición, y procesamiento para satisfacer las necesidades de diversas aplicaciones. [25] [26] [18]



Figure 7. The unimorph actuator (a) unexcited state and (b) electrically excited state.

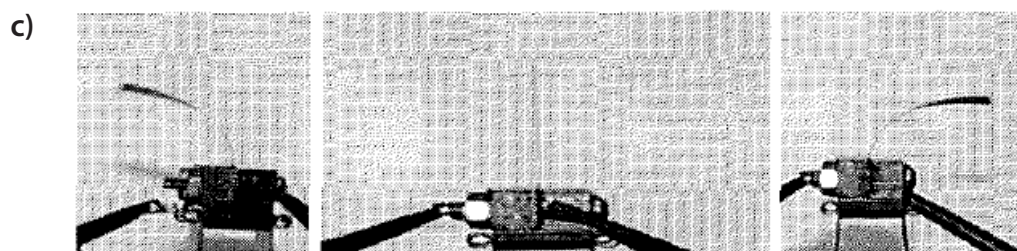


Figure 8. The bimorph actuator in the state of unexcited (middle), one direction excited (left), and opposite direction excited.

APLICACIONES

Músculos artificiales

ELASTÓMEROS ELECTRO-VISCOELÁSTICOS

Los elastómeros viscoelásticos son sólidos que exhiben tanto propiedades viscosas como propiedades elásticas cuando se deforman. [27]

Los elastómeros electro-viscoelásticos se caracterizan por tener rigidez y amortiguación de propiedades que varían con la frecuencia, la temperatura y la tensión aplicada.

Representan una familia de polímeros electroactivos compuestos de silicona elastómero y una fase polar. Antes de la reticulación, en el estado no curado, se comportan como fluidos electro-reológicos.

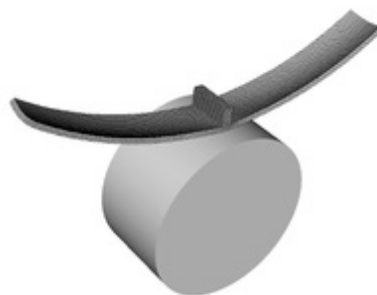
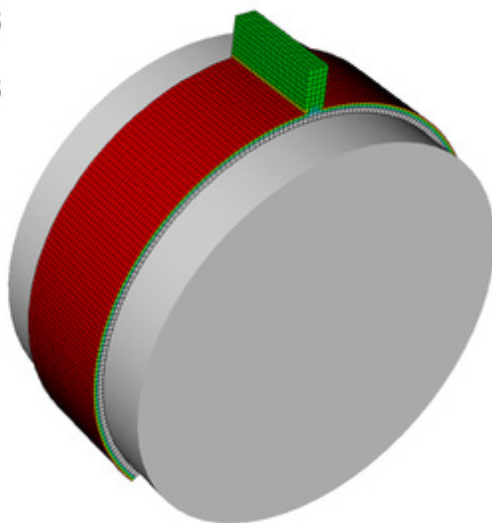
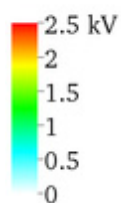
Un campo eléctrico se aplica durante el curado para orientar y fijar la posición de la fase polar en la matriz elastomérica. Estos materiales luego se mantienen en el estado "sólido" pero tienen un módulo de corte que cambia con la aplicación del campo eléctrico ($<6 \text{ V/m}$).

Estos materiales pueden ser utilizados como alternativas a los fluidos para aplicaciones de amortiguación activa electro-reológicas. [18] [26]

APLICACIONES

Aplicaciones adaptativas (pinza) (a)
Músculos artificiales
Válvulas
Frenos
Embragues
Amortiguadores
Microfluidos

a)



PAPEL ELECTROELECTRIVO

Los materiales electroelectrivos, al igual que los piezoeléctricos, soportan un cambio dimensional bajo la influencia de un campo eléctrico aplicado a una polarización bajo una tensión mecánica. La diferencia entre la piezoelectricidad y la electroelectricción aparece cuando se invierte el sentido del campo eléctrico; mientras el piezoeléctrico puede alargarse o comprimirse el electroelectrivo solo puede alargarse, independientemente de la dirección del campo eléctrico aplicado mostrando un comportamiento no lineal.

Los papeles electroelectrivos producen grandes desplazamientos con pequeña fuerza bajo una excitación eléctrica. El papel electroelectrivo es una hoja que se compone de multitud de partículas discretas, principalmente de naturaleza fibrosa, que forman una estructura de red organizada al azar. Se producen en diversos procesos mecánicos con aditivos químicos.

Un actuador de papel electroelectrivo es fabricado mediante la unión de dos papeles laminados de plata con electrodos de plata colocados en la superficie exterior. Cuando se aplica una tensión eléctrica a los electrodos del actuador se produce el desplazamiento.

Estos tipos de actuadores son de peso ligero y fáciles de fabricar.

Los papeles electroelectrivos están todavía en fase de desarrollo pero son susceptibles de ser utilizados en aplicaciones tales como amortiguadores de sonido, altavoces activos flexibles e inteligentes dispositivos de control de la forma. [18] [26]

APLICACIONES

Amortiguadores de sonido
Altavoces activos flexibles
Dispositivos inteligentes de control de forma

GELES DE POLÍMERO IÓNICO

Mediante un gel biomimético que puede andar como un gusano sin utilizar un estímulo externo para generar el movimiento oscilante. Este movimiento se produce por la energía química disipada de una reacción oscilante. Esto genera ondulaciones en su superficie que se transmiten de una punta a otra. Las aplicaciones son la generación de movimiento autónomo mediante la compresión y flexión en forma de ondas a través del cuerpo del material y el uso de estas ondas como transporte de materiales.[1]

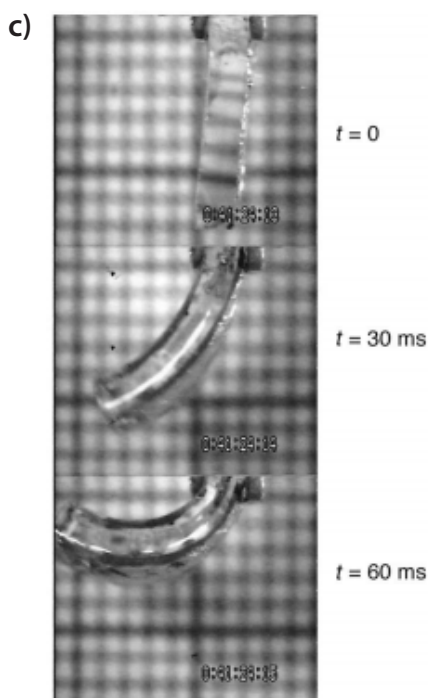
Otra aplicación pasa por la compresión del gel. Al producir una carga de varios voltios el gel se comprime hasta cientos de veces de forma reversible, al desconectar la corriente. Sus aplicaciones pueden ser desde interruptores, a músculos artificiales. Incluso se puede utilizar para almacenar diversas formas, mediante la compresión y expansión del gel. [2]

Se han utilizado geles iónicos en músculos artificiales funcionando mediante electricidad, como por ejemplo dedos artificiales, consiguiendo que este se doblase según la posición de electrodo positivo. Existe un prototipo de una mano robótica con dos dedos capaz de recoger pequeños objetos. [3]

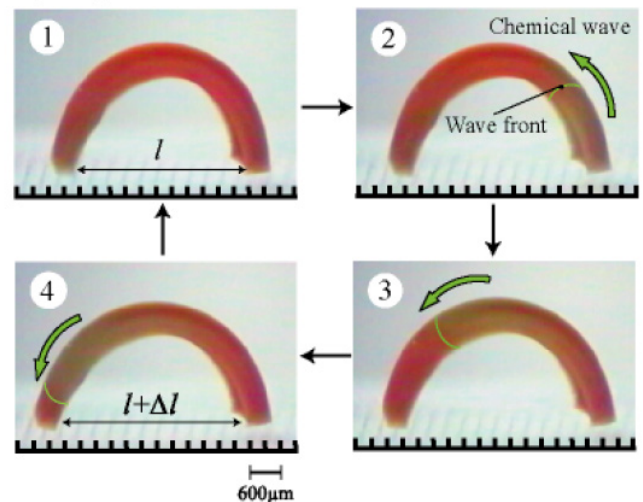
APLICACIONES

Movimiento autónomo (a)
Transporte (b)
Músculos artificiales (c)
Interruptores
Altavoces

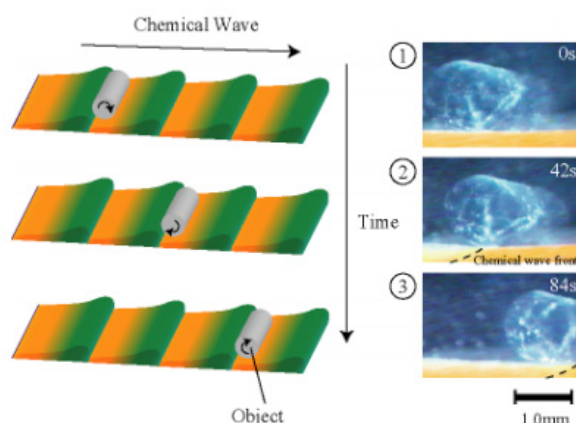
[Video de demostración](#)



a) Cyclic process



b) **Figure 11.** Schematic illustration of the matter transport using peristaltic motion of the gel. Reproduced from [29].



COMPUESTOS POLIMERO-METÁLICOS IONOMÉRICOS (IPMC)

Su respuesta es ligeramente superior a los Shape Memory Alloys y pueden utilizarse para emular las operaciones de los músculos biológicos y tiene propiedades únicas de baja densidad al igual que una alta resistencia mecánica y un gran rango de tensión para actuar.

Dado su desplazamiento debido al bajo voltaje su principal aplicación es para simular dedos, que pueden cerrarse o abrirse. El uso de múltiples dedos es usado como pinzas para agarrar objetos. [4] [5]

Existen actuadores multidireccionales que permiten moverse a lo largo de dos ejes, en lugar de uno que es lo más común, gracias a un transductor de 4 electrodos. Su uso se plantea para realizar cirugía láser ocular. [6]

APLICACIONES

- Músculo artificial (a)
- Esfínter para incontinencia urinaria o para el estomago (b)
- Tratamiento contra la apnea (c)
- Parche para el corazón, que actúa como marcapasos (d)
- Control de microfluidos (e)
- Actuadores lineales (f)

[Vídeo de demostración](#)

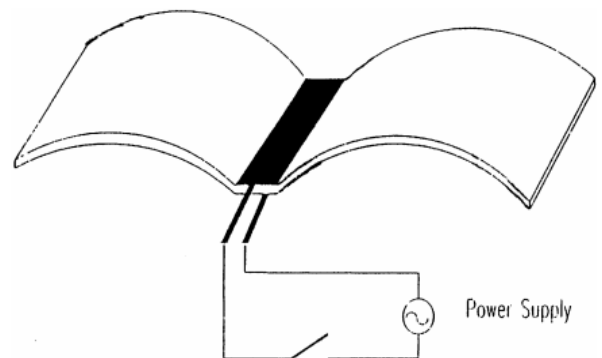
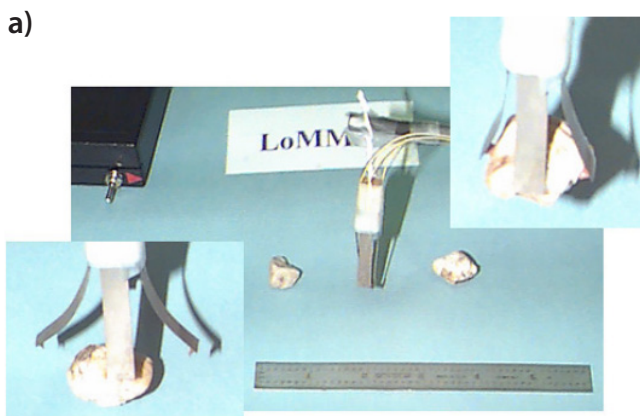


Figure 16. Wing-flapping flying machine design depicted schematically.

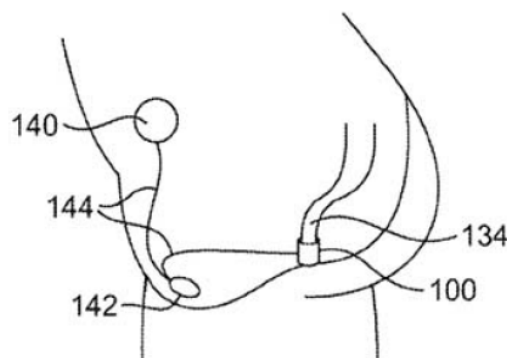
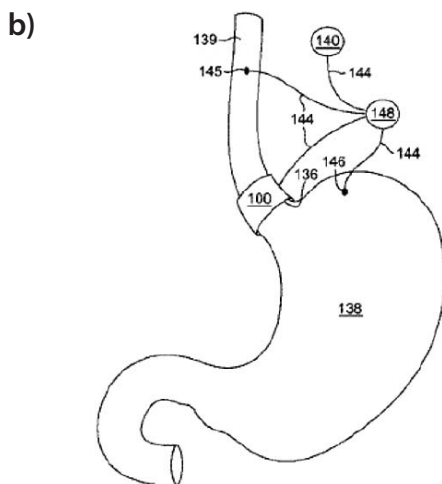


Fig. (2). Cuff sphincter (100) for regulation of the urinary incontinence in a woman patient [5].

Fig. (1). Esophageal sphincter (100) made by IPMC material [5].

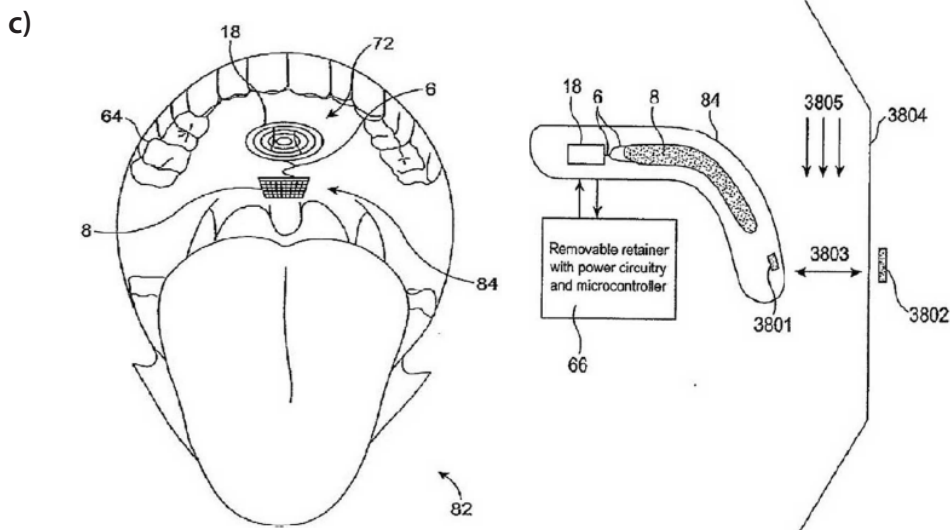


Fig. (18). (a) The IPMC (8) and its power source (18) located in the palate of the mouth. (b) IPMC (84) actuating system, its power and coating layer (84) commanded by the sensor (3801) signal of a closed or open air passage [14].

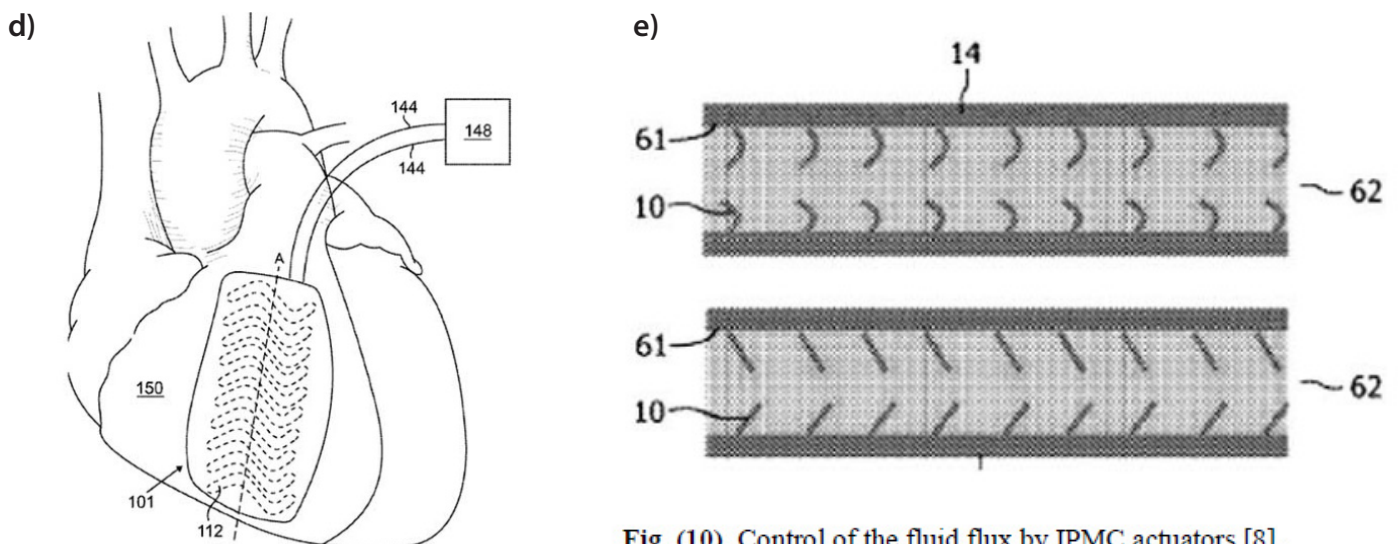


Fig. (3). Artificial muscle patch (101) attached to a heart [5].

Fig. (10). Control of the fluid flux by IPMC actuators [8].

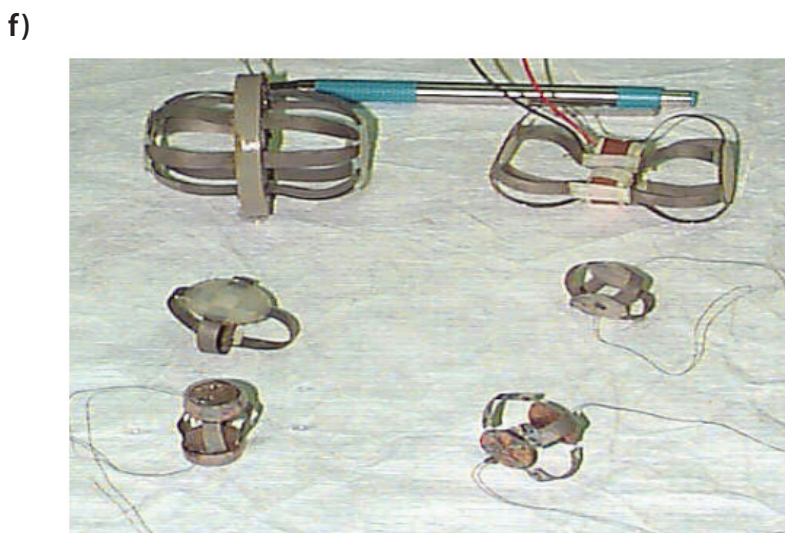


Figure 12. An assortment of linear and platform type actuators based on the design depicted in figure 11.

POLÍMEROS CONDUCTORES

Los polímeros conductores pueden trabajar tanto a contracción como a expansión, los músculos naturales solo a contracción.

La expansión o contracción del polímero es reversible, pues está basada en un proceso electroquímico reversible, y puede ser controlada fácilmente. [7]

Han sido desarrollados músculos capaces de levantar 1000 veces su propio peso a través de 180° . [8]

La ventaja de los polímeros conductores sobre los electrónicos es su bajo voltaje operativo. Algunas de las aplicaciones consideradas son la reconexión de vasos sanguíneos, dispositivos dinámicos para braille, válvulas y catéteres. [9]

APLICACIONES

Músculos (a)
Dispositivos para braille
Válvulas
Catéteres

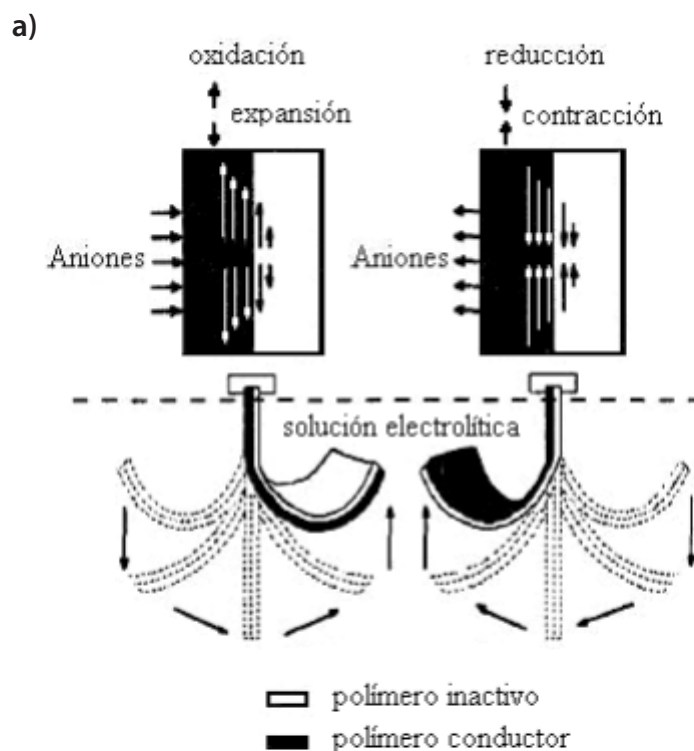


Fig. 3.12. Movimiento de una bicapa polímero conductor/cinta adhesiva, con la distribución de tensiones entre el polímero y la cinta y con los movimientos de aniones [20].

NANOTUBOS DE CARBONO

El principal uso de los nanotubos de carbono es su aplicación como músculos artificiales dadas sus excelentes capacidades mecánicas. Los últimos avances en fibra de nanotubos hiladas pueden elevar 200 veces el peso que podría elevar un musculo de ese tamaño o lo que sería 50.000 el peso del nanotubo. Sus aplicaciones pueden pasar por su uso en sistemas microfluídicos y componentes en cámaras ópticas. [10]

Investigadores del instituto de nanotecnología de Dallas han creado un nuevo tipo de musculo artificial formado por láminas de aerogel de nanotubos de carbono que puede operar entre -196 °C y 1538 °C. Puede llegar a estirarse 10 veces más que un musculo natural y 1000 veces más rápido. Por otro lado puede generar 30 veces la fuerza de un musculo con la misma sección. Mientras que los músculos naturales pueden contraerse al 20% por segundo, estos nuevos músculos artificiales pueden contraerse a 30.000% por segundo. [11]

La alta densidad de trabajo, la fuerza que realiza en función de su densidad, combinado con su resistencia y estabilidad a altas temperaturas, hace a los CNTs unos candidatos perfectos para situaciones donde el peso y la temperatura son importantes, como aplicaciones aeroespaciales. [12]

También puede ser utilizado como lamina para generar válvulas o bombas dada su alta capacidad de trabajo por ciclo. [13]

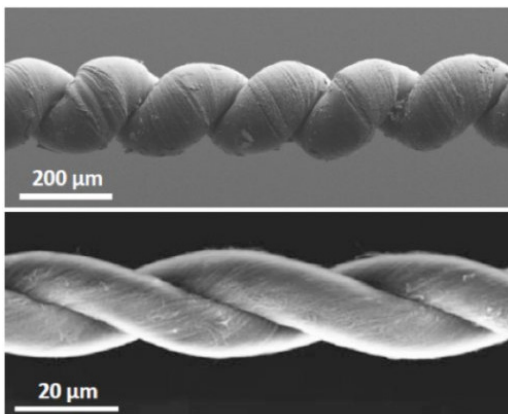
APLICACIONES

Músculos artificiales (a)
Microbombas (b)
Microfluidos
Dispositivos ópticos

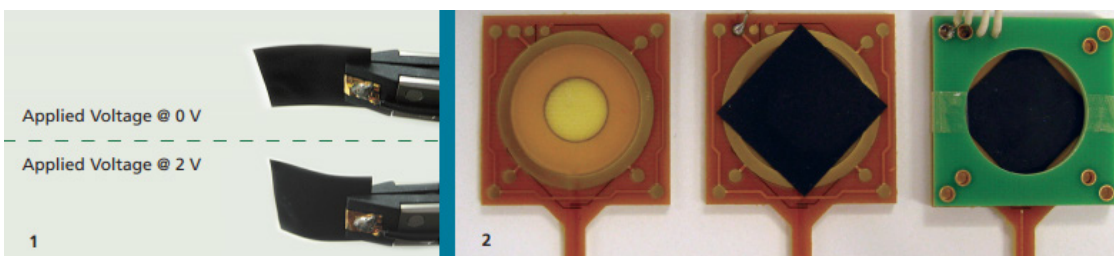
[Vídeo de demostración 1](#)

[Vídeo de demostración 2](#)

a)



b)



FLUIDOS ELECTRO-REOLÓGICOS

Se han creado pequeños actuadores mecánicos con una capacidad de respuesta en menos de 100 ms. Con la capacidad de soportar 1,2 gramos. [14]

La capacidad de endurecimiento en una fracción de segundo de este material tiene múltiples aplicaciones, sobretodo en válvulas hidráulicas, embragues o frenos, donde al aplicar un determinado potencial las válvulas se cierran o las placas se bloquean.

Sus capacidades de cambio de viscosidad también pueden aplicarse en amortiguadores o más recientemente en pantallas flexibles que interesen que sean rígidas en determinados momentos y flexibles en otros.

Motorola posee una patente para un dispositivo móvil de estas características.

Una de las ventajas es que estos fluidos pueden manejar más energía mecánica que la energía eléctrica que usan para controlar el efecto, es decir, pueden ser usados como amplificadores.

Se puede conseguir un cambio de líquido a sólido cuando el líquido experimenta un esfuerzo de compresión. Esta última capacidad está desarrollándose para pantallas en braille y en embragues de mayor eficacia. [15]

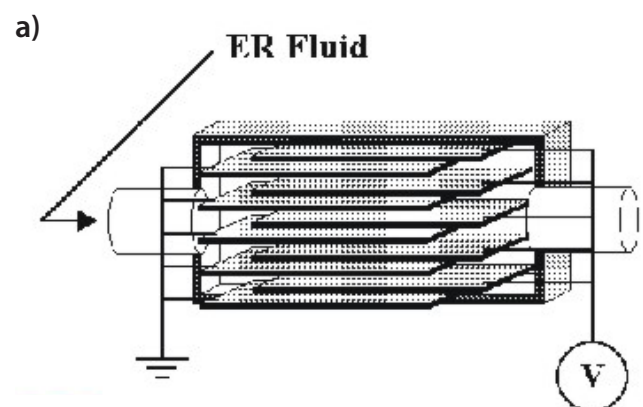
Otro de las aplicaciones testadas en laboratorio es su aplicación en chips microfluidicos, consiguiendo crear las funciones lógicas IF y NOT. [16]

Una de sus aplicaciones actuales son aquellas relacionadas con la recuperación médica tras accidentes y terapias de rehabilitación. Su uso se basa en dispositivos robóticos portables, que pueden usar las victimas en su casa para continuar con la rehabilitación. Estos dispositivos permiten generar movimientos más suaves y ayudar a seguir y medir el progreso del paciente de forma más cómoda y precisa.

Actualmente hay varias universidades trabajando en estos proyectos y ya existen dispositivos para la recuperación de rodillas, caderas, hombros y pelvis, e incluso se está probando su implantación en andadores, aunque su uso quedaría relegado al control de los frenos en las ruedas. [17] [18] [19]

APLICACIONES

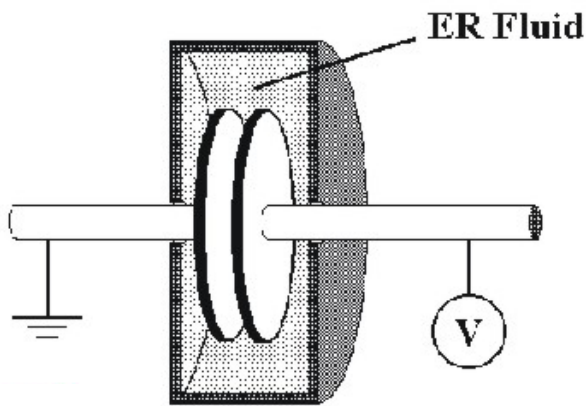
Músculos artificiales
Válvulas (a)
Frenos (b)
Embragues
Amortiguadores (c)
Dispositivos braille/hápticos (d)
Microfluidos (e)
Dispositivos de rehabilitación (f)



Valve

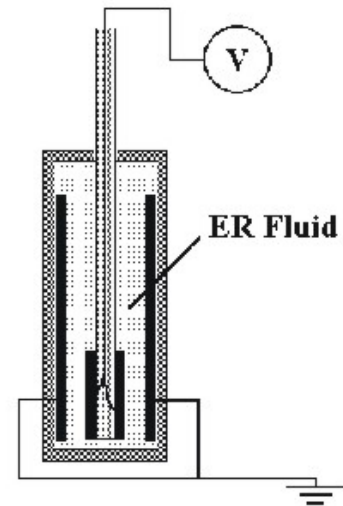
[Vídeo de demostración](#)

b)



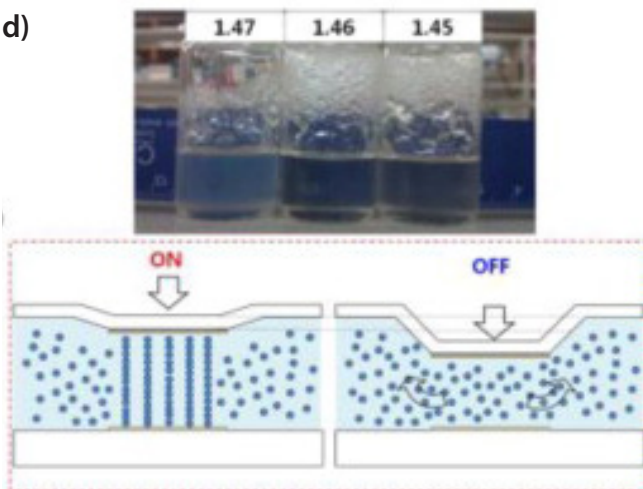
Clutch/Brake

c)



Shock Absorber

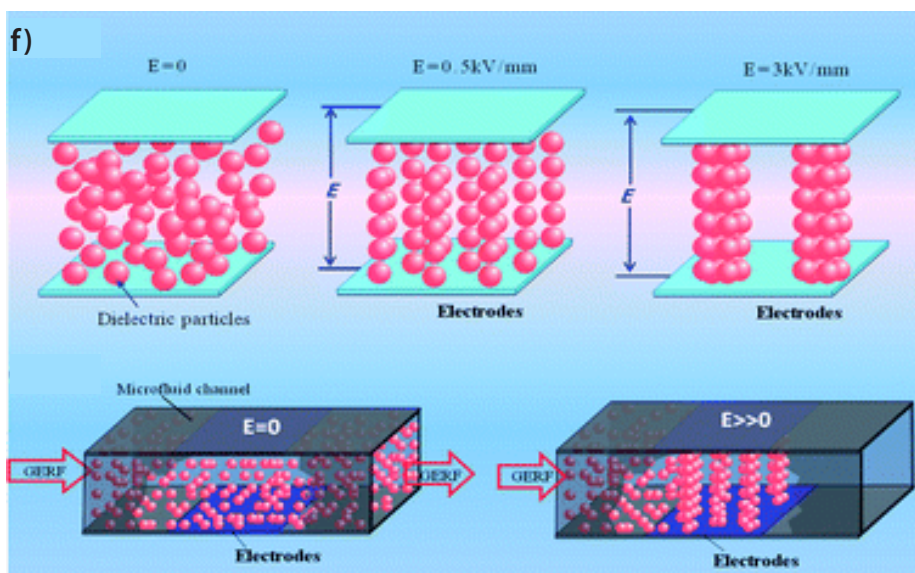
d)



e)



f)



CONCLUSIONES GENERALES

La gran mayoría de las aplicaciones únicamente han sido probadas en laboratorios o centros de investigación y a pequeña escala.

Muchas de estas investigaciones únicamente descubren capacidades de los materiales con posibilidad de ser aplicable a diversos campos pero sin pruebas sólidas de en qué grado beneficiaría su uso, únicamente por suposiciones a partir de los resultados obtenidos.

El potencial de estos materiales queda patente en los buenos resultados tanto mecánicos como de consumo eléctrico, por lo que tienen la capacidad de revolucionar una gran diversidad de campos debido a las múltiples opciones que existen para su aplicabilidad.

Las aplicaciones con mayor desarrollo son aquellas utilizadas para generar músculos artificiales biomiméticos, pero no por ello es la aplicación más importante.

La principal ventaja de utilizar PEAs en lugar de actuadores lineales es que es el propio material el que genera el movimiento, por lo que reduce el número de piezas implicadas.

CONCLUSIONES ESPECÍFICAS

Polímeros dieléctricos: Presentan grandes ventajas competitivas y un mayor número de campos de aplicación. Tienen potencial para reemplazar a muchos actuadores.

Polímeros ferroeléctricos: Debido a su efecto piezoeléctrico se aplican en transductores acústicos.

Elastómeros de cristal líquido: A través de la transición de dos de sus fases se logra la contracción reversible de este. Son idóneos para su aplicación en dispositivos industriales, electrónicos y médicos.

Elastómeros electrostrictivos de injerto: Mejoran muchas propiedades gracias al polímero injertado en el compuesto que responde al campo eléctrico. No se especifican las aplicaciones concretas.

Elastómeros electro-viscoelásticos: Antes de aplicar el campo eléctrico se comportan como fluidos electrorreológicos por lo que se utilizan como alternativas a estos en aplicaciones de amortiguación activa.

Papel electrostrictivo: Sus aplicaciones están menos extendidas ya que todavía se encuentran en fases de desarrollo pero son susceptibles de ser utilizadas en amortiguadores de sonido o altavoces flexibles.

Geles de polímeros iónicos: Altos índices de compresión y expansión, y además pueden generarse geles orgánicos biocompatibles, lo que los hace ideales para aplicaciones biomédicas.

Compuestos polímero-metálicos iónicos: Dado su bajo voltaje y alta resistencia mecánica son los más utilizados para nuevas aplicaciones.

Polímeros conductores: Buena aplicación como músculos artificiales o válvulas, con un bajo voltaje operativo. También se están investigando sus aplicaciones en dispositivos hápticos.

Nanotubos de carbono: Excelentes características mecánicas. Su densidad los hace unos candidatos perfectos para su uso como músculos o válvulas.

Fluidos electrorreológicos: Aplicaciones variadas como frenos, válvulas, embragues, amortiguadores o dispositivos hápticos. Se están empezando a usar como dispositivos de recuperación médica.

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Sesiones de Trabajo	Tiempo dedicado	Semana
Planificación y necesidades de información	1 h. 30 min.	1
Búsqueda de información	4 h.	2
Búsqueda de información	4 h.	2
Puesta en común	1 h. 30 min.	2
Análisis y redacción de la información	2 h.	2
Análisis y redacción de la información	2 h.	3
Diseño del dossier	2 h.	3
Conclusiones	2 h.	4
Maquetación y redacción del dossier	3h. 30 min.	4
Maquetación y redacción del dossier	6h.	4
Total	28h. 30 min.	

Artificial Muscle Technology: Physical Principles and Naval Prospects

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Abstract—The increasing understanding of the advantages offered by fish and insect-like locomotion is creating a demand for muscle-like materials capable of mimicking nature's mechanisms. Actuator materials that employ voltage, field, light, or temperature driven dimensional changes to produce forces and displacements are suggesting new approaches to propulsion and maneuverability. Fundamental properties of these new materials are presented, and examples of potential undersea applications are examined in order to assist those involved in device design and in actuator research to evaluate the current status and the developing potential of these artificial muscle technologies. Technologies described are based on newly explored materials developed over the past decade, and also on older materials whose properties are not widely known. The materials are dielectric elastomers, ferroelectric polymers, liquid crystal elastomers, thermal and ferroelectric shape memory alloys, ionic polymer/metal composites, conducting polymers, and carbon nanotubes. Relative merits and challenges associated with the artificial muscle technologies are elucidated in two case studies. A summary table provides a quick guide to all technologies that are discussed.

Index Terms—Actuators, electroactive polymers, shape memory alloys.

I. INTRODUCTION

ELECTRIC motors and combustion engines are relied upon for propulsion, lifting, rotation, positioning, and the application of pressure. Piezoelectric materials complement these actuator technologies by enabling very fine positioning at high frequencies. What is lacking is an established artificial technology that has properties similar to muscle. The properties of number of actuators are presented that are addressing this need.

Why mimic muscle? There are no actuators that can routinely replace muscle when it fails or assist it where it is weak. A muscle-like technology would be of enormous benefit for medical implants and human assist devices, as well as for minimally invasive surgical and diagnostic tools. **Combustion engines and high revving electric motors feature high specific power [1] but require complex transmission systems to perform discontinuous and nonrepetitive tasks, greatly reducing their efficiency and increasing cost.** Direct drive electric motors are low in force and

torque to mass compared to muscle [1]. These deficiencies make human motion and dexterity challenging to reproduce in robots, toys and medical devices. For example, the walking speed of Honda's impressive humanoid robot, Asimo,¹ is limited to 2 km/h by the torque available in the direct drive motors actuating each joint. Biologically inspired hydrodynamic propulsion and maneuvering strategies are also challenging to reproduce using traditional actuator technologies. The availability of a muscle-like actuator will enable important advances in a number of fields.

This review begins with a description of a number of actuator technologies in sequence. All technologies involve materials that change dimensions in response to input electrical, thermal, or optical power. Fundamental mechanisms, basic properties, synthesis, fabrication, and applications are presented. For each material a table of properties is presented. Some of the key figures of merit that are employed are now described.

Stress is the typical force per cross-sectional area under which the actuator materials are tested, and **peak stress** is the maximum force per cross-sectional area under which a material is able to maintain position (also known as blocking stress). In all the actuator technologies described, force developed scales linearly with cross-sectional area (whose surface normal is parallel to the direction in which actuation is occurring).

Strain represents the displacement normalized by the original material length in the direction of actuation. Typical strain is the strain that is often used in working devices, whereas **peak or max strain** is the maximum strain reported. The peak strain generally cannot be obtained when operating at peak stress.

Strain rate is the average change in strain per unit time during an actuator stroke. Typically the maximum reported rate is given. The maximum strain rate is usually observed at high frequencies where strains are small. **Bandwidth** is also discussed for some actuators, and is taken as the frequency at which strain drops to half of its low frequency amplitude. The highest observed frequencies are also mentioned. These may be of interest for acoustic applications. Limitations on bandwidth and strain rate can result from a range of factors including speed of delivery of the input energy (e.g., RC charging time), rates of diffusion or heating, internal dissipation, inertia related effects including speed of sound, and kinetics associated with the energy transduction method [43], [45]. **Faster responses can often be obtained by optimizing geometry and processing,** and thus the numbers provided are often not ultimate limits but rather represent the current state of the art.

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¹Honda Motor Company, <http://world.honda.com/ASIMO/P3/spec/>

Work density is the amount of work generated in **one actuator cycle normalized by actuator volume**. It is very important to note that this does not include the volume occupied by electrolytes, counter electrodes, power supplies, or packaging, unless otherwise stated. These additional contributions to actuator volume do not always scale linearly with work output and therefore need to be considered separately. Also it is emphasized that the work density is not simply the product of peak stress and peak strain.

Specific power or **power to mass ratio** is the **power output per unit mass** of actuator material. Typically only the mass of the material itself is considered. **Peak power density** can be found from the maximum **product of simultaneously measured stress and strain rate divided by density**. Because of the interdependence of load and rate, peak power is in general less than the product of peak stress and peak strain rate normalized by density.

Efficiency is the ratio of **work generated to input energy expended**. The listed efficiency has not always been achieved in practice, and sometimes requires additional circuitry to attain. Stored electrical energy and even thermal energy can in principle be recovered in order to improve efficiency.

Electromechanical coupling refers to the **proportion of input energy that is transformed into work, including external work done by the actuator and stored internal mechanical energy generated in the actuator itself**. The values represent a best case. The coupling values listed here for ferroelectric polymers, dielectric elastomers, and carbon nanotubes represent the **ratio of mechanical energy stored within these materials upon actuation under zero load to the electrical input energy** [71]. In these cases the most energy that can be extracted to a matched spring is half of the electromechanical coupling ratio.

The coupling is not necessarily the same as the efficiency. In fact in a number of actuators **the efficiency can be much higher than the coupling because input electrical or thermal energy can be recovered**. Several of the actuator technologies respond as capacitors, for example, from which electrical energy can be retrieved. The coupling is nevertheless important as it indicates how much energy in excess of the energy being converted to work must be shunted back and forth between the power supply and the actuator.

Cycle life is the number of useful strokes that the material is **known to be able to undergo**. Cycle life is often highly strain and stress dependent. Frequency dependence can arise due to dissipation and heating.

Elastic modulus is the material stiffness multiplied by sample length and divided by cross-sectional area. Generally it is the instantaneous value that is reported, before any creep is induced. It is important as **it determines the actuator's passive ability to reject load changes and disturbances**, and along with the density and mass determines the frequency beyond which inertial effects become important. Once inertial forces become significant resonance may occur, and at still higher frequencies strains will decrease (typically with the inverse square of frequency).

Many of the materials discussed dissipate mechanical energy, resulting in heating and the damping of mechanical oscillations. Creep and stress relaxation are also important. These effects are seldom characterized and thus are not reported here.

Some materials change stiffness with changing phase or state. Mammalian skeletal muscle changes its stiffness by a factor of 50 [2], for example, a property that is used extensively to assist in control.

Voltage: Most of the technologies described are activated using electrical energy, which serves both to power and control the work that they generate. The **charge density** transferred, and the **dielectric constant** are also important properties.

A number of other properties are often necessary to describe actuating materials including temperature dependence of the response, coefficient of thermal expansion, thermal diffusivity, ionic diffusion coefficients, resistivity, minimum displacement, positioning resolution, and gauge factor. Also environmental resistance can be important in many applications. Unfortunately these characteristics are often not known, or are not included in order to maintain a compact presentation.

The paper concludes with two case studies presenting basic design calculations relevant to the use of artificial muscle technologies to vary propeller blade camber (static) and to increase thrust by generating unsteady flow conditions. A table summarizing properties of all the actuator technologies is also provided.

Previous reviews include a chapter describing classical actuator technologies (electromagnetic actuators, combustion engines, hydraulics, piezoceramics, muscle) by Hollerbach *et al.* [1]. A review of emerging actuator technologies in comparison with muscle written by Hunter and Lafontaine over a decade ago remains relevant [2]. A book with chapters describing in detail many of the technologies presented here, edited by Bar-Cohen, provides a comprehensive introduction [3]. Bar-Cohen also hosts an informative Web site devoted to electroactive polymer actuators and devices.² The proceedings of the **SPIE annual Smart Structures and Materials Symposium** feature sessions on electroactive polymers, ferroelectrics, and ferroelectric shape memory alloys. Papers by Ashby and colleagues describe methods used to create a database of actuator properties [4].

A number of interesting actuator technologies have been omitted from this review. For example, single crystal ferroelectrics such as PZN-PT and PMN-PT are similar to traditional piezoceramic actuators in many respects, but feature significantly larger strains (~1%). These materials are now commercially available and relatively established. In this paper new larger strain polymer-based ferroelectrics are discussed. Shape memory polymers undergo large thermally induced deformations (>100% strain) [5]. Like heat shrink tubing these generally need to be retrained after one actuation cycle. Polymer gels (e.g., polyacrylonitrile [6]) undergo large deformations in response to changes in temperature, pH or solvent environment. These materials can reversibly actuate over many cycles with strains of greater than 100%. Traditionally gels have been slow to respond (seconds to minutes), are relatively weak (~100 kPa), and are low in efficiency, and therefore have not been discussed in detail here. Electrostatic actuators are

²<http://eap.jpl.nasa.gov/>

TABLE I
MAMMALIAN SKELETAL MUSCLE [2], [7]

PROPERTY	TYPICAL	MAXIMUM
Strain (%)	20	> 40
Stress (MPa)	0.1 (sustainable)	0.35
Work Density ($\text{kJ}\cdot\text{m}^{-3}$)	8	40
Density ($\text{kg}\cdot\text{m}^{-3}$)	1037	
Strain Rate ($\%\cdot\text{s}^{-1}$)		> 50
Specific Power ($\text{W}\cdot\text{kg}^{-1}$)	50	284
Efficiency (%)		40
Cycle Life		> 10^9
Modulus (MPa)	10 - 60	

being applied to microelectromechanical systems.³ These employ electrostatic attraction between microfabricated electrodes in order to generate forces and displacements. **Electrostatic actuators are capable of relatively large strains (>50%) at low stress (~ 10 kPa) and moderate to high bandwidth (>100 Hz).** Electrostatic actuators are based on fabricated structures rather than field induced changes in mechanical properties and have been omitted.

II. ACTUATOR DESCRIPTIONS

A. Muscle and Biological Actuators (Table I)

Muscle is a linear actuator technology whose properties, though surpassed in many respects by artificial actuators, are very well suited to providing intermittent displacements and adaptable stiffnesses in organisms ranging from micrometers to meters in length. Details of the mechanisms are provided by Kohl as part of this special issue. The properties vary by species, as described by Full and Meijer [7]. Key characteristics of mammalian skeletal muscle are provided in Table I for ready comparison with other technologies [2].

As mentioned, muscle does not surpass artificial actuators in any one aspect (for example continuous power to mass is an order of magnitude lower than that of an internal combustion engine). However there are a number of attractive design features that could be emulated to great advantage. For example, force can be graded by controlling the number of fibers that are activated in parallel, a process known as recruitment. This grading of force enables efficiency to be optimized over a wide range of loads and contraction velocities, in addition enabling control of acceleration and force. The control of force is made more effective by the fact that inactive muscle fibers are relatively low in stiffness, and therefore do not require significant forces to strain. In most of the materials described below there is little ability to change modulus. As a result attempts to grade force by recruitment are less effective. The ability to change stiffness is also important in control strategies. For example, in catching a ball, too stiff an arm will lead to a large (painful) impulse as the ball makes contact, and provides less time to grasp the ball before it bounces back. A very compliant arm will not be able to stop the ball. The optimum stiffness needs to be adapted to the ball mass and velocity. Such stiffness control can be emulated in artificial actuators by fast feedback control, but at the expense of

added complexity and will only work if the actuator bandwidth is sufficient.

A further advantage of muscle is its ability to convert chemical energy to mechanical work. The “combustion” of sugars and fats using freely available oxygen provides a fuel energy density that is two orders of magnitude greater than that of batteries. Most of the actuator technologies described below require electrical energy and will generally rely on batteries when used in autonomous systems such as autonomous underwater vehicles (AUVs). Improvement in the cost, energy density, and cycle life of fuel cells will alleviate this issue in systems that have access to air. Submersible use is more challenging as both fuel cells and chemical oxidation reactions require the harvesting of dissolved oxygen and of air bubbles, or oxygen must be carried.

Another attractive characteristic of muscle is its integrated circulation system, which delivers fuel (glucose and oxygen), and removes heat and waste. Capillary density is such that molecules and heat need only diffuse over distances of some tens of micrometers. Such local delivery of energy and removal of heat could greatly benefit a number of artificial actuators in which it is desirable to rapidly transfer heat, mass and energy.

Finally, muscle is able to operate for billions of cycles over a period of a hundred years or more. This exceptional performance is made possible by the ability to regenerate proteins in situ.

Many of muscle’s advantages relative to artificial actuator technologies stem from nature’s ability to fabricate and control on length scales ranging from the molecular to the macroscopic. As fabrication technology improves and nature’s mechanisms are better understood, a number of muscle’s properties, including regeneration, nanostructuring and direct chemical actuation, will likely become common in artificial actuators. Nevertheless, some artificial actuator technologies are already matching or exceeding muscle in strain, stress, and specific power, and are thus worthy of attention. Most of the technologies presented, for example, feature peak stresses that can at least match muscle, with the peak forces per cross-sectional area in shape memory alloys exceeding those of muscle by a factor of 500. Furthermore, unlike mammalian skeletal muscle, nearly all of the technologies presented feature a “catch” state, enabling position to be locked against a fixed load without power expenditure.

B. Dielectric Elastomer Actuators (Table II)

Electrostatic attraction between conductive layers applied to two surfaces of elastomer films induces compressive strains under applied fields of ~ 150 MV/m, as depicted in Fig. 1 [8]–[16]. Elastomers are sufficiently compliant that large strains are induced and there is efficient coupling between the electrical energy input and mechanical energy output. Typically the spacing between conductive layers is less than 0.1 mm, so that although strains are large, total displacement is small. Since elastomers maintain constant volume, contraction in one direction leads to expansion in the other two. Most mechanisms make use of the expansion perpendicular to the direction of the applied field because these result in large displacements. By prestraining one of the two axes most of the expansion is

³<http://www.analog.com/>

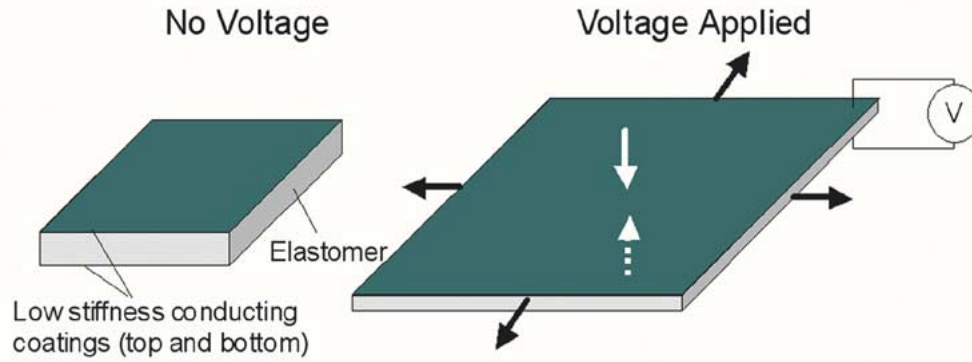


Fig. 1. Diagram depicting the effect of applied voltage on a slab of dielectric elastomer. (Adapted from Kornbluh *et al.* [9].)

TABLE II
DIELECTRIC ELASTOMERS [9]–[15], [17]

PROPERTY	SILICONE	VHB
Maximum Strain (%)	120	380
Stress (MPa)	0.3 typical 3.2 max	1.6 typical 7.7 max
Work Density (kJ/m ³) (Based on internal strain)	10 typical 750 max [20]	150 typical 3400 max [20]
Density (kg/m ³)	1100	960
Peak Strain Rate (%/s)	34,000	450
-Achieved at:	12%, 1400 Hz	2.3%, 100 Hz
-Modified VHB [20]:		4500
Peak Power (W/kg)	5,000	3,600
Taken at Peak Rate w/ load of	300 kPa	1.6 MPa
Continuous Power (W/kg)	500	400
Bandwidth (Hz) - 3 dB:	1400	10 (100 [20])
- maximum observed freq:	> 50 kHz	> 50 kHz
Life (cycles) @ strain	>10 ⁷ @ 5%	>10 ⁷ @ 5%
> indicates no failure observed	10 ⁶ @ 10%	10 ⁶ @ 50%
EM Coupling (%)	80 max	90 max
≅ strain, for small strains [20]	15 typical	25 typical
Efficiency (%)	80 max	90 max
(conversion to internal strain)	25 typical	30 typical
Modulus (MPa)	0.1 to 1.0	1.0 to 3.0
(process and strain dependent)		
Speed of Sound (m/s)	< 30	< 55
Thermal Expansion (m/m/°C)		1.80·10 ⁻⁴
Voltage (V) (Geometry dependent)	> 1000	> 1000
Dielectric constant @ 1 kHz	~ 3	~ 4.8
Max. Field (MV/m)	110 - 350	125 - 440
Temperature range (°C)	-100 to 250	-10 to 90

directed perpendicular to the prestrain [10]. The prestraining can also result in higher breakdown potentials [12].

1) *Features*: The actuators are elegantly simple in mechanism and construction and feature large strains that are typically in the range of 10% to 100% but can reach 380% [9]–[17]. High efficiencies (>30%) are possible with careful design, particularly when energy is recovered. High bandwidths are achievable in silicone (1400 Hz), and moderate bandwidths are possible in acrylic VHB 4910 from 3M (VHB 10 Hz typical) [9]. Small displacements can be achieved at tens of kilohertz in both materials [9]. These materials can also act as generators and sensors.

Finally, dielectric elastomers operate over relatively large temperature ranges. Silicone in particular can operate over a temperature range of -100 to $+250$ °C.

2) *Limitations*: High voltages (>1 kV) can be a concern, particularly in biomedical and toy applications. For large and fast devices the power may provide a real hazard. Generally there is a need to convert line or battery voltages up to kilovolt potentials, which adds cost and consumes volume. Relatively small dc–dc converters are available for moderate to low power applications (e.g., cubes 12.7 mm on each side from EMCO High Voltage), but the cost and size at present are prohibitive for application in small (e.g., handheld) portable devices [11]. Dielectric breakdown can limit actuator yield especially when imperfections exist within films. The materials themselves can actuate at high stresses (up to 7.7 MPa in acrylic and 3.2 MPa in silicone). However, in practical devices the maximum stress is typically an order of magnitude lower due to the reduced electric field required to avoid premature breakdown and to imperfect mechanical coupling with the load. Finally, the mechanisms needed to apply prestrain add significantly to volume and mass [11].

3) *Theory*: The stress or pressure P_z resulting from electrostatic attraction between plates is

$$P_z = \epsilon_r \epsilon_0 E^2 = \epsilon_r \epsilon_0 (V/t)^2 \quad (1)$$

where ϵ_r is relative permittivity (dielectric constant), ϵ_0 is the free space permittivity, E is the applied electric field, V is the applied voltage, and t is the thickness of the polymer. The maximum stress is limited by dielectric breakdown, which in turn is a function of strain.

In attempting to fully model this apparently simple system several complications arise. The resultant strains produced in the polymer are dependent on the boundary conditions and loads on the polymers. Further, the strain depends on the elastic modulus of the polymer, which is nonlinear at large strains. The large prestrains used can cause the effective elastic modulus to be anisotropic. However by assuming that the elastomer is incompressible, the strains S in the x , y , and z directions obey a simple relationship

$$(1 + S_x)(1 + S_y)(1 + S_z) = 1. \quad (2)$$

S is the relative strain, which is the strain difference from pre-strain conditions.

4) *Materials and Dimensions*: A number of elastomers have been tested, with the best results achieved from three commercially available materials, namely, Dow Corning HS3 silicone, Nusil CF 19-2186 silicone, and 3M VHB 4910 acrylic. The silicones are cast into the desired geometries, while the VHB is purchased as an adhesive ribbon. Typical actuator dimensions before stretching are 100 μm thick, 100 mm long, and similar dimensions in width. These films are coated with conductive grease, powder or paint. Prestretching of up to 500% is performed by rolling films, inserting them into a compliant frame, or by using beams to maintain the tension [9]–[16]. Voltage is applied to either side at potentials of up to ~ 10 kV and using currents in the milliamp range.

5) *Devices and Applications*: Recently “spring roll” actuators have been developed that feature up to three degrees of freedom each [11]. These actuators have a helical spring at their core, around which dielectric elastomer sheet is wound. The sheets are coated with electrodes. In order to produce bending motions (in addition to stretching along the axis) the electrodes are patterned such that voltage can be applied independently to each of four sections. The resulting actuator bends in two directions and extends. This mechanism is very similar to that used in piezoceramic tube actuators, but features much larger deflections. These tubes can generate up to 30 N of force or 20 mm of displacement from a 90 mm long, 18 mm diameter device. The effective stress is 0.1 MPa, and the strain is 22%.

Demonstration devices include speakers (tweeters), pumps, and multilegged robots [14].

6) *Rate Limiting Mechanisms*: RC charging, viscoelastic behavior, inertia, dissipation induced heating, and the speed of sound are all rate limiting factors [9]. Interestingly the VHB based actuators exhibit a frequency response that is two orders of magnitude lower than observed in silicone [9].

7) *Temperature*: Dielectric elastomers have been operated successfully between 250 $^{\circ}\text{C}$, and at -100 $^{\circ}\text{C}$ for silicones and -10 $^{\circ}\text{C}$ and 90 $^{\circ}\text{C}$ for acrylic [11]. Operation below glass transition temperatures will be ineffective as the compliance will drop by two or more orders of magnitude. Nevertheless, the temperature range is impressive, especially when compared to relaxor ferroelectrics.

8) *Potential*: Layers of thin films could enable voltage to be substantially reduced. Ideally these layers would be as thin as 100 nm, reducing potentials to the 10 V range. However this may prove difficult if even moderate strain rates are to be achieved due to the conflicting requirements of maximizing the conductivity of the electrodes and minimizing their mechanical stiffness. Increasing dielectric constant is an alternative method for reducing applied voltages, as predicted by (1). It may be possible to devise composite materials with high dielectric constants and moderate breakdown potentials that enable low voltage operation without sacrificing performance.

C. Relaxor Ferroelectric Polymer Actuators (Table III)

1) *Mechanisms*: Ferroelectric materials are the electrostatic analogs of ferromagnets. The application of an electric field aligns polarized domains within the material. When the applied

TABLE III
FERROELECTRIC POLYMERS [20], [24], [26]

PROPERTY	TYPICAL	MAXIMUM
Strain (%)	3.5	7
Stress (MPa)	20	45
Work Density (kJ/m^3) (based on internal strain)	320	> 1000
Density (kg/m^3)	1870	2000
Strain Rate (%/s)		≥ 2000 10 kHz, $\sim 0.1\%$ strain
Bandwidth (Hz)	< 100	> 10,000 for strain $\sim 0.1\%$
EM Coupling S3 (at optimal temperature)	0.1 - 0.2	
EM Coupling S1 (at optimal temperature)	0.4	
Modulus (MPa) (Composition dependent)	400	1200
Voltage (V) (Geometry depen.)		> 1000
Max. Field (MV/m)	13	150
Dielectric Constant varies between ~ 4 & 60.	55	Temp. dependent
Temperature Range	$\Delta T \sim 60$ $^{\circ}\text{C}$	

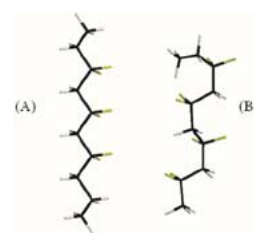


Fig. 2. An example of the molecular shape changes obtained by applying a field to ferroelectrics. A segment of vinylidene fluoride oligomer is shown in two conformations. (A) is a model of the polar all trans conformation that is obtained upon application of a field, while (B) is an alternating trans-gauche form that is nonpolar. The black rods represent the carbon backbone, the green segments are fluorine and the white segments are hydrogen. (Adapted from Xia *et al.* [26].)

field is removed, a permanent polarization remains. As in ferromagnets, ferroelectrics are characterized by a Curie point, a temperature above which thermal energy disrupts permanent polarization.

The ferroelectric polymer most commonly used for actuation is poly(vinylidene fluoride—trifluoroethylene), abbreviated as P(VDF-TrFE). The electronegativity of fluorine creates local dipoles on the polymer backbone. These polar groups align to create polarized domains within a molecule, as depicted in Fig. 2(A), and across crystalline regions. The application of an electric field aligns polarized domains, which remain even after the field is removed. The realignment also produces reversible conformational changes which are made use of in actuation [26].

A key disadvantage of ferroelectric polymers is that there is substantial hysteresis. A large field must be applied in the opposite direction of the initial field in order to reverse the polarization, and substantial energy is dissipated. The highest performance materials have instead been ferroelectric relaxors in

which the long range correlations between polar groups are disrupted by imperfections. These imperfections are introduced by either irradiation [24] or by the incorporation of disruptive monomers along the chain, such as chlorofluoroethylene [26]. The imperfections are used to bring the Curie point below room temperature, such that a nonpolar, paraelectric phase dominates at normal operating temperatures. An example conformation that is in the paraelectric phase is shown in Fig. 2(B). When field is applied to the polymer in this state polarization is induced, resulting in a conformation similar to that shown in Fig. 2(A). The imperfections introduced into the structure reduce the energy barriers to phase change, thereby reducing or eliminating hysteresis [26]. This ferroelectric to paraelectric transition is associated with relatively large molecular conformational changes, leading to macroscopic deformations that are employed to generate actuation.

In P(VDF-TrFE) ferroelectric relaxors, application of field leads to a contraction in the direction between plates (S3), and extension perpendicular to the applied field (S1, S2). Pre-stretching the polymers—e.g., along S2—enlarges the strain in this direction due to alignment of molecules in the stretch direction [26].

2) *Features [18]–[26]*: Moderate strains are achieved (up to 7%), with high stresses (reaching 45 MPa), moderate to excellent frequency response (deflections are observed at up to ~ 100 kHz), large work per cycle (approaching $1 \text{ MJ} \cdot \text{m}^{-3}$), and high stiffness ($>0.4 \text{ GPa}$ depending on the density of imperfections) [20], [24], [26]. The work densities reported for ferroelectrics and dielectric elastomers are based on internal strain, as discussed in the introduction, and at best half of the energy will be extracted to a perfectly matched load. Nevertheless the work density is impressive.

3) *Limitations*: These actuators, like dielectric elastomers, require high fields ($\sim 150 \text{ MV} \cdot \text{m}^{-1}$) and voltages ($>1 \text{ kV}$). Electrodes applied to the surface of the polymer fatigue due to the large strains imposed. Dissipation and the associated heating of the actuators often make the achievement of frequencies above 100 Hz impractical except in small samples or at small strains.

Some of the fluorocarbons used in the synthesis of the materials are difficult to obtain and expensive due to environmental restrictions on their use. The process of e-beam irradiation, used in a number of the materials, is expensive and time consuming. However the methods for polymerizing poly(vinylidene fluoride—trifluoroethylene) itself [23] are similar to those used to create polyethylene, and are therefore readily scaleable and low cost.

These materials feature an optimal loading condition at which maximum strain is achieved. Above and below this value, strain decreases substantially. For example in irradiated P(VDF-TrFE) the peak strain occurs at 20 MPa, dropping to $\sim 50\%$ of its peak value above 40 MPa and below 5 MPa [26].

4) *Potential*: The high voltages can be reduced by using thin layers (100 nm for 15 V) or by creating materials with very high dielectric constants. The relative stiffness of the electrode materials limits the extent by which film thickness and hence applied voltage can be reduced, a limitation that might be over-

TABLE IV
LIQUID CRYSTAL ELASTOMERS [29], [32], [34], [36], [37]

PROPERTY	THERMAL	E-FIELD	
		[29]	[36]
Strain (%)	19–45	4	2
Stress (MPa) – at max. strain – isometric (no strain)	0.01 – 0.12 typ. 0.45 max.		
Work Density (kJ/m^3)	3 – 56		20 internal
Strain Rate (%/s)	6 – 37	1000	
Power (W/kg)	1		
Efficiency (%) – thermal – conversion to internal strain	$< 5\%$ Carnot		75
Modulus (MPa) at 0 % strain 30 % strain 120 % strain	4 0.06 0.3		100
Voltage (V) (applied to a 75 nm thick film)		0.11	
Max. Field (MV/m)		1.5	25
Dielectric Constant – 0.1 Hz – 100 Hz			15–40 3–5

come to some extent by using electrodes that are more compliant than gold and other metals commonly employed. The addition of high dielectric constant filler materials to the polymer matrix is showing promise in greatly reducing the required field strength [18], [21], [26]. The addition of copper phthalocyanine to a P(VDF-TrFE) matrix enabled 2% strain at $13 \text{ MV} \cdot \text{m}^{-1}$ while maintaining a composite elastic modulus of 0.9 GPa. The reduction in applied field is attributed to an increase in applied dielectric constant from ~ 50 to >400 [26].

5) *Temperature*: The Curie point of many of these materials is just below room temperature. The dielectric constant and the efficiency of coupling electrical and mechanical work is also a function of temperature. The operating temperature range ($\sim 60^\circ \text{C}$) is dependent on the density of imperfections (introduced either by irradiation or by the concentration of disruptive monomer units). The Curie point and the temperature range of operation can be tuned up or down by changing the density of imperfections. A typical range is between 20 and 80°C [24].

Heat can be used instead of electrostatic energy to activate ferroelectric polymers [22]. Heating and cooling these polymers around their Curie point produces reversible actuation ($<10\%$ strain), with efficiency determined by the Carnot relationship.

6) *Rate Limiting Mechanisms*: Rates are limited by RC charging times, heating and dissipation within the materials, inertial effects, and ultimately the relaxation times of the polar groups on the backbone.

D. Liquid Crystal Elastomers (LCEs) (Table IV)

Thermal or electrostatic energy are employed to induce phase changes in liquid crystalline polymers [27]–[37]. The changes of order and alignment of liquid crystalline side chains generate stresses in the polymer backbone, resulting in actuation.

1) *Mechanisms*: In 1975 de Gennes [27] predicted that the reorientation of liquid crystal molecules during a phase transition could lead to a mechanical stress and strain. Stress fields in liquid crystals generally induce flow that prevents the buildup of static forces. In liquid crystal elastomers, the free flow of

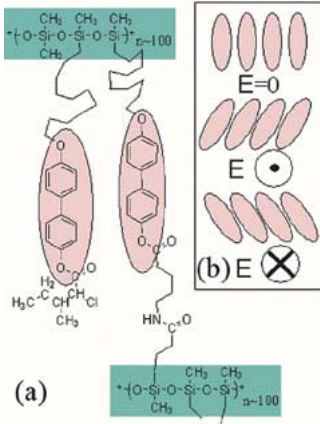


Fig. 3. An example ferroelectric liquid crystal elastomer. (a) The polymer backbone (green square) is siloxane, from which mesogens (ovals) extend. A small fraction of the mesogens are crosslinked to neighboring polymer chains. In the system shown the application of a field normal to the long axis of the mesogens produces a reversible rotation, as depicted in (b), resulting in dimensional changes. (Adapted from Lehmann *et al.* [29].)

the liquid crystal molecules (mesogens) is prevented by bonding them to a cross-linked polymer in which a flexible backbone still allows reorientation of the mesogens, as depicted in Fig. 3(a). The change in orientation of the mesogens upon temperature changes or application of an electric field produces stresses and strains that are transferred via the backbone to perform mechanical work. The mechanisms of field driven actuation in LCEs are similar to those of the ferroelectrics described above, with the exception that the polarized units do not form part of the polymer backbone itself, but rather are appendages extending from it.

Rate is limited by heat transfer time constants when thermally driven. For a step change in temperature applied to the surface of a thin film of material, an estimate of the time constant of the diffusive heat transfer within the polymer itself can be given as

$$\tau = R_{th} \cdot C_{th} = \rho \cdot C_v \cdot L^2 \quad (3)$$

where $R_{th} = \rho \cdot L/A$, $C_{th} = C_v \cdot L \cdot A$, and ρ is the thermal resistivity, C_v is the volumetric heat capacity, A is the area perpendicular to the heat flow, and L is the distance the heat must diffuse. The quantity $(\rho \cdot C_v)^{-1}$ is known as the thermal diffusivity. Leister *et al.* [30] measured the thermal diffusivity for a ferroelectric liquid crystalline elastomer with a polysiloxane backbone and found values of 2×10^{-8} to 4×10^{-8} m²/s in 20 to 100 μ m thick samples. For a flat film with a thickness of 100 μ m, the corresponding time constant is between 0.25 and 0.5 s if heat is transferred on only one side of the film, and less than 0.125 s for both sides. The rate is expected to be proportional to the inverse square of thickness, so it should be possible to activate a 1 μ m thick film in less than 100 μ s.

Ferroelectric liquid crystals contract and expand when an external electric field is applied to the polymer [29], [36], [37]. The mesogenic units in ferroelectric liquid crystals have an intrinsic polarization or feature an anisotropic dielectric constant [36]. The application of field changes the alignment of the mesogens as depicted in Fig. 3(b), with the direction and extent of reorientation depending on the mesogens used. These reorientations induce bulk stresses and strains.

Unlike thermal energy, electric fields can be applied through the bulk of the material very quickly, so the response speed is considerably faster in electrostatic-driven films than during thermally induced activation. The time taken to reorient the liquid crystal units is the ultimate rate-limiting factor in ferroelectric liquid crystalline elastomers. In experiments designed to determine the speed to the mesogenic reorientation, Skupin *et al.* [33] used time resolved Fourier transform infrared spectroscopy (FTIR) to measure a response time constant of ~ 10 ms, thus providing a lower limit on the response time of their material. The response time depends greatly on the specific mesogens used, the polymer backbone structure, and the degree of cross-linking, and thus smaller mesogens, in a less cross-linked matrix could be faster (and would likely exhibit less strain).

In separate experiments by the same group [29], 4% electrostrictive strains were observed in a ferroelectric liquid crystalline elastomer at 133 Hz. In these experiments an electric field of 1.5 MV/m was applied to a thin (75 nm) sample. Recent experiments by Huang *et al.* [36] show a 2% strain at 25 MV·m⁻¹ in a relatively stiff material (100 MPa), with an apparently rapid drop off in frequency response above 1 Hz. The electromechanical conversion efficiency is found to be 75% in this material (conversion is to internal strain in the actuator in this case, and not to external work, as discussed in the introduction).

2) *Features:* These materials can exhibit good response times (~ 10 ms in field driven actuation [29]), and moderate to large strains ($\sim 4\%$ in the field driven materials, and up to 45% in thermally activated polymers). The applied fields (1.5 to 25 MV/m) are significantly lower than those used in other ferroelectrics and in dielectric elastomers, leading to correspondingly lower applied voltages for the same thickness of material.

Thermally driven LCEs can be activated via radiative heating, which can potentially create fast activation, providing that absorption can be made uniform (cooling still relies on thermal conduction and is thus relatively slow in thick samples) [33]. Joule heating of graphite loaded [37] or conducting polymer coated liquid crystal elastomers [35] has also been used to induce actuation.

3) *Limitations:* Investigation of LCEs is still at a very early stage with the result that much information has yet to be collected. These materials are elastomers with low stiffness and tensile strengths so that a relatively small change in load can easily lead to a large change in length. Thermal activation is limited by Carnot efficiency, and heating must continue during activation periods. The rate of thermal actuation is limited by heat transfer rates. Very fast rates might be achieved using laser heating, but at the cost of further reduced efficiency. The low stiffness of these materials means that resonant frequencies and the speed of sound are low. The use of stiffer materials [36] has so far resulted in lower bandwidths.

E. Conducting Polymer Actuators (Table V)

1) *Synonym:* Conjugated polymers.

2) *Mechanisms:* Conducting polymers are electronically conducting organic materials featuring conjugated structures, as depicted in Fig. 4. Electrochemically changing oxidation state leads to the addition or removal of charge from the

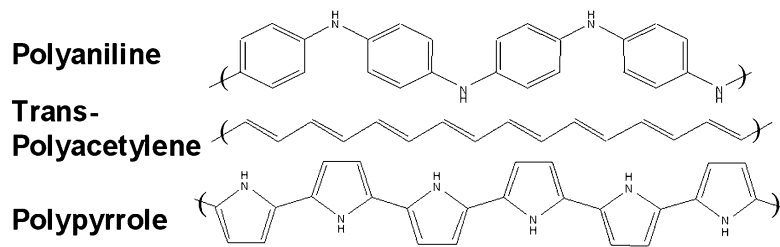
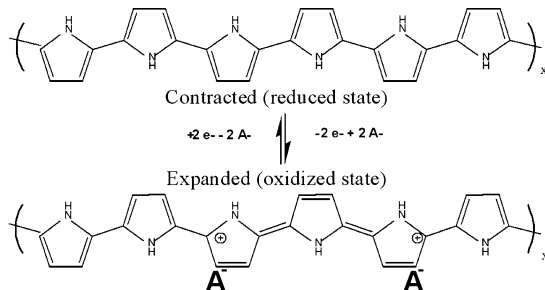


Fig. 4. Structures of three conducting polymers that are employed as actuators.

TABLE V
CONDUCTING POLYMER ACTUATORS

PROPERTY	MIN.	TYP.	MAX.	LIMIT	REFS.
Strain (%)		2	12	> 20	41-44, 60,64
Stress (MPa)		5	34	200	38, 42-45
Work Density (kJ/m ³)		100		1000	38,43
Strain Rate (%/s)		1	12	10,000	46,49
Power (W/kg)			150	100,000	43
Life (cycles)		28,000	800,000		52
Coupling			0.1		45
Efficiency (%)		< 1	18		45
Modulus (GPa)	0.2	0.8	3		43,45,49,52
Tensile Strength (MPa)		30	120	400	38,45
Applied Potential (V)		1.2	10		53
Charge Transfer (C/m ³)	10 ⁷		10 ⁸		43-46
Conductivity (S/m)		10,000	45,000		45,51
Cost (US\$/kg)	3		1000		45

Fig. 5. Conducting polymer actuators undergo dimensional changes in response to changes in oxidation state. In the example shown polypyrrole expands as it is oxidized. Anions (A^{-}) enter to balance charge as electrons are removed. Expansion is generally correlated with net ion flux into the polymers [39].

polymer backbone and a flux of ions to balance charge, as depicted in Fig. 5. This ion flux, which can be accompanied by solvent, is associated with swelling or contraction of the material [38]–[41]. Insertion of ions between polymer chains appears to be primarily responsible for dimensional changes, although conformational changes of the backbone and solvent flux may also play a role. Changes in dimension can also be chemically triggered [41].

3) *Features*: High tensile strengths (can reach >100 MPa [38]), large stresses (up to 34 MPa [42]), and stiffnesses (~ 1 GPa modulus [43]–[45]), combined with low voltages (~ 2 V [38]–[53], [56]–[58]) make this actuator technology attractive.

4) *Limitations*: The electromechanical coupling in these materials is often less than 1%, except at small strains [45], [46]. As a result, efficiency is also low unless a substantial portion of the input energy is recovered. A consequence of the low electromechanical coupling and the low activation voltages is that very high currents can be required to operate at high power [43], putting constraints on the power supply, particularly in autonomous applications. Encapsulation issues need to be addressed in order to isolate actuators from the environment [44], [49], [50], [57], [58]. The moderate strains ($\sim 2\%$) require mechanical amplification in many applications [57]. Strain rates are moderate to small (12%/s max to date). Rates are limited by internal resistance of the polymers and electrolytes, and by ionic diffusion rates of ions inside the polymer [43]–[46].

5) *Modeling*: Experiments show that strain ϵ is proportional to the density of charge ρ transferred over a range of strains of about 1%

$$\epsilon = \frac{\sigma}{E} + \alpha \cdot \rho \quad (4)$$

where σ is the applied stress and E is the elastic modulus [38], [40], [41], [44]–[46]. The strain to charge ratio α is approximately $\pm 1\text{--}5 \times 10^{-10} \text{ m}^3 \cdot \text{C}^{-1}$ ([45, p. 42]). The sign of the strain to charge ratio is negative when cations dominate the ion transfer and positive when it is anions that serve to balance charge [39]. The ion that dominates is generally the smallest of the available cations and anions. For larger strains this relationship continues to hold to first order. At stresses of more than several megapascals, effects of creep and stress relaxation begin to become significant, and so the purely elastic relationship between stress and strain, represented by the first term on the right hand side of (3), is no longer adequate [42].

If the strain to charge ratio is expressed in terms of change in volume per ion transferred, the volume corresponds approximately to the size of an ion ([45, p. 103]), but an intercalation model of actuation is likely an oversimplification. In some cases the polymer may exhibit gel-like behavior, where change in oxidation state is associated with large solvent flux, large volume changes, and significant changes in modulus [60].

Rate of actuation is primarily limited by the rate at which charge can be injected. Charge transfer is restricted by the internal resistance of the cell (when electrochemically activated) and by the rate at which ions are transferred within the polymer [43], [46]. Some of the internal resistance can be compensated for by increasing applied potential in a controlled manner, resulting in substantially improved rates of actuation [53],

[49]. The fastest response is predicted to occur in thin films with closely spaced electrodes that employ highly conducting polymer [43].

6) *Materials and Dimensions*: Polypyrrole and polyaniline are the most widely used materials. There has also been some use of polyacetylenes [48], polythiophenes and polyethyldioxithiophene [56]. Monomers are available (e.g., www.basf.com) for these materials. The most common mode of synthesis is electrodeposition [51], producing thin (~ 40 μm thick) films with typical widths of 10 mm and lengths of up to 1 m or more [45]. Samples can also be electrodeposited as tubes [49], or chemically synthesized [41], [50]. The properties of the polymers are very dependent on the solvent and salts used in deposition [51], [59], and also the electrolyte employed during actuation [39], [44], [52], [59]. The cycle life for example can be extended to approximately 1 million cycles from several tens of thousands by using ionic liquid electrolytes [52].

Forces produced by these actuators have reached tens of Newtons with displacements of several millimeters, and use of mechanical amplification increases displacements up to about 100 mm [57]. Voltages of up to 10 V are used to drive currents that reach several hundred milliamperes. Voltages of only 1–2 V are sufficient for activation, but higher voltages help speed the response [53]. At steady state (no motion) current is minimal, even when forces are applied. Thus a catch state is available, with essentially no energy being expended in order to maintain a constant force.

7) *Temperature*: Little work has been done to characterize the response of conducting polymer actuators under conditions other than room temperature. The conductivities of the polymers are known to be functions of temperature and synthesis conditions [54], [55]. Electrolyte conductivity and ion diffusion rates are anticipated to decrease in proportion to the square root of absolute temperature, thereby affecting rates at low temperatures. Finally, electrolyte freezing will drastically reduce rate. Typical freezing temperatures are between -60 and 0 $^{\circ}\text{C}$.

8) *Applications*: Demonstration braille cells [52] and variable camber blades have been built [57]. On the microscale, cell traps and medical devices are being created.⁴

9) *Potential*: Layers of thin porous films could enable extremely fast, high power response (>100 kW/kg) [43], [45], [46]. Recovery of stored electrochemical energy should enable moderate efficiencies to be achieved even at full strain. Recent results in polypyrrole demonstrate strains of 12% under moderate stresses [0.5 (MPa)] [60]. Newly designed conducting polymers promise larger strains and higher electromechanical coupling, but are still at an early stage of development (see next section).

Data and models valuable to engineering design of conducting polymer actuators, and particularly polypyrrole based actuators, are provided by Madden [43], [46], while a discussion of current status, promise and remaining challenges is given by Smela [59]. A paper by Madden *et al.* in this issue reviews practical considerations associated with the application of conducting polymer actuators.

⁴<http://www.micromuscle.com>

F. Polymeric Molecular Actuators

Muscle employs individual chemically driven molecular conformational changes to produce macroscopic deformation and forces. Synthetic chemistry has produced a number of interesting actuating molecules that contract, slide, rotate, and ratchet on the molecular scale [61]–[63]. Polymeric molecular actuators attempt to harness such molecular interactions on larger scales by linking together many active components into a macromolecule, as depicted in Fig. 6. Actuation is achieved by chemically or electrochemically modifying bonds along polymer chains and between chains to induce conformational changes [64], [67], [68]. Photoinduced changes are also employed [61], [69]. These technologies are at an early stage of research. Two approaches are briefly discussed.

1) *Mechanisms*: Molecular conformational changes are induced in materials designed to utilize a variety of mechanisms such as *cis-trans* photoactivated transitions, molecular bending due to changes in hybridization and π – π molecular dimerization [61], [64]–[69]. In principle, the molecular structural changes are designed in order to maximize mechanical performance.

2) *Example*: *Poly(Calix[4]Arene Bis-Bithiophene)*: Poly(calix[4]arene bis-bithiophene) [poly(CalixBBT)] employs hinge molecules (calix[4]arene) interconnected by rigid rods (quarterthiophene). The rods attract one another in the oxidized state, contracting the material into a folded molecular structure. This molecular contraction is driven by the π – π dimerization (π – π stacking) of thiophene oligomers upon oxidation, which is intended to produce a reversible molecular displacement [64]. The cone conformation of the calix[4]arene scaffold allows generation of an accordion-like molecule upon electrochemical polymerization.

Key features of this material include the deformable calix[4]arene scaffold and the redox active quarterthiophene redox units. The proposed actuation mechanism and a three-dimensional space-filling model are shown conceptually in Fig. 6. The initial polymer displays an equilibrium conformation that has the quarterthiophene groups in a nonaggregated state. Upon oxidation the quarterthiophene groups have a strong tendency to aggregate into π -stacked structure. Inspection of the space-filling model suggests that one-dimensional changes of more than 100% are possible.

The mechanism presented above and referred to as π dimerization or π – π stacking makes use of wavefunction overlap in π -conjugated polymers. The π -dimerization is attractive in the oxidized state (electron deficient) and repulsive in the reduced state (filled electronic levels) [65], [66].

It is hoped that these materials will overcome two limitations of conducting polymer actuators, namely, the limited strain and the low degree electromechanical coupling, while maintaining the advantage of low voltage operation. To date $\sim 20\%$ strains have been reported in similar electrochemically activated π – π -stacking polymers [64].

This technology is in an early phase of research. A challenge is that the new molecules are unlikely to achieve the same high conductivity as polypyrrole and polyaniline. Low conductivity

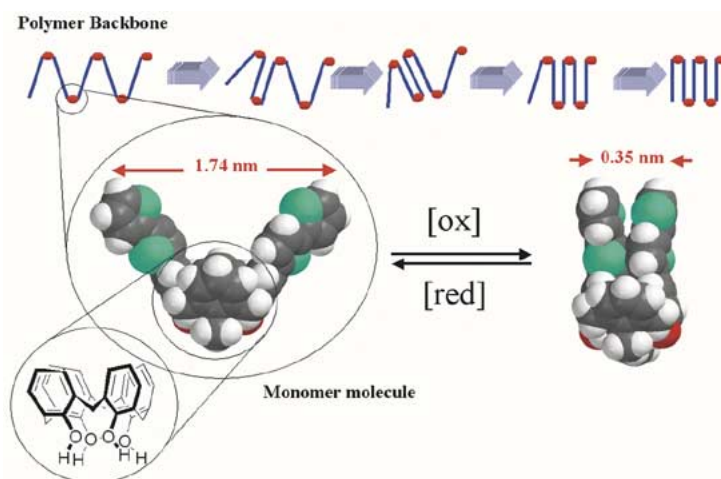


Fig. 6. Schematic of the actuation mechanism of poly(CalixBBT) [64]. The polymer consists of hinge molecules (calix[4]arene) linked by stiff quarterthiophene rods. The polymers are designed such that oxidation of the rods leads to an attractive force between them, resulting in contraction of the polymer.

slows charging and reduces power output [43]. However, conductivity is not as important in these new materials because the number of charges required to achieve displacement is substantially smaller ($\sim 100\times$). A further challenge is to effectively coordinate molecular motions to create larger scale deformations and forces. More information on this technology is provided in a paper by Swager and Yu in this issue.

Marsella and colleagues achieve actuation by electrochemically switching polymerized cyclooctatetraene and related materials. These materials are predicted to undergo reversible planar to “boat”-shape conformational changes. In theory strains should reach $\sim 6\%$ [67], [68]. It remains to be demonstrated that observed actuation in these materials and in the quarterthiophene-based actuators result directly from conformational changes on the backbone, and are not a result instead of ion and solvent insertion.

3) *Photoinduced Mechanical Response in Polymers*: Zimmerman and Stille [61] among others have demonstrated that molecular scale activation can be harnessed to actuate bulk materials using photoactivated cis-trans isomerizations. Molecular force probes have been used to directly measure similar cis-trans isomerizations in single molecules [69]. Three percent strains are observed, which is about half of the 7% strain predicted for these azobenzene based oligomers. Fig. 7 depicts the photoactivated conformational changes that are induced in azobenzene containing polymers.

In order to achieve conversion between cis and trans states an activation barrier must be overcome. Absorbed photons provide the energy to overcome this barrier. Most of the input energy is expended in overcoming the barrier rather than in performing mechanical work. Hugel *et al.* [69] estimate a peak efficiency of 10% for azobenzene, which is reduced to $\sim 6\%$ when the photon energies required to both contract and elongate the polymer are included. Observed efficiencies obtained to date are far lower.

The stress can be estimated from the molecular cross-sectional area and the applied force (200 pN typical, no actuation observed above 500 pN), yielding an estimated peak stress of ~ 1 MPa. If the estimated peak stresses, strains, and efficiencies are to be achieved in bulk materials all molecules must be aligned in the direction of the applied force.

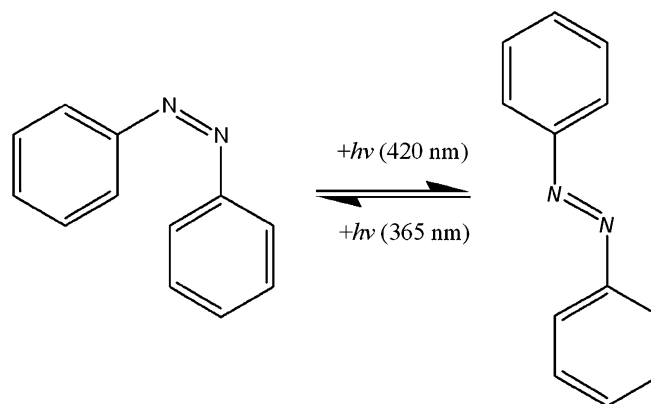


Fig. 7. Schematic of the photoinduced cis (left) to trans conformational change in azobenzene. Monomers containing azobenzene and similar subunits are polymerized to create long actuating molecules [61], [69].

Photoinduced actuation may prove effective for medical applications, micro/nano devices, and perhaps even submersibles tethered to an optical cable.

G. Carbon Nanotube Actuators (Table VI)

Carbon nanotubes (CNTs) are hollow cylinders consisting solely of carbon. These tubes have diameters that are typically 1.2 nm or larger [70], [71]. Their structure is that of a single rolled sheet of graphite that can have lengths on the micrometer scale. These tubes are either conductive or semiconductive, with one-third exhibiting metallic properties [70]. Van der Waal's forces cause the tubes to aggregate in bundles, with bundle diameters of 10 nm being typical in samples used in actuation studies [71]. Multiwall nanotubes are also observed and consist of concentric tubes [70]. Multiwall nanotubes are thought to be less effective actuators because their solvent accessible surface area is typically lower than that of single walled nanotubes, even in bundled form. Surface area is important because actuation is associated with the charging of exposed nanotube surfaces. This is achieved by immersing nanotubes in an electrolyte and applying a potential between the nanotubes and a counter electrode. Ions are attracted to the nanotubes, leading to the accumulation of ionic charge at their surfaces, which is balanced by electronic charge within the tubes. The

TABLE VI
CARBON NANOTUBE ACTUATORS [71], [72], [73], [74]

PROPERTY	TYP.	MAX	LIMIT
Strain (%)	0.2	~1	> 1
Stress (MPa)	1	27 ~0.15 % strain	20,000
Work Density (kJ/m ³)	2	40	3·10 ⁴
Strain Rate (%/s)	0.6	19	190,000
Power (W/kg)	10	270	10 ¹⁰
Coupling (internal)	0.001		0.43
Efficiency (%)	0.1		> 22
Density (kg/m ³)	230	1000	
Modulus (GPa)	1 paper	10 fiber	640 single tube
Tensile Strength (MPa)	5	> 40	40,000
Cycle Life, 1 Hz, ±0.5 V	33 % reduction in strain over 140 kcycles		
Applied Potential (V)	1	30 fast activation	
Charge Transfer (C/m ³)	6·10 ⁶		~10 ⁸
Conductivity (S/m)	40,000		500,000
Cost (US\$/kg)	<< 50,000	500,000	

charging leads to a rearrangement of the electronic structure of the nanotubes, and to Coulombic forces, both of which result in dimensional changes. In tube bundles some slip may also occur between the outer charged tubes and inner isolated layers [74]. For moderate to large levels of charging the Coulombic forces dominate, resulting in a parabolic relationship between strain and applied potential [71]. The parabolic relationship is lost at high potentials as ions and solvent in solution begin to exchange electrons with the nanotubes, discharging the double layer and thereby limiting the maximum achievable strains. Strains reach between 0.1% and approximately 1% [71]. Although these strains are small compared to those obtained in dielectric elastomers and even ferroelectric polymers, individual carbon nanotubes feature high elastic moduli (640 GPa) and enormous tensile strengths ($\gg 1$ GPa), potentially enabling unprecedented work densities to be achieved (~ 200 MJ/m³).

As in conducting polymers, it is the rate at which charge can be injected which determines the strain rate. The enormous internal surface area provided by the carbon nanotubes results in an enormous capacitance (26 F/g) [72]. Given the applied potentials are on the order of 1 V, the resulting charge transfer is ~ 26 C/g. Once again the reduction of cell internal resistance is critical to achieving high strain rates [43]. Speeds of ion transport within the carbon nanotube papers and fibers may also limit rate. As in conducting polymers, very high rates will be observed in nanoscale devices. As an extreme example, in a short 1.2 nm diameter nanotube immersed in aqueous potassium chloride electrolyte that is separated from another tube by 10 nm, the RC charging time constant is estimated to be on the order of 0.1 ns, and the diffusion time constant is approximately 1 ns. In large devices these rates drop off rapidly, with timescales on the order of seconds being typical in actuators that are approximately 30 μ m thick. In composite carbon nanotube fibers in which a binder such as polyvinylalcohol is present [75] rates are

TABLE VII
IONIC POLYMER METAL COMPOSITES

PROPERTY	MIN.	TYP.	MAX.
Strain (%)		0.5 [82]	3.3 [81]
Stress (MPa)	0.23[90]	3 [86]	15 [84,86]
Work Density (kJ/m ³)			5.5 [81]
Strain Rate (%/s)			3.3 [81]
Power (W/kg)			2.56 [81]
Coupling (%)			3
Efficiency (%)		1.5 [86]	2.9 [86]
Modulus (GPa)	0.05[90]	0.1 [90]	
Density (kg/m ³)		1500 [89]	
Applied Potential (V)	1	1-4	7 [89]
Charge Transfer (C/m ³)		900,000	
Charge Transfer (C/m ²)		900	
Cost (US\$/kg)		500	100,000
Min est. materials cost w/ Pt electrodes, Max. - [91].			

much slower still due to the slow rate of ion transport within the binder [74]. If large nanotube actuated devices are to be practical, microstructuring of the materials will be necessary to ensure that electrode spacings, diffusion distances and conduction paths are minimized [43]. Resistance compensation techniques can be employed to improve actuation rates, at the expense of some efficiency [53], [73]. Such techniques have enabled response times of several milliseconds to be achieved and effective strain rates of 19%/s [74].

1) *Materials*: Carbon nanotubes can be synthesized by laser ablation, arc discharge, chemical vapor deposition, and deposition from low cost precursors [70]. They are commercially available from many sources. CNT papers and fibers are filtered [71] or spun [75] from large numbers of nanotubes suspended in solution.

2) *Limitations*: The small to moderate strains require some mechanical amplification for most applications. The electro-mechanical coupling is poor, requiring substantial energy recovery to achieve reasonable efficiencies. The material cost is currently very high ($\sim \$100$ /g). Films and fibers still exhibit bulk mechanical properties that fall far short of those of single nanotubes. This actuator technology is very new, however, and progress on many of these issues is expected to be rapid. Newly reported porous metals and oxides appear to be actuated using mechanisms similar to those in CNTs, and also promise to provide relatively high performance [76].

H. Ionic Polymer/Metal Composites (IPMCs) (Table VII)

An IPMC consists of a polymer electrolyte sandwiched between two thin metal layers [77]–[86].⁵ Deflection of the layered structure toward one of the metal electrodes occurs as a result of a field induced change in ion concentration, which attracts water molecules (or other solvents) to one side of the polymer. The nonuniform distribution of water produces swelling of one side

⁵Biomimetic Products Inc. and EAMEX Corp., <http://www.biomimetic.com/>, <http://www.environmental-robots.com/>, http://www.eamex.co.jp/index_e.html

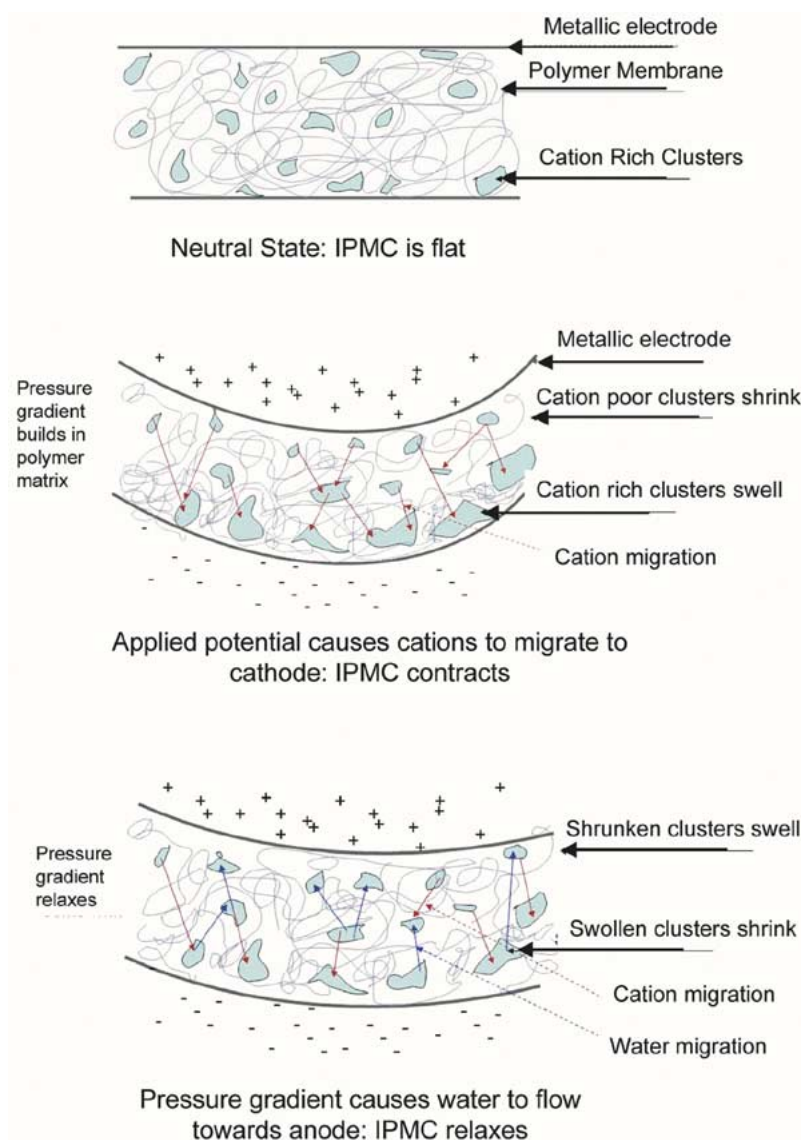


Fig. 8. Mechanisms of IPMC actuation. The clusters shown above represent hydrophilic regions containing ions and solvent.

of the actuator and contraction of the other, generating torque on the member and a bending motion.

1) *Mechanisms*: The ionic polymers used in IPMC actuators are generally negatively charged, with this charge being balanced by mobile cations. There are also pockets of solvent (e.g., water) in which the cations are dissolved. When an electric field is applied across a strip of IPMC, the ions redistribute themselves, resulting in the formation of two thin boundary layers—a cation-poor layer on the anode side of the polymer and a cation-rich layer on the cathode side, as depicted in Fig. 8. As cations travel to the cathode side of the IPMC, water follows, causing the hydrophilic expansion. The strain in the cathode layer induces stresses in the rest of the polymer matrix, resulting in a fast bending motion toward the anode [80], [81]. After this immediate response, the pressure from the strained polymer matrix causes water to diffuse out of the cation-rich areas, resulting in a slow relaxation toward the cathode [80], [81]. Reversing the applied potential inverts the bending and the subsequent relaxation. The degree of actuation exhibited is dependent on the type of polymer, the counter ion used, and amount of water present

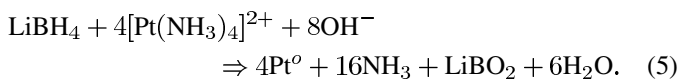
[80] as well as the quality of metallization [83], the thickness [77], and the surface area of the polymer membrane [84].

2) *Materials and Fabrication*: Typical polymers are perfluorinated alkenes with anionic-group-terminated side chains, such as Nafion [77], [79] and Flemion [80] or styrene/divinylbenzene-based polymers with ionic groups substituted from phenyl rings [77]–[79]. Styrene/divinylbenzene based polymers tend to be highly cross-linked, so their potential as an actuator is severely limited by their stiffness. The perfluorinated alkenes form a more flexible matrix [77]–[79]. In the IPMC matrix, the backbone of the polymer is hydrophobic while the anionic sidechains are hydrophilic. This causes the polymers to make clusters of concentrated anions, neutralizing cations and water within the polymer network [79]–[83].

In most cases, a commercially available polymer membrane is used for the polymer layer. These membranes are not manufactured specifically for IPMCs, however, and limit the choice of film thicknesses [77]. Kim and Shahinpoor have addressed this problem by solution recasting Nafion to thicknesses ranging from 30 μm to 2 mm [77]. Noh *et al.* also used a recasting

method to make Nafion membranes with much higher surface area [84].

Both sides of the polymer membrane are loaded with metal nanoparticles and then metal plated [77]–[85]. The nanoparticles balance the charging that occurs in the boundary layers of the polymer, while the metal plating increases surface conductivity and reduces solvent loss upon actuation [86]. The metal nanoparticles are usually 3–10 nm in diameter and are distributed in a 10–20 μm deep layer at both surfaces. This is often done by allowing the polymer to soak in a solution containing a metal salt, such as $\text{Pt}(\text{NH}_3)_4\text{HCl}$, so the metal ions can diffuse into the polymer. The polymer is then treated with a reducing agent, such as LiBH_4 or NaBH_4 , to metalize. The primary reaction for platinum IPMCs is as follows [77]–[79], [82]–[85]:



This metallization process is expensive. Shahinpoor and Kim have shown that the cost can be reduced by physically loading the metal particles into the polymer [79]. The electrode layer can then be deposited onto the surfaces. IPMCs manufactured in this way have shown comparable properties to chemically loaded IPMCs, at 1/10 of the manufacturing cost [79].

After the metal particles have been incorporated into the polymer, a metal coating (usually 1–5 μm thick) is deposited [79]. This plating involves reduction of a metal salt, but instead of impregnating the metal into the polymer the reaction coats the surface of the composite. Electrode materials that have been successfully used for this process include platinum, palladium, silver, gold, carbon, copper, graphite, and carbon nanotubes [79], [83]. Platinum is most commonly used as it has the widest potential region over which it is resistant to corrosion, enabling larger deflection and higher work density. The metal electrode reduces the surface-electrode resistance down to as little as 8.6% of its original value [83], enabling higher current densities and faster actuation.

IPMCs are further described in a paper by Paquette and Kim in this issue, and more details on the manufacturing of IPMCs are available in a recently written review [86]. Samples are now commercially available.

A number of swimming and flapping applications of IPMCs have been reported, representing preliminary uses of polymer artificial muscle technology for hydrodynamic propulsion [87], [88].

I. Thermally Activated Shape Memory Alloys (SMAs) (Table VIII)

Over a century after Joule's discovery of the equivalence of energy and heat the shape memory effect was reported by Chang and Read [93]. They observed that an alloy of gold and copper returns to the same shape if heated after deformation. The same effect was later discovered in indium–titanium alloys by Basinski and Christian [89], and nickel–titanium alloys by Buehler *et al.* [92]. These researchers used the term “shape memory effect” (SMA) to describe the phenomena. Of all the SMAs, nickel–titanium (NiTi) alloys (better known as Nitinol) are the most extensively studied [95]. NiTi fibers and springs

TABLE VIII
THERMAL SHAPE MEMORY ALLOYS [2]

PROPERTY	MIN.	TYP.	MAX.
Strain (%)		5	8
Stress (MPa)			200
Work Density (kJ/m^3)		1,000	10,000
Strain Rate (%/s)		300	
Power (W/kg)		1,000	>50,000
Life (cycles) at a amplitude strain of:	300 ~ 5 %		10^7 ~ 0.5 %
Efficiency (%)			< 5
Modulus (GPa)	20		83
Tensile Strength (MPa)		1,000	
Density (kg/m^3)		6,450	
Applied Potential (V)		4	
Conductivity (S/cm)		12500	14250
Cost ($\text{US\$}/\text{kg}$)		300	

have often been studied and used as artificial muscles [91], [96], [98], [101], [102] because of their relative nontoxicity, reasonable cost, and an electrical resistivity that easily lends itself to Joule heating (passing of an electrical current to generate heat).

1) *Mechanism:* Martensitic transformations are at the heart of the shape memory effect as shown by Otsuka and Shimizu [104]. Martensitic transformations were discovered by the metallurgist Adolf Martens in steels [105]. It was found that the transformation from the high-temperature, body-centered cubic lattice austenitic phase to the low temperature, face-centered tetragonal lattice takes place without atomic diffusion. Martensitic transformations are phase changes that occur as a displacive, lattice-distortive, first order diffusionless athermal transformations. In NiTi alloys with a surplus of nickel or with nickel partly replaced with a third element, a two-stage martensitic transformation may occur. The intermediate phase has a rhombohedral crystal structure.

In most NiTi alloys the shape memory effect is only observed when an external stress is applied. In the martensitic phase the alloy has a twinned martensite that can be easily deformed as it de-twins. As it is heated it returns to its parent austenitic phase, which is a highly ordered state, and the alloy retrieves a well defined high-temperature shape.

NiTi alloys may also exhibit a two-way shape memory effect (TWSM) first observed by Delaey *et al.* in 1975 and by which the alloy will exhibit the shape memory effect without an external stress [94]. In the two-way shape memory effect NiTi alloys also have a “remembered” state at low temperature as well as all the intermediate shapes between the high temperature and low temperature. The origin of TWSM is stress-biased martensite and it can only be obtained by special conditioning involving thermomechanical treatment.

The contraction time of NiTi is governed by the speed at which the martensitic to austenitic phase transformation occurs and hence by the electrical power when electrical Joule heating is used. By using very large current pulses this contraction time can be reduced to several milliseconds [101]. The NiTi contraction and expansion cycles are mainly limited by the time

required for NiTi to cool and return to its lower temperature shape. The cooling time is governed by thermal diffusion and convection. Factors such as **heat capacity and latent heat involved in the phase transformation** between the austenitic and martensitic phases **must be considered** when designing an actuator. **Use of water cooling and nucleate boiling can dramatically reduce cooling time, enabling millisecond response times** [101].

2) *Features* [89]–[105]: Shape memory alloys can exert very **large forces per unit area** (exceeding 200 MPa), operate at **very high strain rates** (300%/s) and undergo relatively **large deformations** (>5% for polycrystalline NiTi fibers). The peak energy density ($10^7 \text{ J}\cdot\text{m}^{-3}$) and power per unit mass ($50 \text{ kW}\cdot\text{kg}^{-1}$) of these actuators is unmatched.

3) *Limitations*: SMAs have several characteristics that impede their use as muscle-like actuators. One of them is the **difficulty of controlling the length of NiTi fibers as they undergo a phase transformation**. The change in length is observed over a narrow temperature range and a significant hysteresis is observed between the martensitic to austenitic and austenitic to martensitic phases. The phase transformation temperatures vary more or less linearly with stress and the cycling characteristics also change if only partial transformations occur. All of these factors must be modeled appropriately when NiTi fibers are used in a servo-actuator.

NiTi actuators also have a limited cycle life. At very large strains their shape memory effect degrades significantly, from millions of cycles at 0.5% strains to a few hundred cycles at strains of 5% [95] depending on the alloy and conditioning. Their usage is also limited by the **low efficiency of NiTi fibers in converting electrical energy to mechanical work** which is found to be **5% in the best case** (including recovery of energy from heat, [103]) and is usually much lower.

4) *Materials*: Nickel–titanium shape memory alloys are commercially available from several sources including Shape Memory Applications Inc. (<http://www.sma-inc.com>)

5) *Applications*: NiTi wires, tubes, and components are widely used in medical applications due to their super-elasticity, a property related to the memory effect. Little use is made of the actuation properties.

J. Ferromagnetic Shape Memory Alloys (FSMAs) (Table IX)

Interest in the conversion of magnetic energy to mechanical work dates back to Joule and his discovery of the magnetostrictive effect, in which he measured microstrain in a nickel rod placed in a magnetic field. Little advance had been made in the capabilities of magnetic actuators until work on lanthanide metals led to the discovery and development of giant magnetostrictive materials. These materials continue to be a viable actuator choice to this day, with the benchmark, the commercially available alloy Terfenol-D ($\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$) obtaining typical strains of 0.2% at fields of 2000 kA/m against 20 MPa stresses and with frequency responses in the kilohertz range. More information on these materials is available from reviews on giant magnetostrictive materials by Clark [106] and Jiles [107], and in commercial specifications.⁶ Modeling [108], and samples of

TABLE IX
FERROMAGNETIC SHAPE MEMORY ALLOYS [115], [116], [119]

PROPERTY	MIN.	TYP.	MAX.
Strain (%)		6	10
Stress (MPa)	0.005	1	9
Work Density (kJ/m^3)	< 1 including coils	100 without coils	
Strain Rate (%/s)		10,000 (5% @ 1kHz)	
Coupling (%)		75	100 theorized
Density (kg/m^3)		8000	
Modulus (GPa)	0.02 mixed variant	2	90
Saturation Magnetization, $\mu_0 M$ (T)		0.6	
Cost (US\$/kg)		10,000	

characterization and device research [109]–[111], are also found in the literature.

While the giant magnetostrictive materials provide a small stroke actuator technology, discovery of the shape memory effect in a magnetic material led to the development of ferromagnetic shape memory alloys (FSMAs). Following the discovery of the thermally induced martensitic transformation below the Curie temperature in the ferromagnetic Ni_2MnGa Heusler alloy in 1995 [112], it was postulated that large strains could also be obtained magnetically. Scarcely a year later, strains of 0.2% were observed in a single crystal of the same composition upon the rotation of a magnetic (H) field of order 600 kA/m [113], surpassing the strains achieved with Terfenol-D. Further investigation into the effects of **varying the atomic composition of the alloy on the martensitic transition and Curie temperatures** [114] along with better characterization techniques have since led to measurements of 6% [115] and even 10% [116] linear strains under applied fields of the same order of magnitude. **These strains may be obtained against stresses of order 1 MPa and with response times in the milliseconds at room temperature.**

1) *Mechanism*: The mechanism involves transitions between variants of the tetragonal martensite phase that are formed upon cooling from the cubic austenite phase. The martensite unit cell is shorter than the cubic cell in one axis (typically referred to as the c-axis) and longer in the other two. Cooling under zero load results in the presence of all three possible anisotropic variants organized into domains. The martensite unit cell is magnetically easy along its shortest (c) axis and may be transformed into one of its orthogonally aligned neighbor variants mechanically or magnetically. Typically, samples are prestressed in compression to align the sample along the shorter c-axis. Upon the application of a magnetic field orthogonal to the direction of stress, regions of the magnetically favored variant nucleate and grow. These regions may be monitored by the appearance of twin boundaries, which are observed to move along the sample as the intensity of the field is increased [117], [118]. The magnitude of the bias or prestress is important as an insufficient stress will leave the sample uncompressed and an

⁶<http://www.etrema-usa.com>

overstress will block the transition. **Blocking stresses between 2 and 9 MPa have been reported [115]. Following the removal of the field, stresses above 0.5 MPa are sufficient to return the sample to original dimensions [115].**

2) *Modeling*: Modeling of the FSMA effect is complicated by the many responses a material may exhibit under a large magnetic field. O'Handley first discussed this phenomenon in terms of the anisotropy energy, or energy required to change the magnetization of the material away from its easy axis [120]. Simple rotation of the magnetization and subsequent crystalline distortion is the basis for magnetostriction and has led to some confusion within the FSMA literature. In the case of FSMA materials, however, the anisotropy energy is relatively large, resulting in the favorable transformation of the unit cell into an orthogonally aligned variant. This changes the crystal lattice but keeps the magnetization in the easy axis. Further development of the model [121] along with experimental results have led to the following expression for strain, ε , as a function of magnetic field H

$$\varepsilon(H) = [2 \cdot K_u \cdot h \cdot (1 - h/2) - \sigma \cdot \varepsilon_o] / (C_{\text{eff}} \varepsilon_o) \quad (6)$$

where K_u is the uniaxial anisotropy constant, typically of order $1 \cdot 10^5 \text{ J/m}^3$, $h = (M_s \cdot H_o) / (2 \cdot K_u)$ is the ratio of magnetic saturation multiplied by the applied field to twice the anisotropy constant, σ is the uniaxial applied stress, ε_o is the maximum transformation strain (taken to be 0.06 in [115]), and C_{eff} is the effective modulus of the twinned state, taken to be 20 GPa [115].

A simpler mechanistic approach was proposed by Tickle *et al.* [122], in which it was postulated that the easy axis remain fixed to the crystal lattice and the strain response governed by the volume fraction of each of the three variants. This approach led to linear models of the average magnetization and the average uniaxial strain $\langle \varepsilon \rangle$

$$\langle \varepsilon \cdot \hat{e}_1 \rangle = \varepsilon_2 \cdot \xi_1 + \varepsilon_1 \cdot (\xi_2 + \xi_3) \quad (7)$$

where ε_1 and ε_2 are the strains associated with the long and short axes, $\hat{e}_1$, and $\hat{e}_2$, of the martensite, taken to be 0.013 and -0.048 , respectively, in the reference, and ξ_i is the volume fraction of the variant with its easy axis in the i direction. Note that the model is oriented along the $\hat{e}_1$ axis. By combining the volume fraction strain model with the magnetic saturation, qualitative predictions of strain and strain direction are achieved.

3) *Materials*: Single crystal Ni_2MnGa and slight variations are used. Other ferromagnetic alloys (such as Fe-Pd and Fe-Ni-Co-Ti) show similar effects, but smaller strains. Polycrystalline Ni_2MnGa also exhibits FSMA behavior, but at reduced strains due to alignment and loading within a matrix [123].

4) *Features*: **Large strains ($\sim 10\%$) are obtained in stiff (up to 90 GPa modulus) crystalline alloy systems. Fast response ($\sim 1 \text{ kHz}$) and reasonable cycle life ($\sim 5 \times 10^7$ cycles) are also observed in the commercially available materials.⁷**

5) *Limitations*: **High intensity magnetic fields are required ($\sim 600 \text{ kA/m}$) and the fields need to be applied orthogonal to stroke direction, adding challenge to the device design.** Although the stresses against which the actuators will work are relatively large (several megapascals), this stress value does

not account for the cross-sectional area needed to generate the magnetic fields. For example, in Adaptamat Ltd. products the active material produces 1 MPa stresses, but once the coils necessary to produce field are added, the effective stress drops to $< 20 \text{ kPa}$. The presence of the coils also drops the work density to $0.12 \text{ kJ}\cdot\text{m}^{-3}$. Furthermore, repeated actuation requires a compressive restoring force (e.g., a spring). Finally, modulus appears to change tremendously via mechanical alignment of the twin variants in the martensite phase (dropping to 0.02 GPa as the sample transitions from multiple variants to one single variant [115]). The compliance may result in low resonance frequencies.

6) *Temperature*: Operation must be near the martensitic transformation temperature (ranging between 200–350 K) and below Curie temperature (325–350 K), both of which vary with composition [114].

7) *Applications*: **Linear motors are available from Adaptamat Ltd. operating with strains $\sim 3\%$ at 2 MPa** (not including the electromagnets).

8) *Potential*: Observed strain has reached the known theoretical limit. However, new passive shape memory effect discoveries may lead to higher strains [124].

III. CASE STUDIES

Two case studies that represent promising applications of artificial muscle technology are presented. Both applications are targeted at AUVs, where size, power consumption, and cost need to be minimized. The examples represent situations that are very commonly encountered in engineering design across all applications. In the first case, varying propeller blade camber using artificial muscle is proposed. In the second, amplification of propeller thrust by the generation of unsteady flow is presented. In the first application rates are relatively slow—the challenge is to incorporate the actuator within the space allotted. In the second, specific power and fuel efficiency become critical.

A. Case Study: Variable Camber Propeller

Controllable pitch propellers are employed in situations where vessels operate under a range of flow conditions. The hypothesis is that AUVs could benefit tremendously from the added efficiency, maneuverability, and the potentially lower noise emissions afforded by variable shape propellers [87]. The objective is to find an alternative to the gearing mechanisms employed in larger vessels, in which force and displacement are projected down a rotating shaft to the blades. We seek to determine, based on the force and displacement requirements, whether any of the artificial muscle technologies are suitable for this application.

The target vehicle for variable camber is the Expendable, Mobile Antisubmarine Warfare Training Target (EMATT) from Sippecan Inc, Marion, MA. The expendable nature of the vehicle makes cost a key consideration. (Details on this application are provided in an accompanying article by Madden in this issue, and in [125].)

1) *Specifications*: This design is for a propeller blade that has a span (length) of 50 mm, a chord (width) of 25 mm, and an average thickness of 6 mm. The last 10 mm of the chord at

⁷<http://www.adaptamat.com>

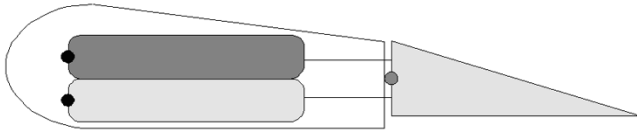


Fig. 9. Lever arm design for creating variable camber. The triangular tail section pivots about a joint (gray circle). Torque is applied to the trailing edge section via an antagonistic actuator pair (ovals) coupled via tendons.

the trailing edge can be pivoted so as to enable variable camber. Fig. 9 shows the approximate geometry. The angle of the trailing edge is to be adjusted up or down by 22° under a force of up to 3.5 N. The dimensions and blade loading are estimated based on the specifications, size and speed of the EMATT vehicle. The numbers are not exact, but allow a demonstration of the methodology used in actuator selection.

In order to simplify the calculations the unknown distribution of the force is applied at a single point at 3 mm from the trailing edge, or, equivalently, 7 mm from the pivot point. The force of 3.5 N generates a torque of $T = 25 \text{ mN}\cdot\text{m}$ about the pivot. If the angle of deflection is $\theta = 45^\circ$, the work that must be done is $W = T \cdot \theta = (25 \text{ mN}\cdot\text{m}) \times (\pi/4) = 19 \text{ mJ}$.

In the EMATT vehicle a dc electrical power source composed of 15 DD size lithium primary batteries is capable of delivering up to 9 A at battery voltages. The vehicle mission lifetime is up to ten hours, over which time up to 10 000 actuation cycles will be performed. Typically these vehicles are expendable, as their name implies, so the mission length represents the total lifetime. Minimizing cost is also be important in these AUVs.

Will the actuator fit within the space? Ideally the mechanism employed will fit within a propeller blade. The nonpivoting portion of each blade has a volume of $6 \text{ mm} \times 15 \text{ mm} \times 50 \text{ mm} = 4.5 \times 10^{-6} \text{ m}^3$. Given the required work, the minimum work density in order to fit the actuator within the propeller volume is approximately $4.2 \text{ kJ}\cdot\text{m}^{-3}$. In fact the work density will need to be at least double this value, or $>8 \text{ kJ}\cdot\text{m}^{-3}$ as otherwise no space is allotted for structural elements, power delivery, encapsulation and any desired sensors. The higher the work density of an actuator material is above this value, the smaller the volume that will be required and the easier will be the fit.

The data in Table X suggest that silicone dielectric elastomers and IPMCs do not currently demonstrate sufficient work density for this application. Inclusion of activation coils needed to generate magnetic field in the energy density calculation eliminates the ferromagnetic SMAs. Note that the lower energy densities of these technologies could be compensated for by using multiple actuator strokes to deflect the trailing edge (e.g., using a ratchet mechanism). However, this adds to the complexity and cost of the device.

2) *Mechanical Amplification*: The linear actuators discussed range in strain from less than 1% to more than 100%, and the stresses from the low kPa range up to 200 MPa. If the force divided by the cross-sectional area of the blade ($3.5 \text{ N}/(50 \text{ mm} \times 6 \text{ mm}) = 12 \text{ kPa}$) is less than the stress that an actuator is capable of generating, then no amplification of the force is required. Furthermore, if the strain multiplied by the length of the actuator is roughly equal to the required displacement of the trailing edge ($=3 \text{ mm} \times \sin(45^\circ)/15 \text{ mm} = 14\%$

TABLE X
COMPARISON OF WORK DENSITIES AND STRAINS

MATERIAL	WORK DENSITY (kJ/m^3)	STRAIN (%)
Skeletal Muscle	< 40	20
IPMC	5.5	0.5
Dielectric Elastomer (Silicone)	10 [#]	120 max
Field Driven Liquid Crystal Elastomer [39]	20 [#]	2
Carbon Nanotubes	40	0.2
Thermal Liquid Crystal	56	19 - 45
Ferromagnetic SMA	100 [*]	6
Conducting Polymer	100	2
Dielectric Elastomer (VHB)	150 [#]	380 max
Ferroelectric Polymers	320 [#]	3.5
Thermal SMA	1000	5

[#] Represents internal energy density that must be coupled to the load.

^{*} Coupling will reduce energy density by a factor of 2 at least.

^{*} Does not include the coil volume.

strain), then little or no amplification of the strain is required, simplifying design and fabrication. (In this estimate it is assumed that some mechanical amplification is occurring, with the actuators attaching at points 3 mm above and below the joint, and the actuators running the length of the leading section. This amplification will roughly require a doubling of the actuator stress.) The ideal actuator will feature both high strain and high stress. Low values of either indicate a need for mechanical amplification, and the smaller the values the greater the amplification.

Based on strains, as listed in Table X, carbon nanotube actuators are excluded from initial consideration as a mechanical amplification factor of 70 is needed. As carbon nanotube energy densities get closer to the upper bound of $30 \text{ MJ}/\text{m}^3$ (determined by the properties of individual tubes) the relatively small strains should eventually be compensated for by the minimal actuator volume requirements, making mechanical amplification worthwhile.

3) *Example—Thermal LCE Actuation*: To make these considerations more concrete, consider designing a liquid crystal elastomer-based actuator for this application. The highest strain thermal liquid crystal elastomer reported in the literature [34] deforms by 40% under a load of 140 kPa yielding a work density of $56 \text{ kJ}/\text{m}^3$, well over the required work density.

As a simple design exercise, we can model a lever arm that pulls around the pivot, as depicted in Fig. 9, deflecting the trailing edge segment. If the muscle attachment points are a distance of 2 mm from the pivot (in the vertical direction), the muscles must exert a force F to balance the torques

$$F = \frac{(3.5 \text{ N})(7 \text{ mm})}{(2 \text{ mm})} = 12.5 \text{ N}. \quad (8)$$

The liquid crystal elastomer can exert a stress of 140 kPa and thus the cross-sectional area needed to generate a force of 12.5 N is

$$A = \frac{12.5 \text{ N}}{140 \text{ kPa}} = 90 \times 10^{-6} \text{ m}^2 \quad (9)$$

or, if the width of the muscle is taken to be the length of the blade (50 mm), the thickness h of the muscle must be

$$h = \frac{A}{L} = 1.8 \text{ mm.} \quad (10)$$

The muscle length that is needed to get a 45° rotation of the trailing edge is roughly $\Delta x = 2 \text{ mm} \times \sin(45^\circ) = 1.4 \text{ mm}$. If the total strain of the actuator is 40%, then an actuator length of only 3.5 mm is needed to give the required deflection. The calculations show that an LCE actuator could be used for this application based on these considerations alone.

In changing camber, a 1 s response time is ample. All the actuators presented can reach this target. However, thermally activated liquid crystal elastomers, in which heat must be transferred to or from the polymer, will need to be laminated into layers on the order of $100 \mu\text{m}$ in thickness, and have a mechanism for transferring heat to and from each layer [refer to (3)]. Increasing temperature of the elastomer is relatively easy as this can be done via resistive heating. Removing heat will be more challenging, likely requiring a copper heat sinks or even water cooling.

Conducting polymers must also be laminated in order to achieve the required response time [43]. The actuator material thickness cannot exceed $\sim 30 \mu\text{m}$ if the actuator is to respond within 1 s—otherwise diffusion of ions into the polymer will be too slow. A laminated or porous structure is required. Other actuators will require laminated structures, but for different reasons. In dielectric elastomers and relaxor ferroelectrics thin layers ($\sim 100 \mu\text{m}$ thick) are used to keep voltages in the low kilovolt range. Thermally activated shape memory alloys employ wires that are $\sim 100 \mu\text{m}$ in diameter. Larger diameters would reduce resistance and may require excessive currents during Joule heating. Like LCEs, SMAs will require cooling.

4) *Voltage Requirements:* Ferroelectric polymers, dielectric elastomers, and, to a lesser degree, field driven liquid crystal elastomers all require high fields in order to produce substantial displacement. In order to prevent voltages from being excessive, these materials will need to be layered. One hundred μm thick layers require 1.5 kV in ferroelectric polymers and dielectric elastomers, and as low as 150 V in LCEs. For optimum performance, these layers should also be prestrained, adding to complexity of assembly. Note that for the ferroelectrics and dielectric elastomers in particular, additional cost and space will be needed for dc–dc power converters [125].

5) *Catch State:* In varying camber it is anticipated that one angle of deflection may prove optimal over long periods of time. Thus, it is best if no power input is required to maintain the desired position. Thermally activated SMAs and LCEs generally require continued heat input in order to hold a fixed position, and thus consume substantial power even when no work is being performed. As a result, SMAs and thermal LCEs are not suited for steady state applications.

6) *Continuously Variable Positioning:* Actuation of SMAs (including ferromagnetics) involves phase changes. It is easy to run these phase changes to completion each time actuation is performed, but it is a challenge to control the phases such that an intermediate state is reliably reached [2]. For this reason SMAs and thermal liquid crystals are again not appropriate for the variable camber application.

TABLE XI
ACTUATOR SELECTION: VARIABLE CAMBER

MATERIAL	ACCEPT?	POTENTIAL PROBLEMS
Skeletal Muscle	No	Not an engineering material (yet).
Ferromagnetic SMA	No	Coil volume prohibitive. Binary positioning only.
Dielectric Elastomer (Silicone)	o.k.	High voltage requirement & encapsulation. Energy density only just sufficient.
Carbon Nanotubes	No	Strain too small.
IPMC	No	Work density too low.
Thermal Liquid Crystal Elastomer	No	Heat exchange, control & no catch state.
Dielectric Elastomer (VHB)	Yes	High voltage & encapsulation
Conducting Polymer	Yes	Lamination, encapsulation & amplification.
Ferroelectric Polymers	Yes	High voltage & encapsulation.
Thermal SMA	No	Binary positioning only, no catch state.
Field Driven Liquid Crystal [36]	No	Not enough work density. Mechanical & voltage amplification required.

Having considered energy density, mechanical amplification, voltage, controllability, and energy expenditure, each actuator technology may be accepted or rejected, as presented in Table XI.

Table XI lists candidate actuator technologies that are potentially suitable for the variable camber application. Of these VHB-based dielectric elastomers, ferroelectric polymers, and conducting polymers are most attractive on a work density basis. Field actuated liquid crystal elastomers are eliminated from consideration because although their work density exceeds the 8 kJ/m³ required, the useable work density will be at least a factor of four lower. The listed work density is internal energy, or which at most half can be extracted, bringing the effective work density to $< 10 \text{ kJ/m}^3$. Furthermore, the actuation mechanism will likely require antagonistic pairs of actuators, each of which actuate for only half of the stroke, thereby reducing the effective work density to $< 5 \text{ kJ/m}^3$, below the desired 8 kJ/m³.

Encapsulation of the actuators to separate them from the saline environment is a technological challenge remaining for all the technologies. Conversion of the available power to kilovolt level potentials will be required in order to operate dielectric elastomers and relaxor ferroelectric polymers. The relatively low degree of electromagnetic coupling in conducting polymers will make energy recovery circuitry necessary in cases where camber is being varied often or continuously as otherwise substantial energy may be required, significantly shortening the life of the power source.

Three technologies are promising for the variable camber application, namely dielectric elastomers, conducting polymers, and ferroelectric polymers.

B. Case Study 2: Unsteady Flow Hydrodynamics

Flapping and rolling motions in a critical range of frequencies to foils and propellers may increase thrust for a given propeller rotation rate (e.g., see Triantafyllou *et al.* in this issue). Lower

TABLE XII
ACTUATOR SUMMARY

Actuator	Advantages	Disadvantages	Comments
Mammalian Skeletal Muscle	Large strains (20 %). Moderate Stress (350 kPa blocking). Variable stiffness. High energy fuel (20-40 MJ/kg). Efficient (~ 40 %). Good work density (< 40 kJ/kg). High cycle life (by regeneration).	Not yet an engineering material. Narrow temperature range of operation. No catch state (expends energy to maintain a force w/o moving, unlike mollusk muscle).	Incredibly elegant mechanism that is a challenge to emulate. Muscle is a 3D nanofabricated system with integrated sensors, energy delivery, waste/heat removal, local energy supply and repair mechanisms.
Dielectric Elastomers	Large strain (20% - 380 %). Moderate stress (several MPa peak). Large work density (10k to 3.4 MJ/m ³). Moderate to high bandwidth (10 Hz to > 1 kHz). Low cost. Low current. Good electromechanical coupling & efficiency (> 15 % typical, 90 % max).	High voltages (> 1 kV) and fields (~150 MV/m). Typically requires DC-DC converters. Compliant ($E \sim 1$ MPa). Pre-stretching mechanisms currently add substantial mass and volume, reducing actual work density and stress.	Potential to lower fields using high dielectric materials. Small devices are favored for high frequency operation eg. MEMS. (due to the more efficient heat transfer which prevents thermal degradation, and the higher resonant frequencies). Starting materials are readily available.
Relaxor Ferroelectric Polymers	Moderate strain (< 7 %). High stress (45 MPa blocking). Very high work density (up to 1 MJ/m ³ internal strain). Stiff (400 MPa). Strong coupling (0.4) & efficiency. Low current.	High voltages (typically > 1kV) and fields (~150 MV/m). Typically need DC-DC converters. Synthesis of typical materials involves environmentally regulated substances. Cycle life is unclear & may be limited by electrode fatigue and dissipation. Limited temperature range.	Lower voltages and fields are being achieved using new high dielectric composites. Small devices are favored for high frequency operation eg. MEMS. Unique combination of high stiffness, moderate strain & reasonable efficiency.
Liquid Crystal Elastomers	Large strains in thermally induced materials (45%). Moderate strains in field induced materials (2-4 %). High coupling (75%) in electrical materials.	Subject to creep. Thermal versions are slow unless very thin or photoactivated. High fields (1-25 MV/m). Low efficiency in thermal materials.	New material with much promise and much characterization to be done. Photo-activation has been achieved.
Conducting Polymers	High stress (34 MPa max, 5 MPa typical). Moderate strain (~ 2 %). Low voltage (~ 2 V). High work density (100 kJ/m ³). Stiff polymers (~ 1 GPa).	Low electromechanical coupling. Currently slow (several hertz maximum to obtain full strain). Typically needs encapsulation.	Promising for low voltage applications. Speed and power will improve dramatically at small scales.
Molecular Actuators	Large strain (20 %). Moderate to high stress (> 1 MPa). Low voltage (2 V). High work density (> 100 kJ/m ³)	Currently slow. Need encapsulation.	Great promise of overcoming many of the shortcomings of conducting polymer actuators, but still very early in development.
Carbon Nanotubes	High stress (> 10 MPa). Low voltage (2 V). Very large operating temperature range.	Small strain (0.2 % typical). Currently has low coupling. Materials are presently expensive.	Great potential as bulk materials approach properties of individual nanotubes.
Ionic Polymer Metal Composites (IPMC)	Low Voltage (< 10 V). Large displacement (mechanical amplification built into the structure).	Low coupling and efficiency. Usually no catch state (consumes energy in holding a position). Requires encapsulation.	IPMC driven toys and demonstration kits are available.
Thermally Activated Shape Memory Alloys	Very high stress (200 MPa). Unmatched specific power (> 100 kW/kg). Moderate to large strain (1-8 %). Low voltage (actual voltage depends on wiring). Great work density (> 1 MJ/m ³)	Difficult to control (usually run between fully contracted and fully extended but not between). Large currents and low efficiencies (<5%). Cycle life is very short at large strain amplitudes.	Readily available. Generally thought of as slow, but can achieve millisecond response times using short high current pulses and water cooling.
Ferromagnetic Shape Memory Alloys	High stress (< 9 MPa). High frequency (> 100 Hz). Moderate strain (up to 10%). High coupling (75%).	Bulky magnets are required which greatly reduce the work density. Costly single crystal materials.	Operates in compression and thus needs a restoring force. Displacement is typically all or nothing, as intermediate states are difficult to reach reproducibly. Commercially available.

rotation rates can thus be used for a given thrust level, which has implications for noise emission [87].

Can the artificial muscle technologies meet the demands of this high power application?

The Remus AUV⁸ is chosen as an example platform for application of novel propulsion concepts. Remus has been

⁸<http://www.hydroidinc.com/>

selected by the U.S. Navy for performing very shallow water mine counter measures (VSW-MCM).

1) *Rate*: The Remus propeller runs at ~ 25 Hz. To create optimum unsteady flow conditions, the blades must then flap at > 50 Hz. This bandwidth requirement immediately eliminates thermally activated LCEs, IPMCs, and conducting polymers as candidate materials. As discussed above, it should be possible to drive these materials up to kilohertz frequencies by modifying their geometries, but current demonstrations operate at only several hertz. Based on speed of response alone the candidate actuator technologies are reduced to thermal SMA, ferroelectric polymers, ferromagnetic SMAs, silicone elastomers, carbon nanotubes, and field driven liquid crystal elastomers.

2) *Cycle Life*: A Remus mission lasts up to 22 h, which corresponds to ~ 4 million actuator cycles. This cycle number is approaching or exceeding the limits so far measured for most technologies. In order to achieve this cycle number, the amplitude of actuation will need to be reduced to $< 3\%$ in thermally activated SMAs. Actuators will generally need to be replaced following each mission.

3) *Input Energy and Power*: Remus is equipped with a 1 kW·h lithium ion cell. Thermally activated SMAs and LCEs as well as conducting polymers, carbon nanotubes, and IPMCs all operate at low voltages and are thus well matched to the lithium ion cell. The low electromechanical coupling of these actuators however results in input electrical powers that are $\sim 100\times$ greater than the work output resulting in a need for currents that are $\sim 100\times$ larger than are needed for an actuator with perfect coupling. The battery thus drains $\sim 100\times$ faster, and $100\times$ more power is demanded. The battery mass required in order to employ the flapping foil actuators would need to be about 30 times greater than it is at present to generate the required currents. Rates of energy expenditure can be reduced by recovering stored energy in some actuators, thereby improving efficiency. However, high currents will still be needed, which will result in more battery mass being required due to the relatively low power to mass of battery technologies. Therefore these low voltage actuator technologies are not currently practical for such high bandwidth, high power applications when only finite energy and power are available.

In ferroelectrics and dielectric elastomers, dc to dc converters will be required to convert battery voltages to kilovolt levels. It remains to be determined how much space this will occupy over and above the cell. Energy recovery circuitry may also be needed to obtain reasonable efficiencies and mission lengths in these actuators, further increasing the volume required.

Ferromagnetic SMAs can easily achieve the required bandwidths and the coils needed to produce the required fields can operate at the available voltages. The low energy density of ferromagnetic SMAs (once coils are included) may be a limiting factor.

4) *Results*: Based on preliminary design considerations, ferroelectric polymers, dielectric elastomers, and ferromagnetic SMAs all merit consideration for generating unsteady flow in Remus. These technologies all operate effectively at high bandwidths. Cycle life, encapsulation, and voltage conversion are among the challenges that may prevent or impede the use of these actuators.

IV. DISCUSSION

Table XII presents a summary of the properties of the actuator technologies discussed.

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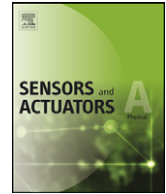
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A micro-robot fish with embedded SMA wire actuated flexible biomimetic fin

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ABSTRACT

A flexible biomimetic fin propelled micro-robot fish is presented. Fish muscle and the musculature of squid/cuttlefish fin are analyzed firstly. Since the latter one is easier to be realized in the engineering field, it is emulated by biomimetic fin. Shape memory alloy (SMA) wire is selected as the most suitable actuator of biomimetic fin. Elastic energy storage and exchange mechanism is incorporated into the biomimetic fin for efficiency improvement. Furthermore the bending experiments of biomimetic fin were carried out to verify the original ideas and research concepts. Thermal analysis is also conducted to find a proper actuation strategy. Fish swimming mechanism is reviewed as the foundation of the robot fish. A radio frequency controlled micro-robot fish propelled by biomimetic fin was built. Experimental results show that the micro-robot fish can swim straight and turn at different duty ratios and frequencies. *Subcarangiform*- and *carangiform*-like swimming modes were realized. The maximum swimming speed and the minimum turning radius reached 112 mm/s and 136 mm, respectively.

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1. Introduction

Fish tail-like propeller is considered as an alternative apparatus for thrust to commonly used rotator of underwater vehicle (UV). As the propulsive efficiency of small UVs is usually below 40%, fish tail-like propeller is superior to rotator used in small UVs [1]. Another advantage of fish tail-like propeller is that the steering radius can be small even at high swimming speed. Micro-robot fish have great advantages in exploring complex, narrow underwater environments. They may even be used in blood vessels for microsurgery. Many micro-robot fish have been developed in recent years. Most reported micro-robot fish are driven by shape memory alloys (SMAs) [2,3], Ionic exchange Polymer Metal Composites (IPMCs) [4–6] or piezoelectric (PZT) actuators [7,8]. The swimming performances of some micro-robot fish were investigated. For instance, the IPMC actuated tadpole robot, which is 96 mm in length and 16.2 g in weight, reached a maximum speed of 23.6 mm/s at 4 Hz driving frequency, and the IPMC actuated micro-robot fish, which is 230 mm in length and 295 g in weight, reached a peak speed of 6.3 mm/s at 2 Hz. The difficulties of developing a micro-robot fish mainly lie in selection of actuators, sealing, compactness, wireless controlling, reducing noise and improving propulsive efficiency.

In this paper the development of a micro-robot fish driven by an embedded SMA wire actuated biomimetic fin is investigated. The flexible bending biomimetic fin simulates the musculature and flexible bending of squid/cuttlefish fin, which is supported and driven by a special skeleton—'muscular hydrostat' [9,10]. SMA wires act as 'transverse muscles' of the biomimetic fin. Elastic energy storage and exchange mechanism [11] is incorporated in the bending of the biomimetic fin. The radio frequency controlled micro-robot fish can swim straight and turn noiseless at different duty ratios and at different frequencies.

The paper is structured as follows. In Section 2, the musculature of cuttlefish fin and the structure of biomimetic fin are investigated, furthermore the bending experiments of the biomimetic fin were conducted to verify the concept. In Section 3, thermal analysis for control strategy of biomimetic fin is applied. In Section 4, the design of the micro-robot fish propelled by biomimetic fin is discussed in detail. In Section 5, straight swimming and turning capability of the micro-robot fish are investigated and discussed. Finally, the conclusions are given in Section 6.

2. Embedded SMA wire actuated flexible biomimetic fin

2.1. Musculature of cuttlefish fin

The design of propulsor is the foundation of micro-robot fish. Since evolutionary processes of millions of years have almost optimized the shape and structure of aquatic animals, it is an effective way to mimic the structure and function of fins of aquatic animals

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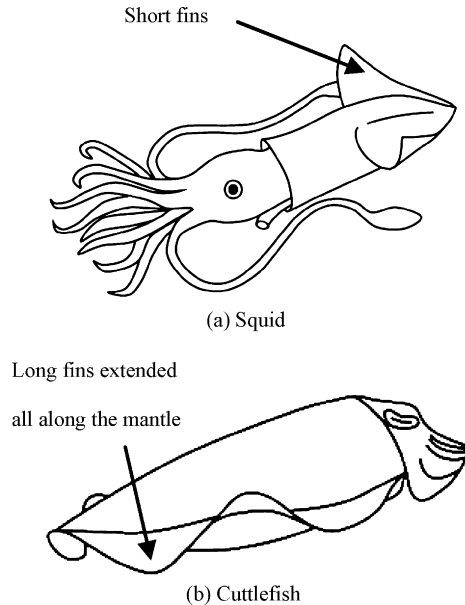


Fig. 1. Squid and cuttlefish.

directly. The flexible bending fin like structure is called biomimetic fin in this paper.

Fish of body and/or caudal fin (BCF) propulsion modes bend their propulsor flexibly by activating alternate sides of W-shaped segmented muscles in sequential manner, to form a backward propulsive wave. Obviously, the most direct way to realize flexible bending is to mimic the W shaped muscles, connective tissue and bones by using artificial materials. However, it is difficult to realize this structure because of the complexity of segmented arranged W shaped muscles, especially for micro-robot fish.

Besides fish, another two kinds of aquatic animals with excellent swimming capability are squid and cuttlefish (shown in Fig. 1), which belong to Cephalopoda. Squid and cuttlefish swim by using a combination of jet propulsion at high speed and fin undulatory/oscillatory propulsion at low speed [12,13]. Squid fins are short while cuttlefish fins are long, however their structures are similar. Therefore, the cuttlefish fin structure is selected for explanation. The frill-like cuttlefish fins extend all along the mantle and they can bend flexible into an undulatory motion for propulsion. If a short segment of cuttlefish fin is taken, the movement is flexible bending upward and downward only, which is similar to the movement of fish. So the muscular structure of cuttlefish fin is worthy to be investigated to realize flexible bending. The cuttlefish fins consist of a tightly packed 3-dimensional array of musculature called 'muscular hydrostat', which can generate force and support movement without bony skeleton support or fluid-filled cavities for hydrostatic skeletal support.

Fig. 2 shows the muscular structure of cuttlefish fin. The fin extends from fin cartilage (FC). The median connective tissue fascia (MF) divided the fin into two similar parts: dorsal part and ventral part. Transverse muscle fibers (T) extend parallel to the fin surface from the fin base to the fin margin, some of them insert on MF. Dorsalventral muscle fibers (DV) extend from dorsal and ventral connective tissue fascia (DF and VF) to MF. Longitudinal muscle fibers (L) lie adjacent to both the dorsal and ventral surface of MF. The connective tissue fibers (CT), which are oriented at 45° to the long axes of T and DV, are presented among the T and DV. L and DV control the length and thickness of the fin, respectively. Transverse muscle fibers control the curvature of the fin, namely lets the fin bend. CT provides skeletal support. There is little fluid into

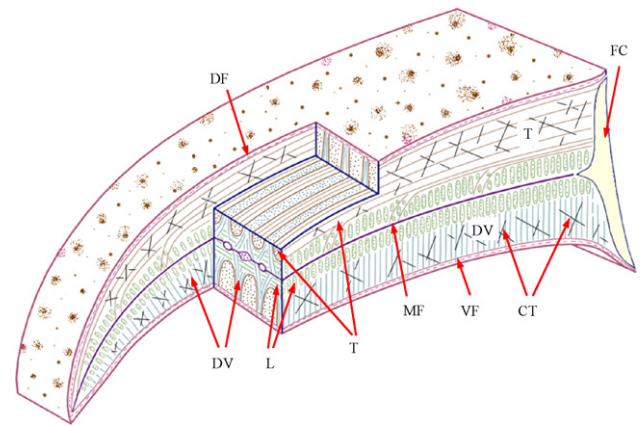


Fig. 2. Schematic diagram of the musculature of squid/cuttlefish fin.

or out of the fin and there are no compressible gas-filled cavities in the fin, so the fin volume almost remains constant. When the transverse muscle fibers of dorsal part and ventral part contract and relax in sequence, the fin is laterally compressed and can bend dorsally and ventrally. During bending, connective tissue fibers provide resistance to prevent the fin contracting wholly, and they may store elastic energy together with skin and other muscles. During the subsequent motion of unbending, the stored elastic energy is released to support the movement. The elastic energy storage and exchange mechanism, which can increase efficiency and improve locomotor performance, is also commonly existed in other animals. There are two kinds of transverse muscle fibers: aerobic and anaerobic fibers. The former one is for gentle movements while the latter one is for vigorous fin movements.

2.2. Structure of biomimetic fin

To realize flexible bending by emulate the structure of a short segment of cuttlefish fin, some simplifications must be done. When the fin segment is short enough, dorsalventral and longitudinal fibers can be neglected. Then the problem turns to find proper actuators to imitate the transverse muscle fibers. Motors, PZT and IPMCs are apparently not suitable. SMA is the alloy being able to return to a predetermined shape and it can be processed into wires. The most sophisticated SMA is TiNi, the advantages of which are noiseless actuation, large recovery strain ($<8\%$), high recovery stress (>500 MPa) [14], low actuation voltage, operational frequency similar to that of animal muscles, long life (up to 10^6 action cycles under a strain of 1%) [15]. The efficiency of SMA is low, but it is not a primary concern for the prototype. When SMA wire is thin, the activated electric value is similar to that of small DC motors. These considerations determined our choice of thin SMA wires as the most suited actuator to mimic the transverse muscle fibers. In the stress-free state, the four transition temperatures are Martensite Finish (M_f), Martensite Start (M_s), Austenite Start (A_s) and Austenite Finish (A_f).

Fig. 3 shows the structure and bending movement of biomimetic fin. Elastic substrate divides the biomimetic fin into two symmetric parts. Skins are adhered to elastic substrate, one or more SMA wires are embedded in the skin, lying adjacent to both sides of the elastic substrate. The materials for elastic substrate and skins are plastic and rubber/silicone, respectively. SMA wires serve as 'transverse muscle fibers', providing lateral compressing force. Elastic substrate is used to provide resistance and store elastic energy together with the skins. When the SMA wires of two sides are resistant heated by pulse and cooled alternatively in sequence, the biomimetic fin can

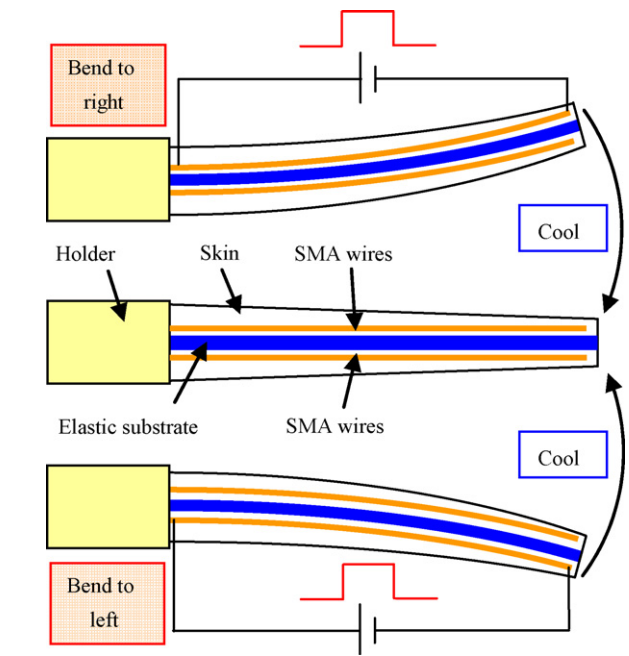


Fig. 3. The structure and the schematic of bending movement of biomimetic fin.

bend to both sides flexibly. During the process of bending movements, elastic energy is stored and relaxed just like it does during the movements of real fin. The stored elastic energy during bending is the key issue since it is the energy to let the biomimetic fin return to the straight state. Fish caudal fin like component can be attached at the tip of the biomimetic fin to enlarge control surface and thrust.

2.3. Initial experiments of bending

A biomimetic fin was built and tested in water environment to validate the concept. Table 1 illustrates the specifications of the biomimetic fin. TiNi (52 at% Ni) SMA wires are employed. In the stress-free state, the four transition temperatures are $M_f = 25.90^\circ\text{C}$, $M_s = 32.71^\circ\text{C}$, $A_s = 57.60^\circ\text{C}$, $A_f = 60.64^\circ\text{C}$, respectively. The materials for substrate and skin are polypropylene and silicone, respectively. The temperature of water (T_0) was 21°C . The voltage and pulse width of the pulse are denoted by U and t_{on} , respectively. The two kinds of pulse sequences employed were (1) $U = 4.7\text{ V}$, $t_{on} = 0.5\text{ s}$ and (2) $U = 11.0\text{ V}$, $t_{on} = 0.06\text{ s}$. After each pulse of the pulse sequence, an interval of 1.8 s was added to cool the SMA wires prior to the heating of the antagonistic SMA wires. Fig. 4 shows the curves of pulse width, bending angle and return time of the biomimetic fin activated by the two kinds of pulses. The angle of first bending of each bending sequence is defined as positive value. Fig. 5 shows the status of maximum bending angles to both sides. Over 90° of maximum bending angles to both sides were obtained. Experimental results show that the biomimetic fin can bend flexibly to both sides. When this biomimetic fin was activated by pulse

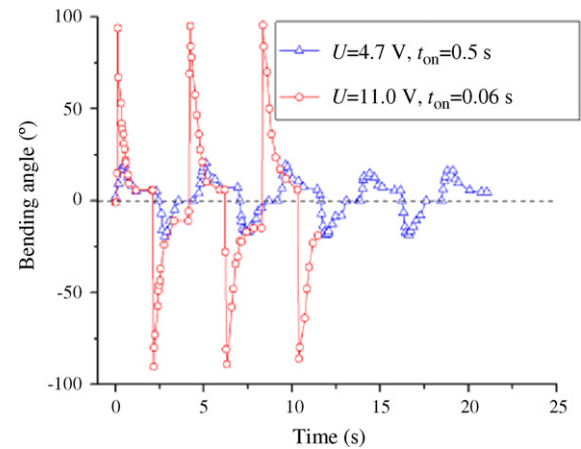


Fig. 4. Experimental results of bending of biomimetic fin.

sequence (1), small bending angle was obtained even using long pulse width. This indicates that the temperature of SMA arises slowly with light electric current. When the biomimetic fin was activated by pulse sequence (2), the bending speed was much higher and large maximum bending angle could be obtained in very short time. The return speed was lower than the corresponding bending speed in experiments. In accordance to the experimental results, we know that short pulse with heavy current could be applied to activate the biomimetic fin in order to achieve high frequency actuation, and the return speed would restrict the bending frequency of the biomimetic fin driven by the $\varnothing 0.2\text{ mm}$ TiNi wires.

3. Theory analysis of the biomimetic fin

Since shape memory effect is induced by temperature, heating speed and cooling speed are the major influencing factors. SMA wires are embedding in the skin, so the temperature of SMA wires is difficult to measure directly. Therefore, the thermal analysis is used to estimate the temperature of SMA wires and to find proper actuation strategy.

In order to simplify the analysis, several simplifications are made: (1) radiation effect is ignored; (2) there is no heat transfer between SMA wires and elastic substrate; (3) the skin is simplified as heat sink of SMA wires, so heat convection is considered as the only way of heat transformation, an equivalent heat transmission coefficient, h'_w ($\text{W}/(\text{m}^2\text{K})$), is used to replace the original heat transmission coefficient; (4) h'_w , specific electric resistance ρ_e (Ωm) and specific heat c ($\text{J}/(\text{kgK})$) are assumed to be constant.

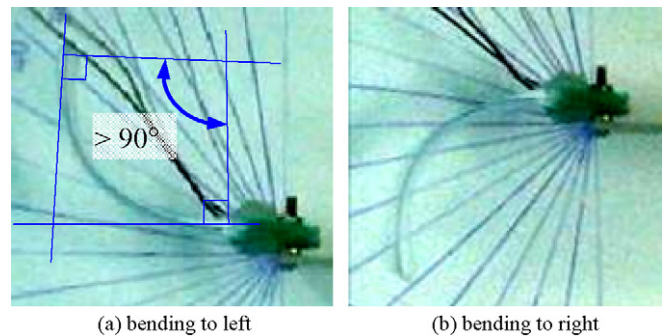


Fig. 5. Maximum bending angles of biomimetic fin.

Table 1
Specifications of biomimetic fin for initial experiments

Width (mm)	14
Diameter of SMA wire (mm)	0.2
Length of SMA wire (mm)	48
Numbers of SMA wires	2
Length of bending segment (mm)	50
Thickness of the skin (mm)	0.6–0.7
Thickness of the substrate (mm)	0.36

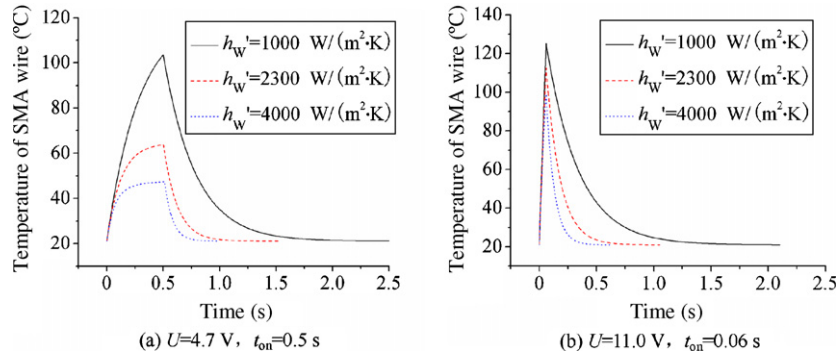


Fig. 6. Simulation curves of the biomimetic fin used in Section 2.3.

When SMA wires are heated, the equation describing the energy input, heat transfer and the temperature of SMA wires is given as:

$$\int_t \frac{\pi d^2}{4 \rho c l} U(t)^2 dt = \int_t h'_w \pi dl [T(t) - T_0] dt + \int_t c \rho \left(\frac{\pi d^2}{4} \right) l dT(t) \quad (1)$$

where $U(t)$ is the voltage supplied to SMA wires (V), d is the diameter of SMA wires (m), l is the total length of SMA wires of one side (m), $T(t)$ is the temperature of SMA wires (K or °C), ρ is the density of SMA wires (kg/m³) and t is the time (s).

When SMA wires are cooled, the equation describing heat transfer and temperature of SMA wires is given as:

$$\int_t h'_w \pi dl [T(t) - T_0] dt + \int_t c \rho \left(\frac{\pi d^2}{4} \right) l dT(t) = 0 \quad (2)$$

The equivalent heat transmission coefficient h'_w can be obtained by experiments. Simulation is carried out to the biomimetic fin used in Section 2.3 (shown in Fig. 6). The result shows that the corresponding h'_w was about 2300 W/(m² K). From the simulation curves we can see that in order to increase operational frequency, short pulse width with heavy electric current (or high voltage) should be supplied to SMA wires. Furthermore, SMA wire with smaller diameter could be applied to achieve higher frequency as long as the contract force is enough.

4. The design of micro-robot fish

4.1. Fish swimming mechanism

According to the momentum theorem, when fish swim by pushing water away behind them, momentum is transferred from the fish to the surrounding water and thrust is generated. Other kinds of forces acting on a swimming fish are drag, weight, buoyancy and hydrodynamic lift in the vertical direction. Swimming drag consists of viscous drag and pressure drag. Viscous drag is skin friction between the fish and the boundary layer of water, and it depends on the wetted area and swimming speed of the fish and the property of the surrounding fluid. Pressure drag is caused by distortions of flow around fish body and energy lost in the vortices formed by the fins as they generate lift or thrust.

Precision calculation of thrust is complex, so simplification by assuming steady or quasisteady flow is usually used. When a fish swim forward at a constant speed, the total thrust is equal to the total drag. On a small scale, thrust is defined as follows:

$$F_T = \frac{C_D \rho_W A V^2}{2} \quad (3)$$

Where F_T is thrust (N), C_D is drag coefficient, ρ_W is water density (kg/m³), A is wetted surface area (m²) and V is swimming speed (m/s).

When fish is swimming, it can narrow the wake by ensuring no vortex shed from the body but one or two vortices shed from the tail tip every fin tail beat. By doing this, reverse Karman vortex street is formed and a jet can be induced to increase thrust (shown in Fig. 7). The wake also store energy and fish can recapture energy from the vortices to enhance swimming performance and to save energy.

Two important nondimensional parameters which affect the swimming are Reynolds number (Re) and Strouhal number (St , reduced frequency). Reynolds number is the ratio of inertial over viscous forces, defined as

$$Re = \frac{LV}{\nu} \quad (4)$$

where L is a characteristic length (of either the fish body or the propulsor) (m), ν is the kinematic viscosity of water (m²/s).

When Re is larger than 1000, inertial forces are dominant and viscous forces are usually neglected and when Re is smaller than 1. Viscous forces are dominant. Inertial forces and viscous forces must be both considered when Re is between 1 and 1000 [16].

Strouhal number can be approximated as

$$St = \frac{f A_{pp}}{V} \quad (5)$$

where f is tail-beat frequency (Hz) and A_{pp} is the wake width (approximately as tail-beat peak-to-peak amplitude) (m).

When St lies in the range 0.25–0.35, the swimming and thrust generation are considered as optimal.

Froude number is used to define the propulsive efficiency. It is the ratio of the useful propulsive power over the total power expended by the fish.

4.2. Structure of the micro-robot fish

Since the micro-robot fish is propelled by biomimetic fin, there are no traditional components like gears, bearings and joints. In order to activate the biomimetic fin, control circuit and batteries should be required. As a result, the micro-robot fish consists of body and biomimetic fin based propulsor (shown in Fig. 8). The micro-robot fish prototype is 146 mm in length, 17 mm in width and 34 mm in height. The weight is about 30 g. The propulsor consists of a biomimetic fin (active component) and a caudal fin (passive component). The caudal fin is used to enlarge the control surface and the thrust. *Subcarangiform* swimming can be formed by softer caudal

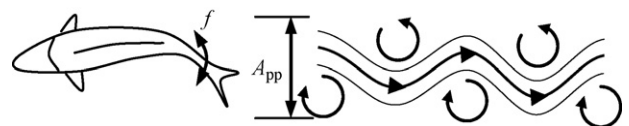
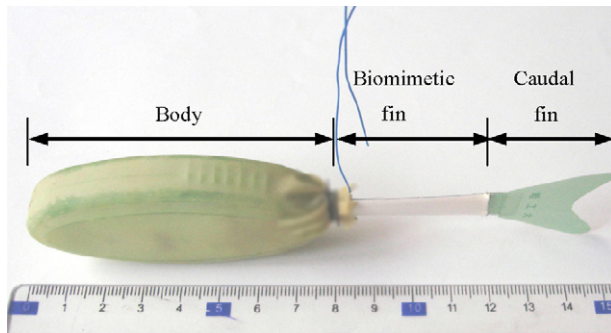
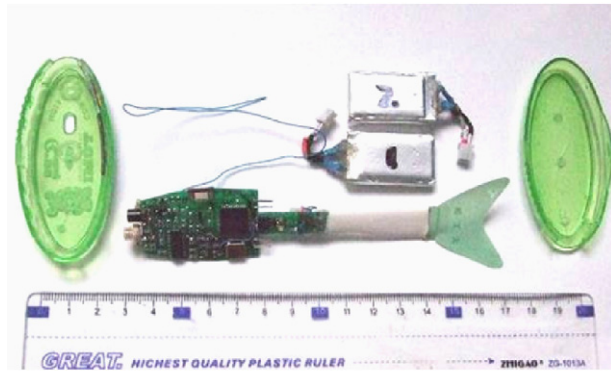


Fig. 7. The reverse Karman vortex street.



(a) After assembly



(b) Before assembly (without skin)

Fig. 8. Micro-robot fish prototype.

fin while *carangiform* swimming can be obtained by harder caudal fin. To decrease the electricity value of driving the biomimetic fin and increase frequency, TiNi (50.2 at% Ni) wires with the diameter of 0.089 mm are used. In the stress-free state, the four transition temperatures are $M_f = 43.4^\circ\text{C}$, $M_s = 52.2^\circ\text{C}$, $A_s = 51.4^\circ\text{C}$, $A_f = 58.8^\circ\text{C}$. The control circuit and two 310 mAh Li-polymer batteries are enveloped

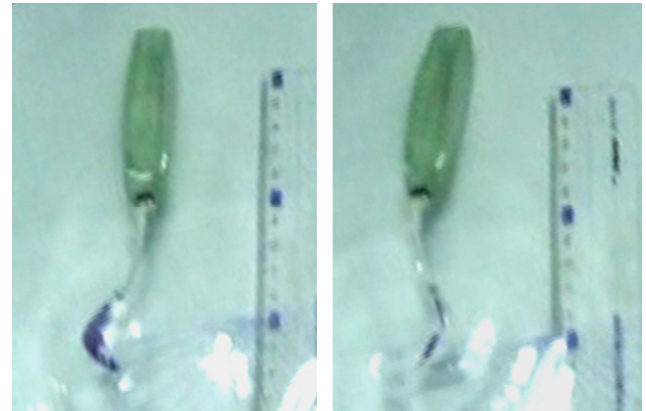


Fig. 9. Subcarangiform-like swimming.

in the body by shell and sealing skin. The control circuit consists of radio frequency remote control module and MCU (PIC16F877A) based open-loop driving module. The propulsor is connected to the control circuit directly.

4.3. Swimming modes

The micro-robot fish can swim forward and turn with only one biomimetic fin. When the robot fish swims forward, the biomimetic fin bend back and forth, just as illustrated in Fig. 3.

When the robot fish turns, there are three turning modes [17]:

- (1) The biomimetic fin bends only to one side. The body is equivalent to a rudder and the propulsor are equivalent to a rotator of the ship. It is the most fundamental and important turning mode as the robot fish can change the turning radius and speed in this mode, and it is the simplest one.

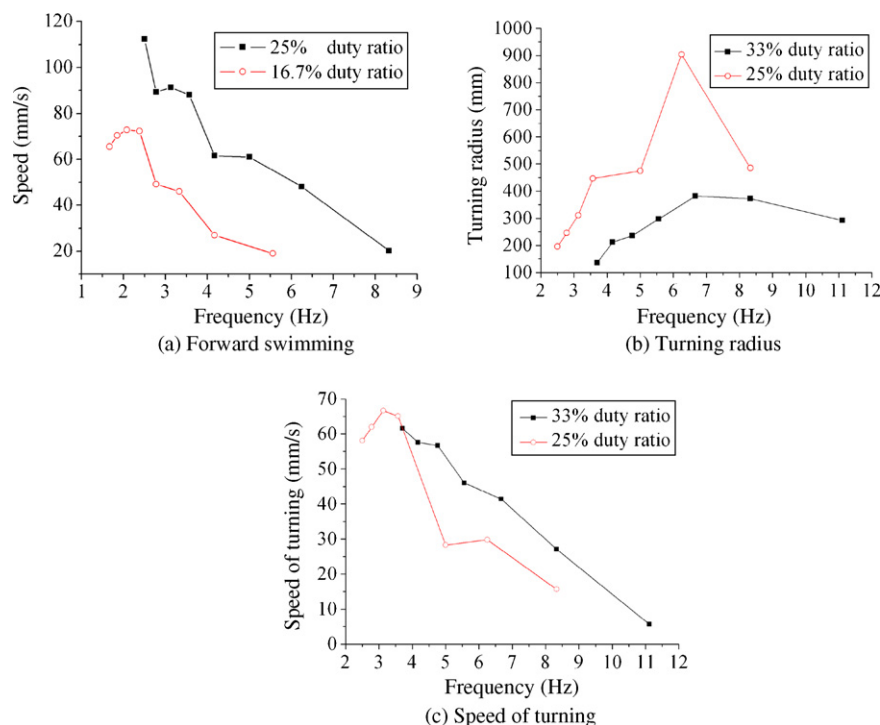


Fig. 10. The speed of swimming forward, turning radius and speed of turning of the micro-robot fish.

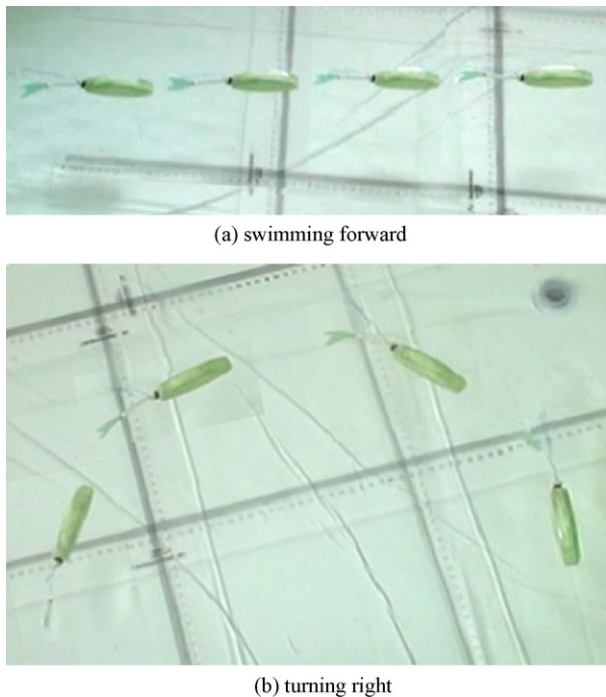


Fig. 11. Synthetic images of the status of swimming forward and turning right of micro-robot fish at 2.78 Hz, 25% duty ratio.

- (2) The biomimetic fin bends to one side and keeps the posture after the robot fish swims forward at a certain speed. The robot fish turns by hydrodynamics force. Smaller turning radius can be obtained by using this mode. This mode is difficult to achieve by an open-loop control method.
- (3) The biomimetic fin bends to one side rapidly from stationary state. Inertia force and friction force of the propulsor and the body are changed to the moment of rotation. Turning from a stationary state can be achieved by this turning mode. The turning radius is the smallest among the three turning modes.

5. Experiments

Swimming forward and turning capabilities were investigated. Square wave voltage was applied. Duty ratio is defined as the ratio of power on time of a period over the periodic time. Because the biomimetic fin is open-loop controlled, longer power on time means larger bending angle.

Fig. 9 shows the *subcarangiform*-like swimming status while swimming forward at a 25% duty ratio, 2.5 Hz. The average swimming speed was about 58 mm/s.

More experiments were conducted on *carangiform*-like swimming. The bending angle of the biomimetic fin increases with decreasing the driving frequency at a certain duty ratio. Turning mode (1) was applied. Prior to turning, the robot fish swam forward for 8 cycles at 25% duty ratio with the same pulse width as the turning to get an initial forward speed. Fig. 10 illustrates the speed of swimming forward and turning radius at different duty ratios and frequencies. In the case of swimming forward, a maximum frequency of 8.33 Hz was tested at a 25% duty ratio. For turning, a maximum frequency of 11.1 Hz was tested at a 33.3% duty ratio. When swimming at the same frequency, swimming speed and turning curvature (1/turning radius) of the higher duty ratio are larger than their values at lower duty ratio.

In the case of swimming forward, the peak speed at 16.7% duty ratio was obtained at 2.1 Hz, meanwhile the speed at 25% duty ratio decreased with the increase of frequency. The turning radii of both duty ratios increased firstly and then decreased with the increase of frequency. The speed of turning at 33% duty ratio decreased with the increase of frequency while at 25% duty ratio, the peak value appeared at 3.13 Hz.

A maximum speed of swimming forward of 112 mm/s was obtained at a 25% duty ratio, 2.5 Hz. A minimum turning radius of 136 mm was obtained at a 33% duty ratio, 3.7 Hz. Fig. 11 shows the status of swimming forward and turning right at a 25% duty ratio, 2.78 Hz. The Strouhal number at the maximum swimming speed was 0.58.

As the robot fish is open-loop controlled, the bending of biomimetic fin may be influenced by the water flow and the temperature inequality of water. The bending angles to each side may be different and it would result in course deviation.

6. Conclusions

A micro-robot fish propelled by a biomimetic fin is presented in this paper. The micro-robot fish has no traditional components such as gears and bearings, and it can swim noiseless and flexibly. The embedded SMA wire actuated biomimetic fin imitates the structure of squid/cuttlefish fin. Simplifications are made for the squid/cuttlefish fin to build up the biomimetic fin. The biomimetic fin consists of elastic substrate, skin, and transverse muscle-like SMA wires. Elastic energy storage and exchange mechanism is incorporated during the bending of biomimetic fin. Initial experiments of bending were conducted to verify the concept of biomimetic fin. Thermal analysis is also applied to find proper actuation strategy. Then a radio frequency controlled micro-robot fish prototype was built based on the biomimetic fin. With different tail fin, *subcarangiform*- and *carangiform*-like swimming movements were realized. Experimental results show that the micro-robot fish can swim forward and turn with a biomimetic fin. A maximum swimming speed of 112 mm/s and a minimum turning radius of 136 mm were obtained.

Further research on the structure, material, and control strategy would be made to improve the performance of biomimetic fin. We believe that using biomimetic fin, robot fish with smaller size could be built.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.sna.2008.02.013](https://doi.org/10.1016/j.sna.2008.02.013).

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Biographies

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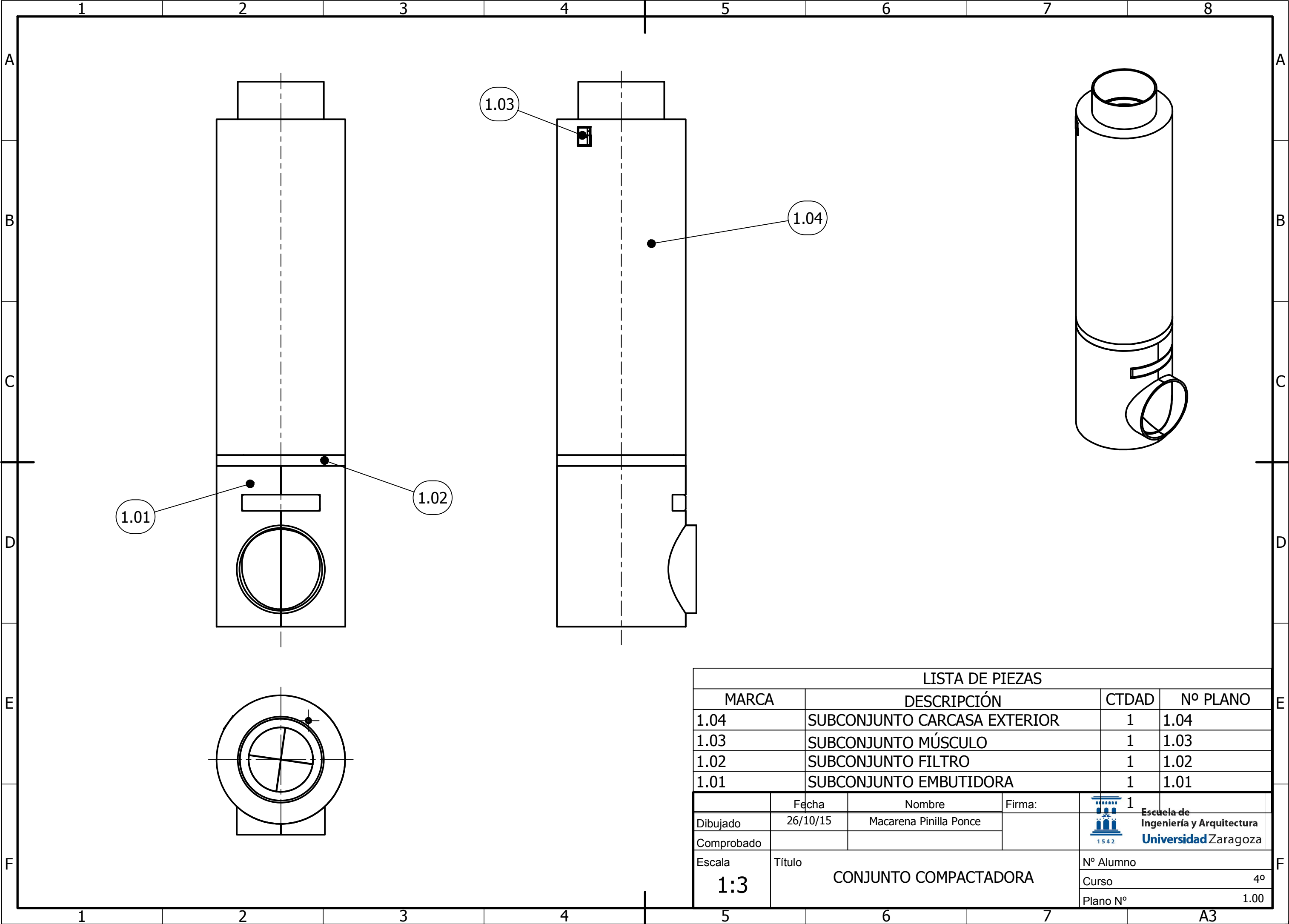
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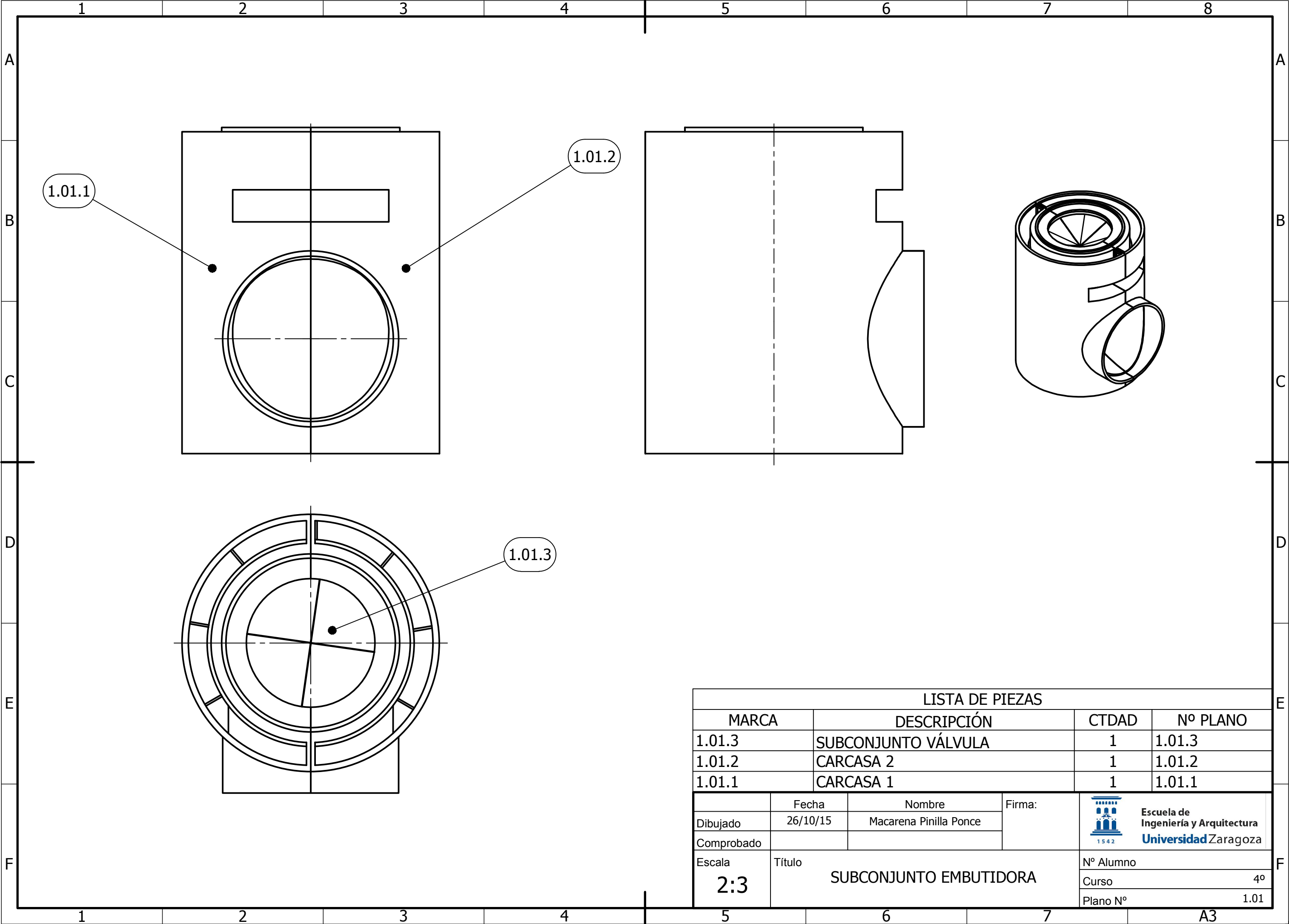
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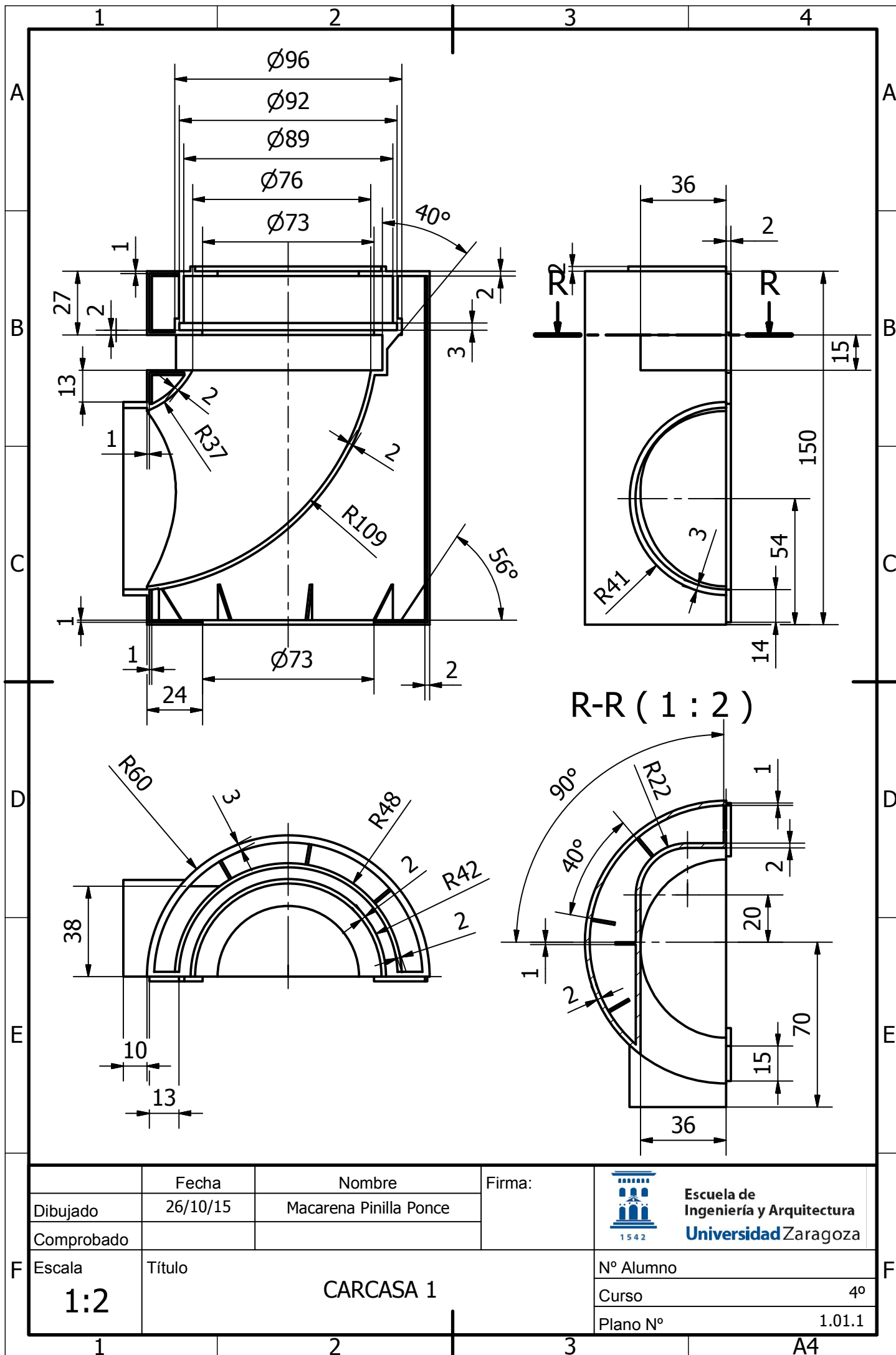




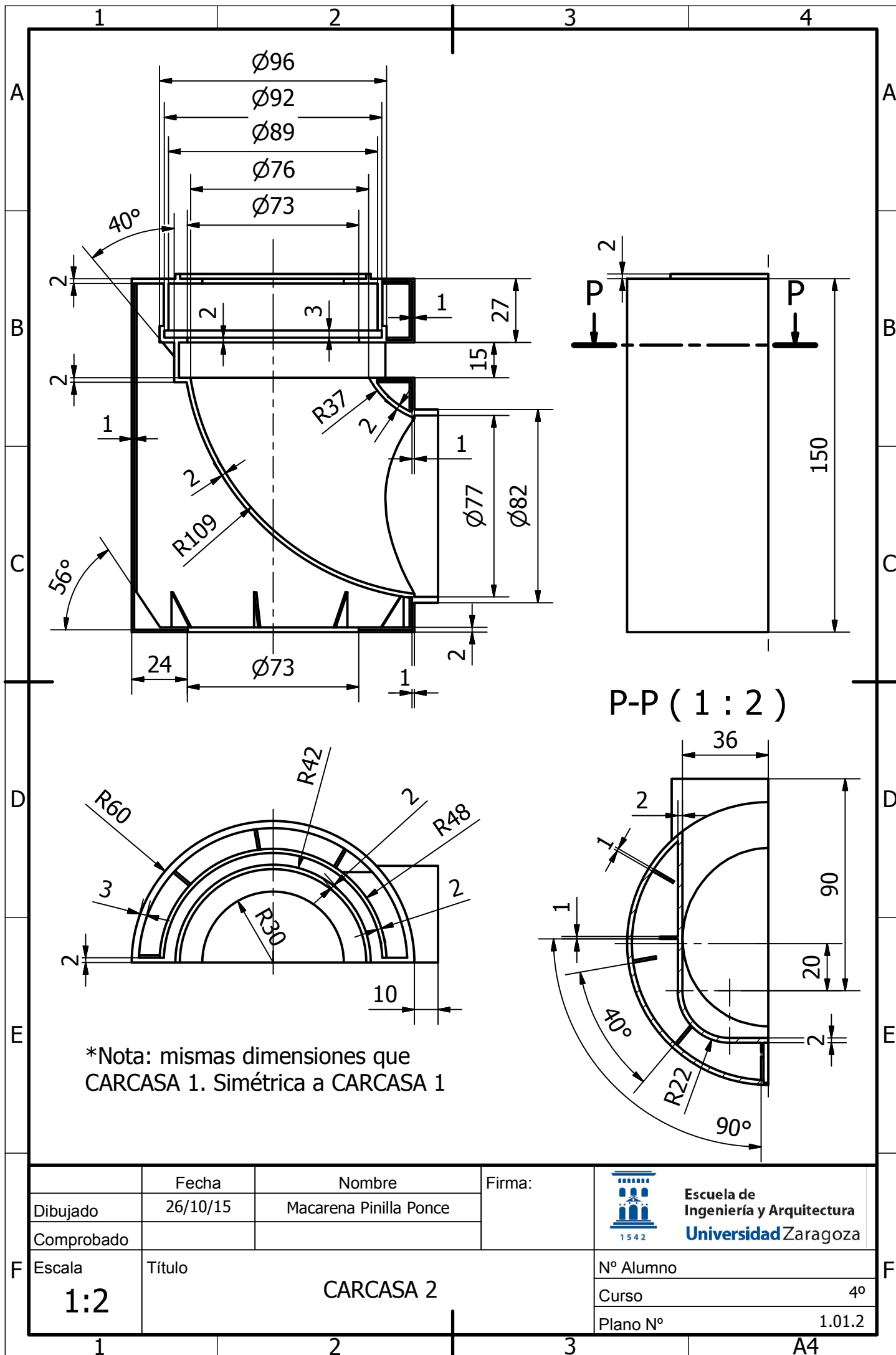
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1.03		SUBCONJUNTO MÚSCULO			1	1.03	
1.02		SUBCONJUNTO FILTRO			1	1.02	
1.01		SUBCONJUNTO EMBUTIDORA			1	1.01	
	Fecha	Nombre	Firma:		1		
Dibujado	26/10/15	Macarena Pinilla Ponce				Escuela de Ingeniería y Arquitectura	
Comprobado						Universidad Zaragoza	
Escala	Título CONJUNTO COMPACTADORA				Nº Alumno		
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LISTA DE PIEZAS					
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1.01.2		CARCASA 2		1	1.01.2
1.01.1		CARCASA 1		1	1.01.1
	Fecha	Nombre	Firma:	 Escuela de Ingeniería y Arquitectura Universidad Zaragoza	
Dibujado	26/10/15	Macarena Pinilla Ponce			
Comprobado					
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Escala 1:2	Título CARCASA 2	Nº Alumno		
		Curso 4º		
		Plano Nº 1.01.2		

1	2	3	4																													
A				A																												
B				B																												
C				C																												
D				D																												
E	LISTA DE PIEZAS <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 20%;">MARCA</th> <th style="width: 40%;">DESCRIPCIÓN</th> <th style="width: 15%;">CTDAD</th> <th style="width: 25%;">Nº PLANO</th> </tr> </thead> <tbody> <tr> <td>1.0.1.3.3</td> <td>SOPORTE VÁLVULA</td> <td style="text-align: center;">1</td> <td>1.01.3.3</td> </tr> <tr> <td>1.01.3.2</td> <td>PIEZA MÓVIL</td> <td style="text-align: center;">4</td> <td>1.01.3.2</td> </tr> <tr> <td>1.01.3.1</td> <td>CAUCHO SEGURIDAD</td> <td style="text-align: center;">1</td> <td>1.01.3.1</td> </tr> </tbody> </table>			MARCA	DESCRIPCIÓN	CTDAD	Nº PLANO	1.0.1.3.3	SOPORTE VÁLVULA	1	1.01.3.3	1.01.3.2	PIEZA MÓVIL	4	1.01.3.2	1.01.3.1	CAUCHO SEGURIDAD	1	1.01.3.1	E												
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Dibujado	26/10/15	Macarena Pinilla Ponce																														
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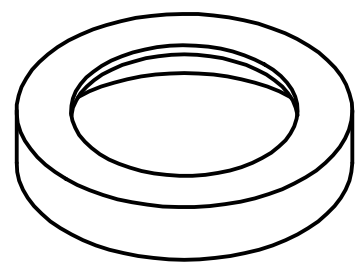
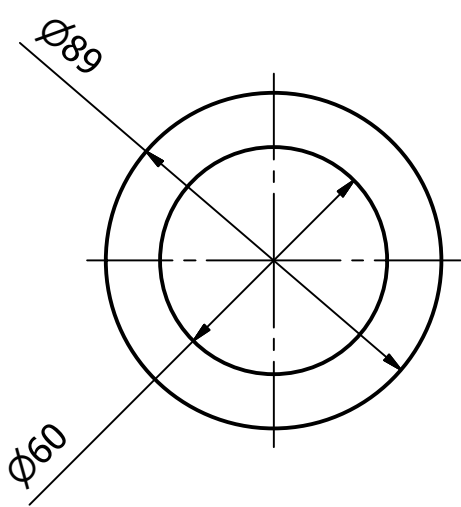
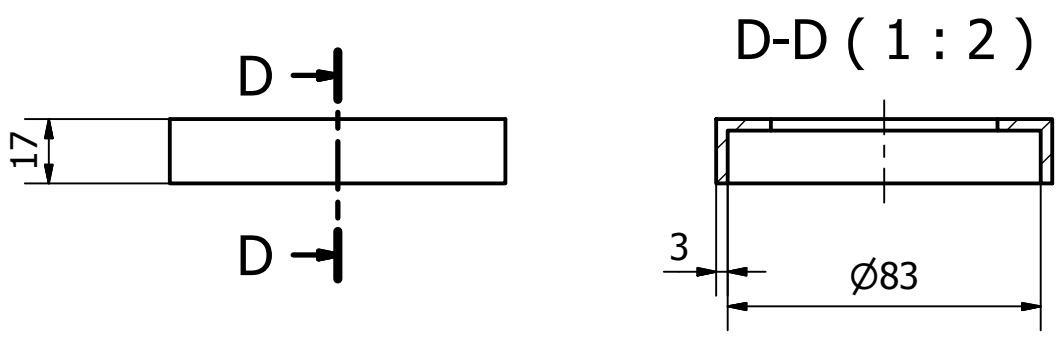
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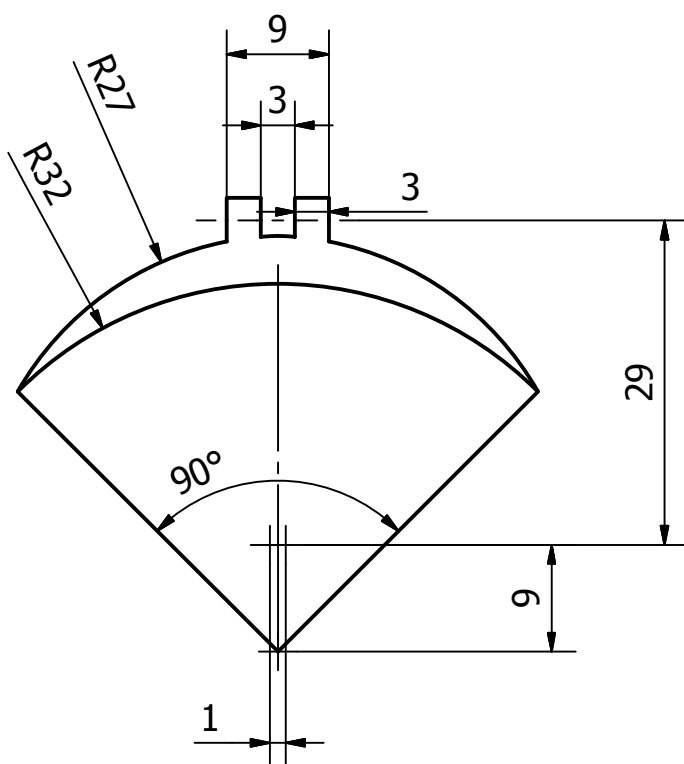
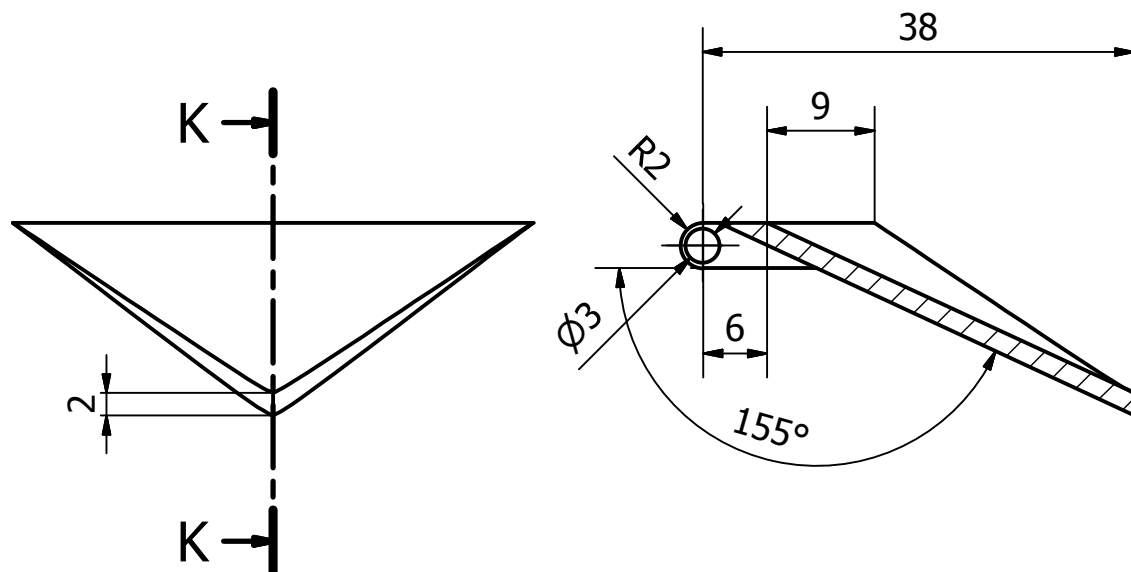
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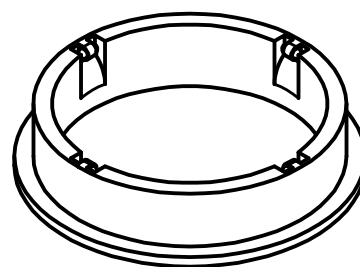
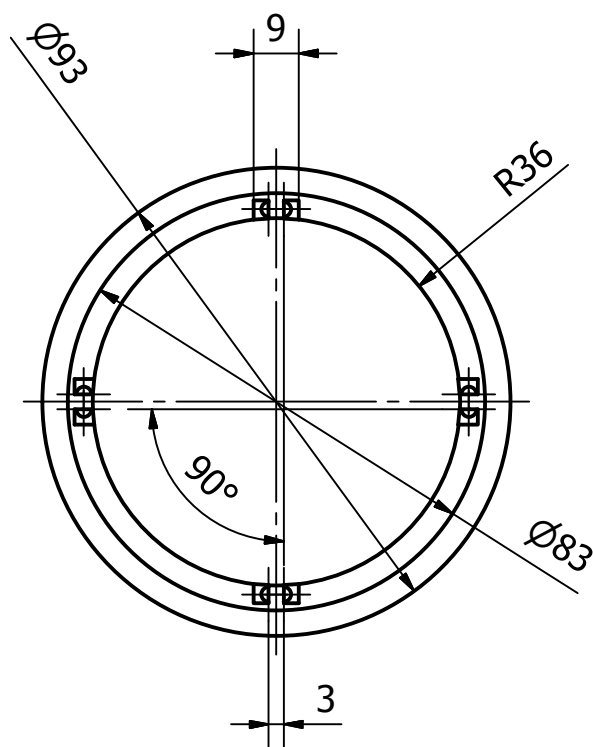
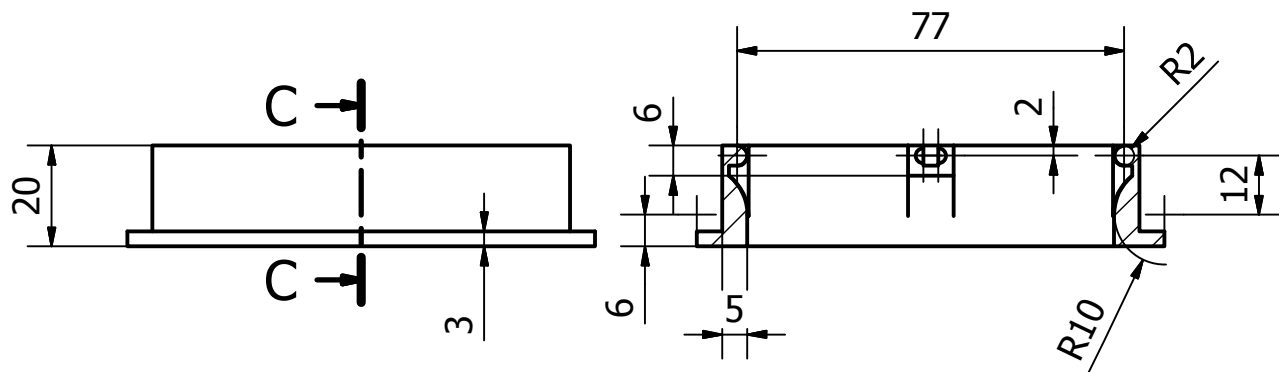
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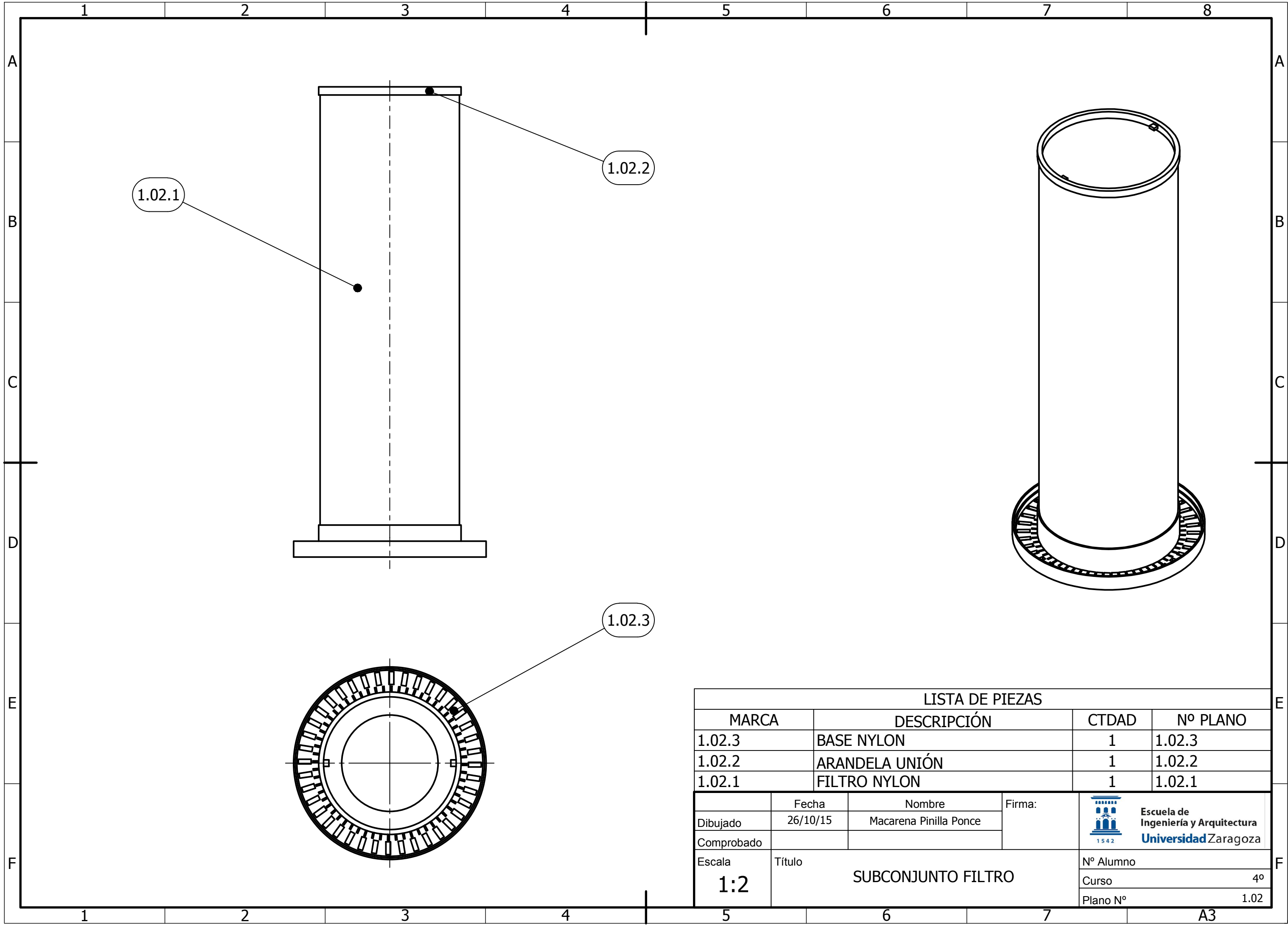


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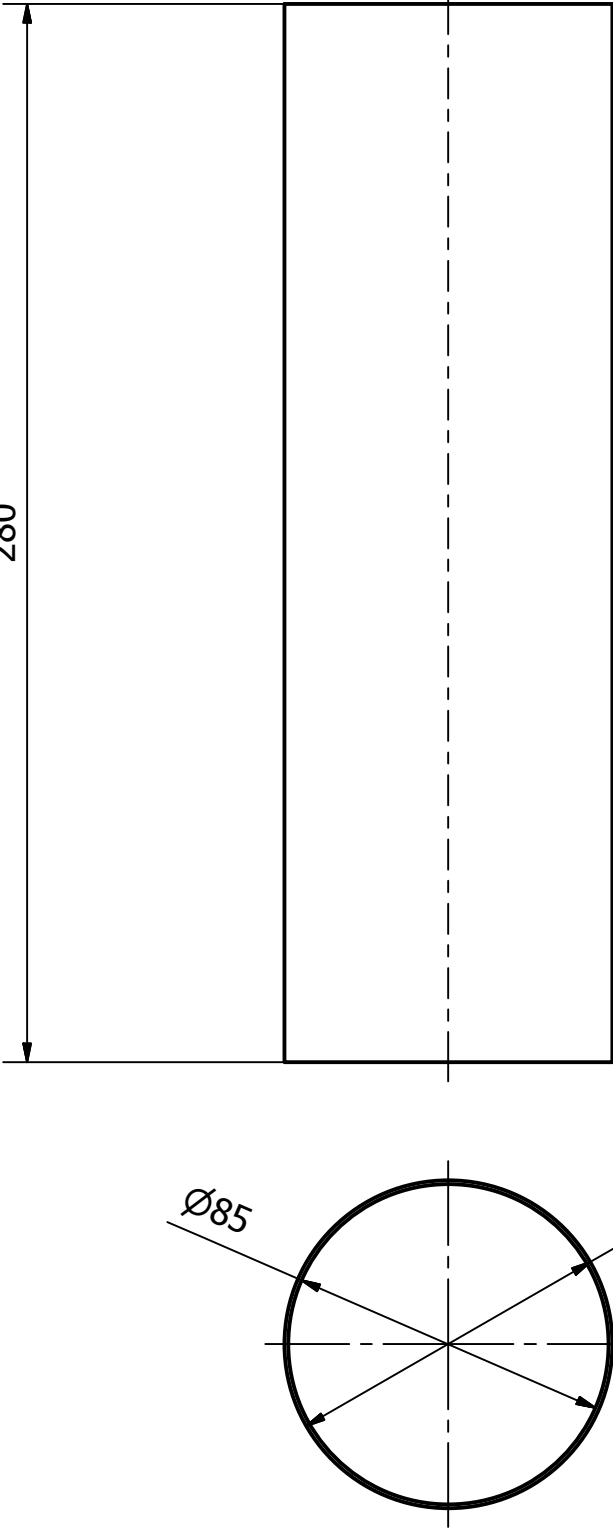


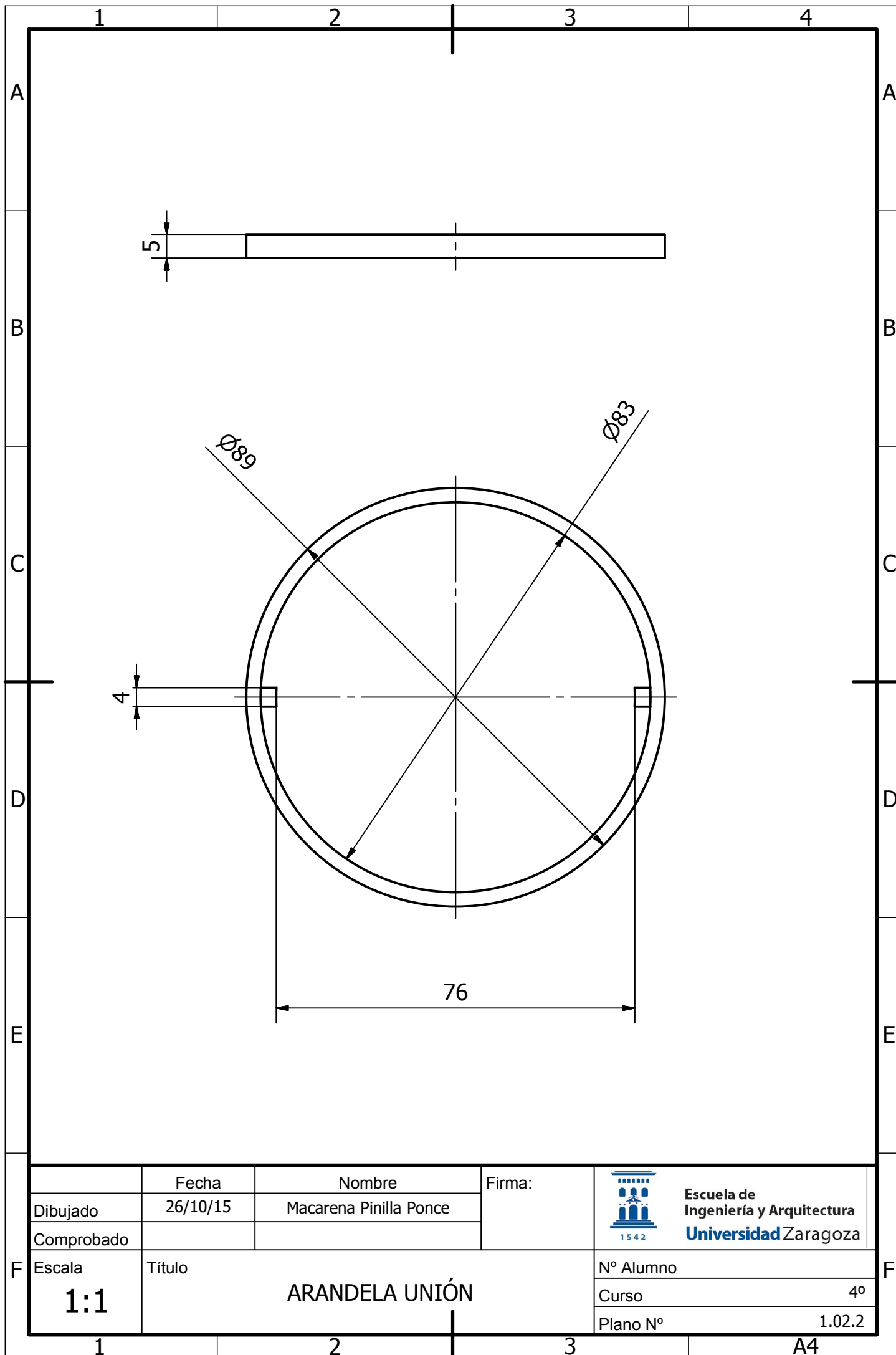
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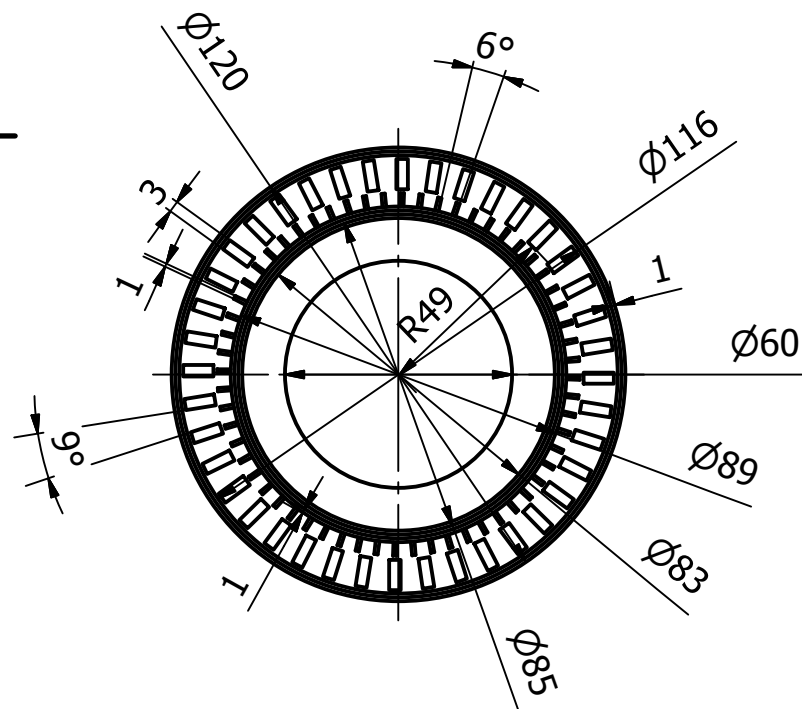
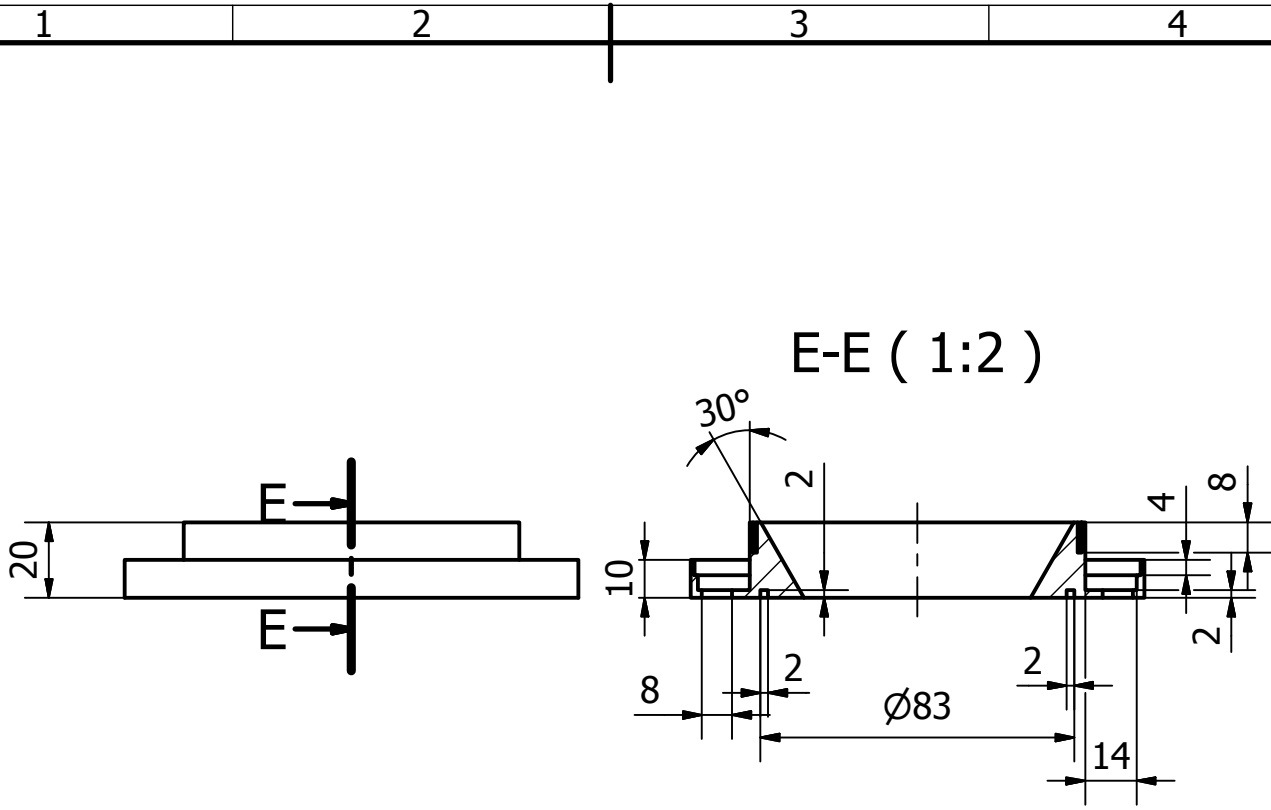
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1.02.1		FILTRO NYLON		1	1.02.1

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Dibujado	26/10/15	Macarena Pinilla Ponce		
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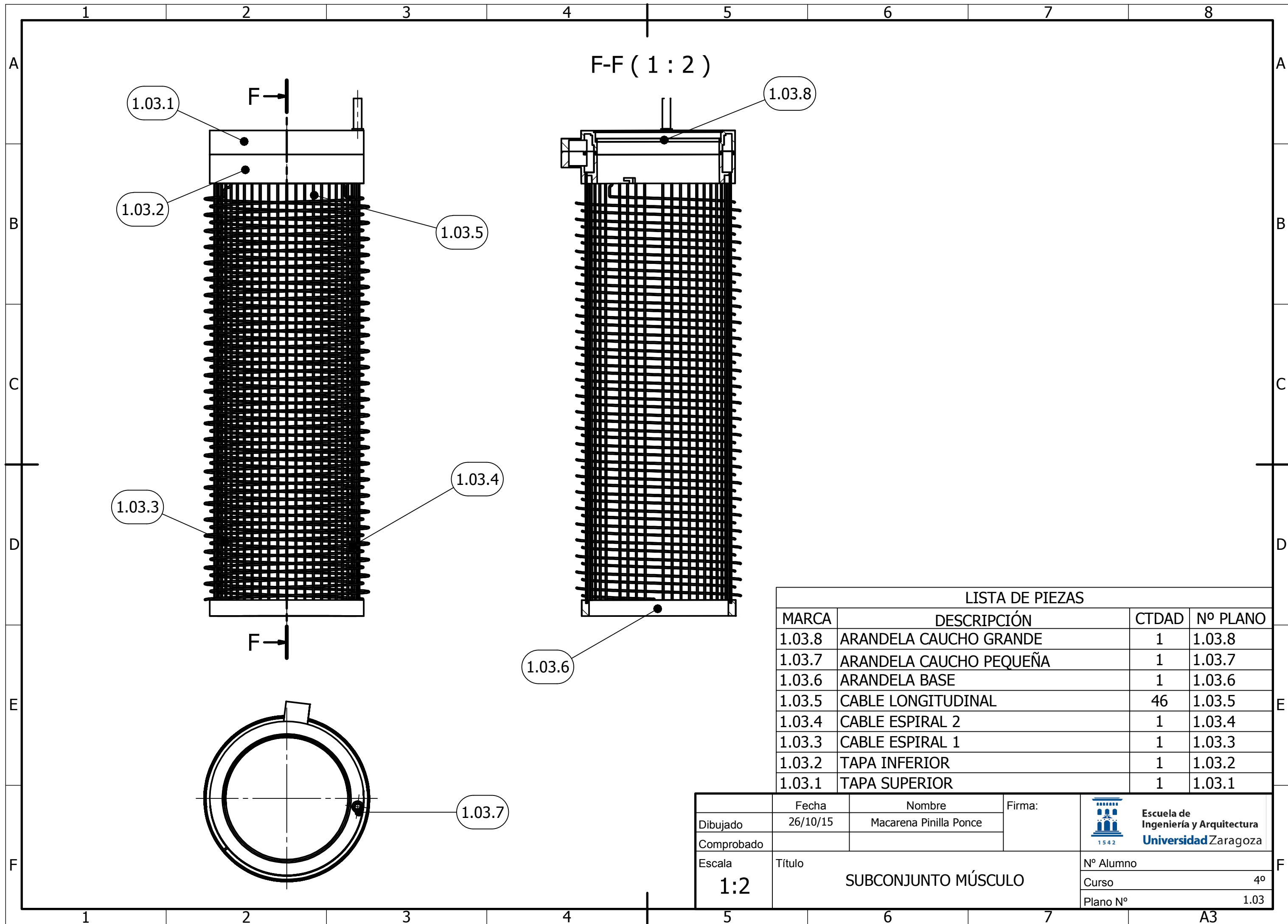
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Dibujado		26/10/15		Macarena Pinilla Ponce		 Escuela de Ingeniería y Arquitectura Universidad Zaragoza	
Comprobado							
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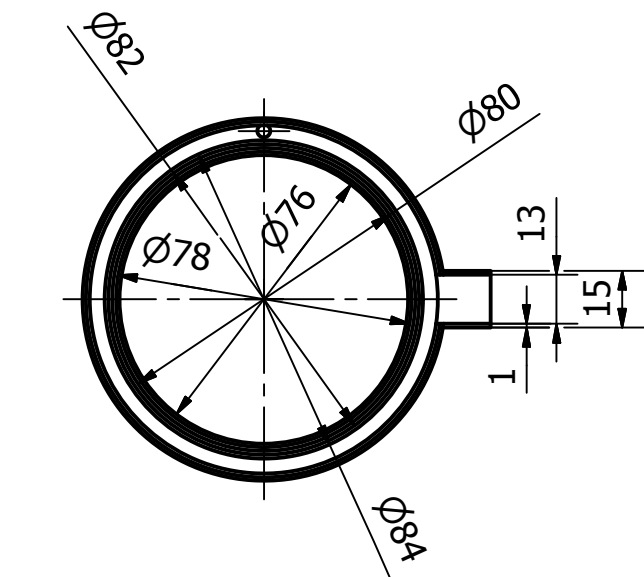


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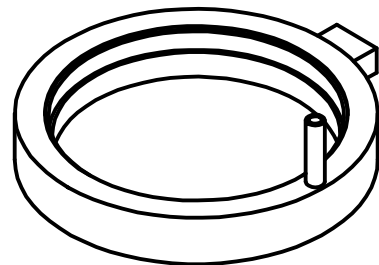
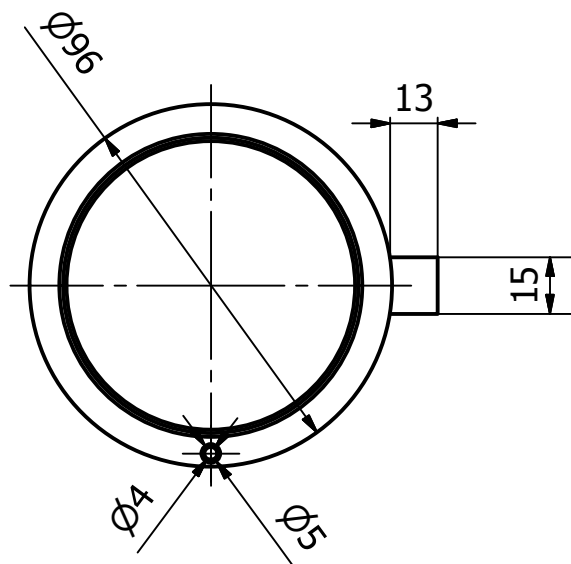
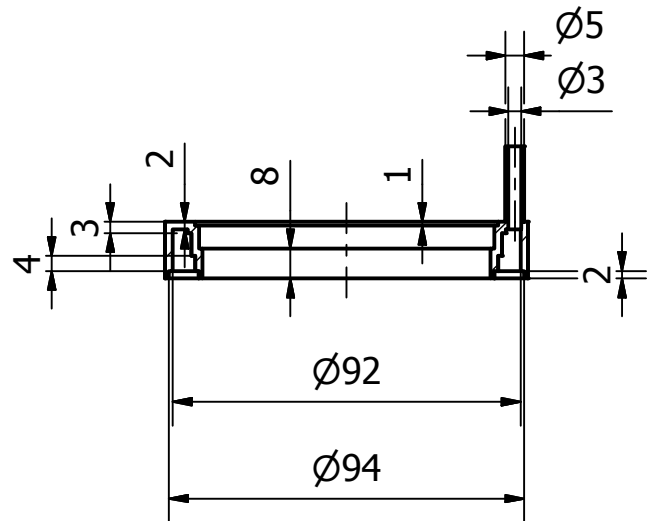
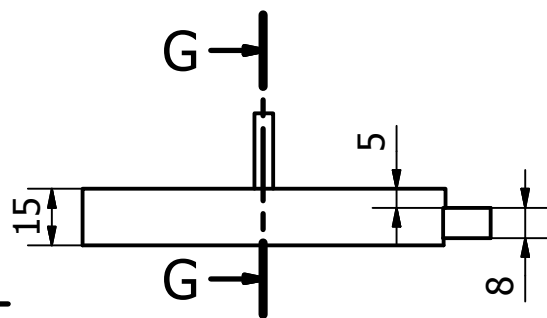


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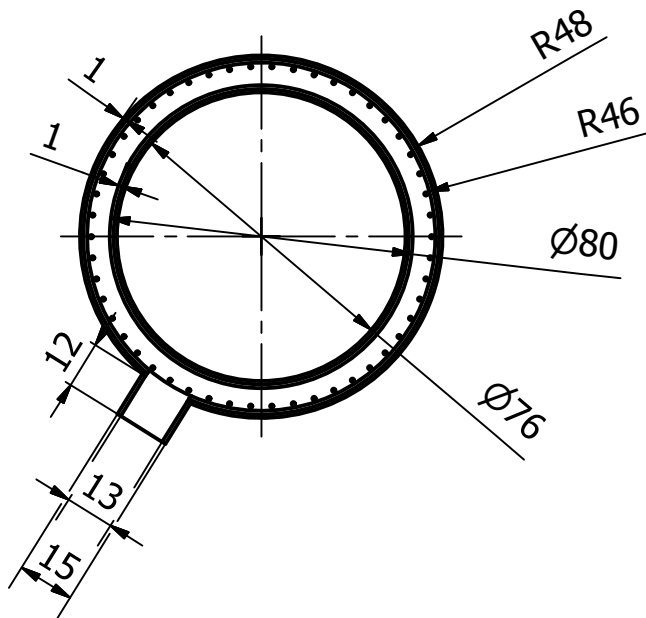
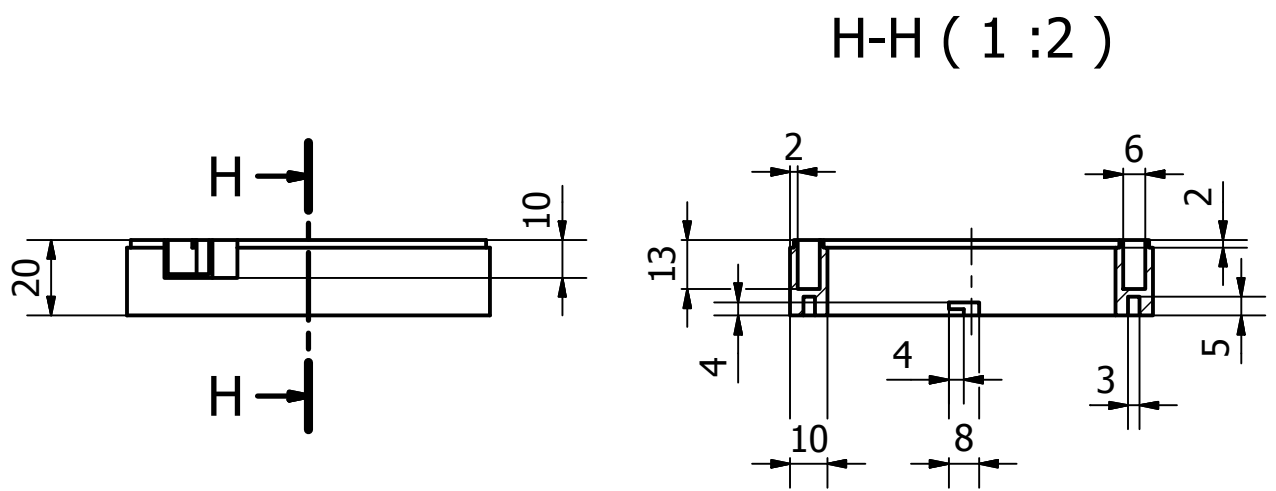




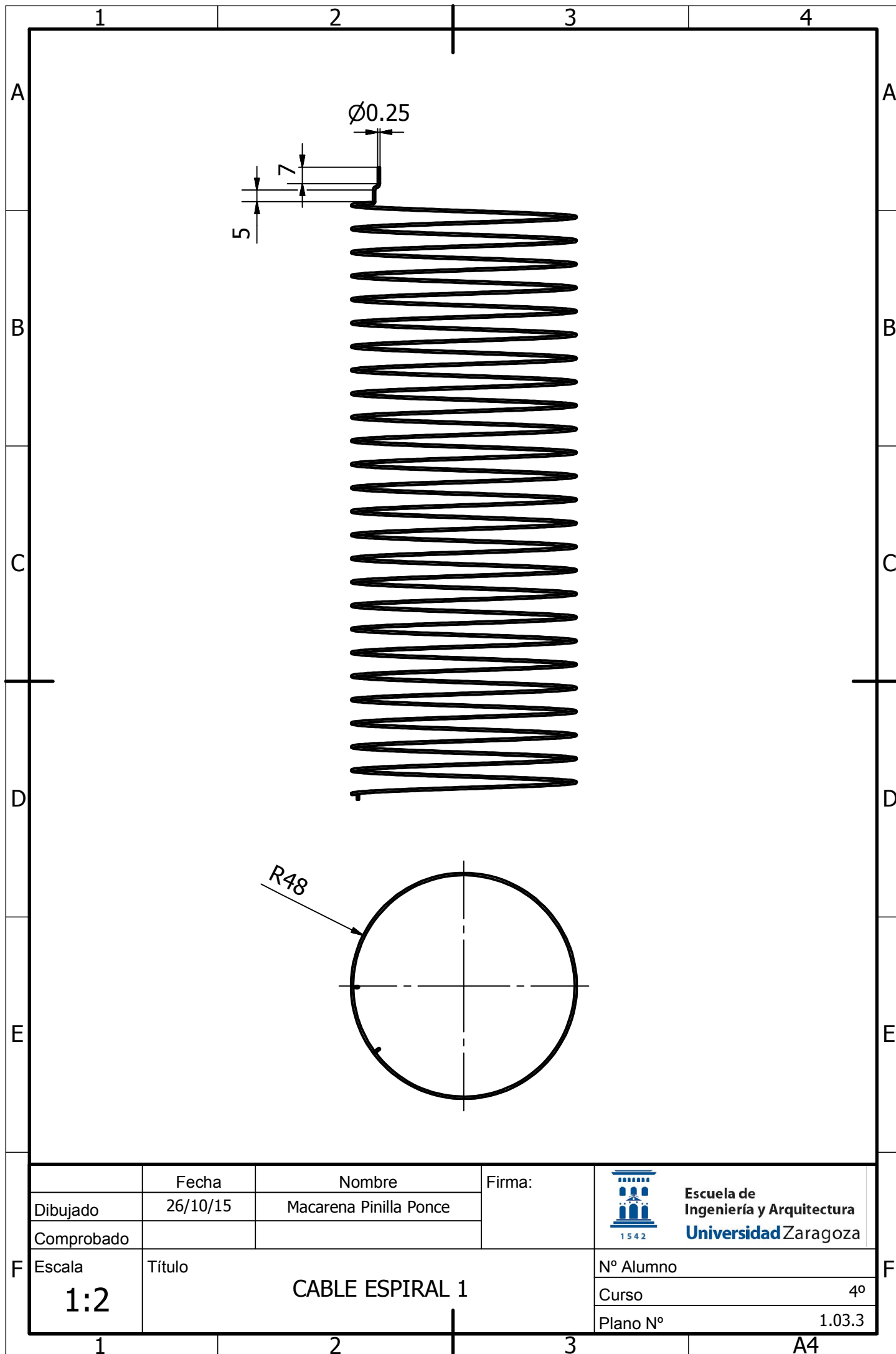
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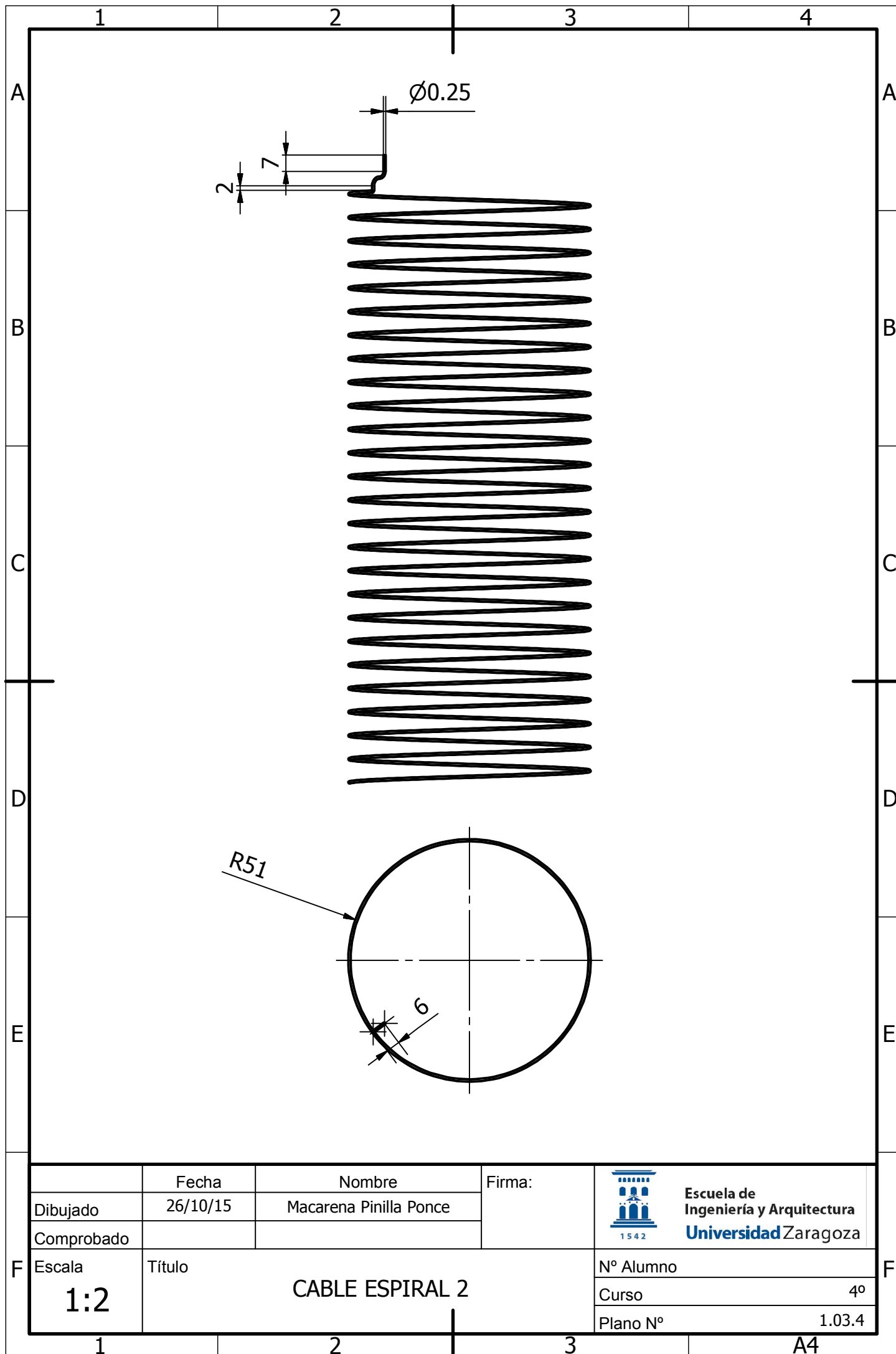
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F	Nº Alumno	Curso	Plano Nº	4º 1.03.1



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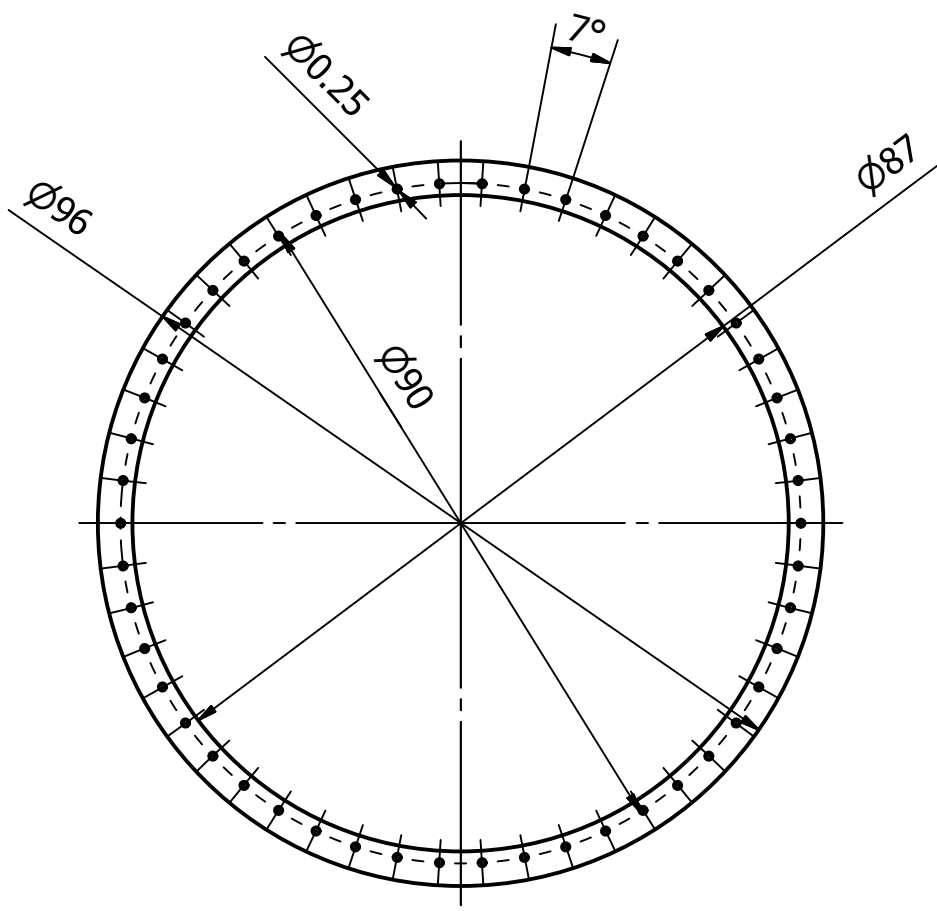
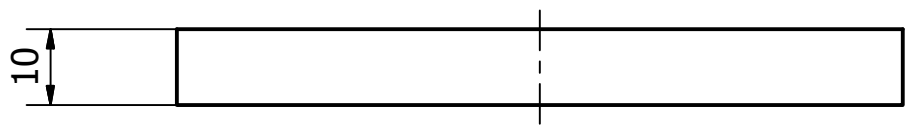


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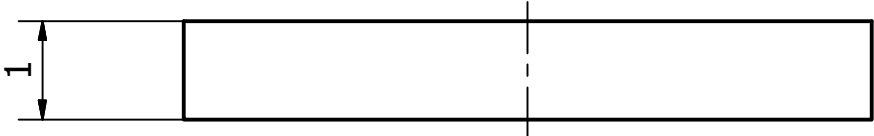
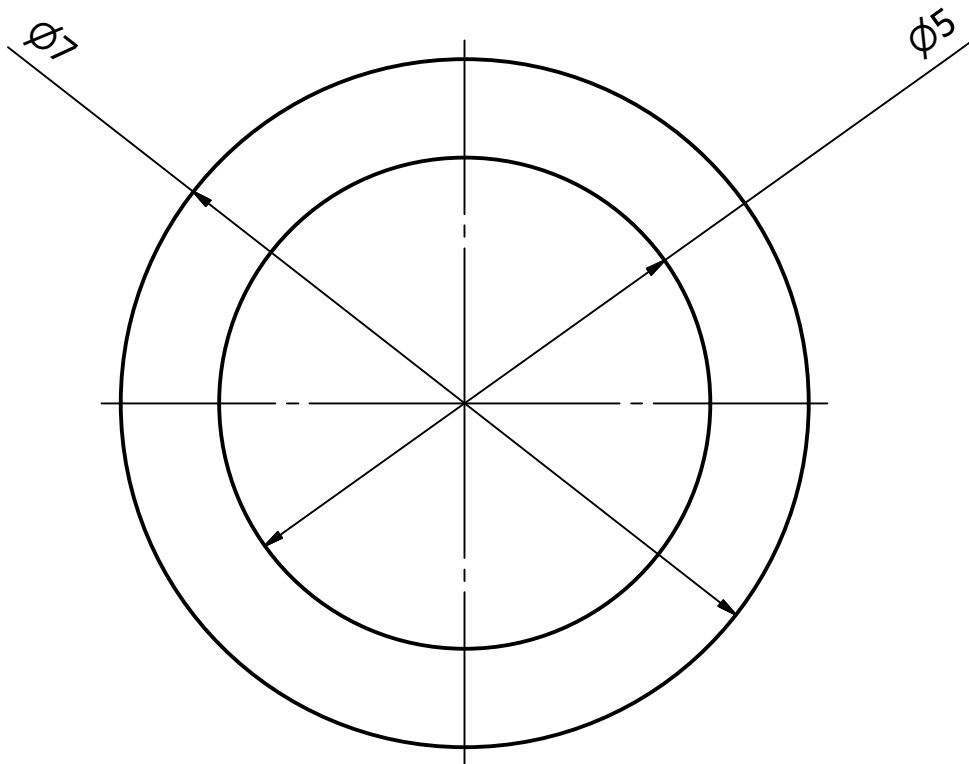


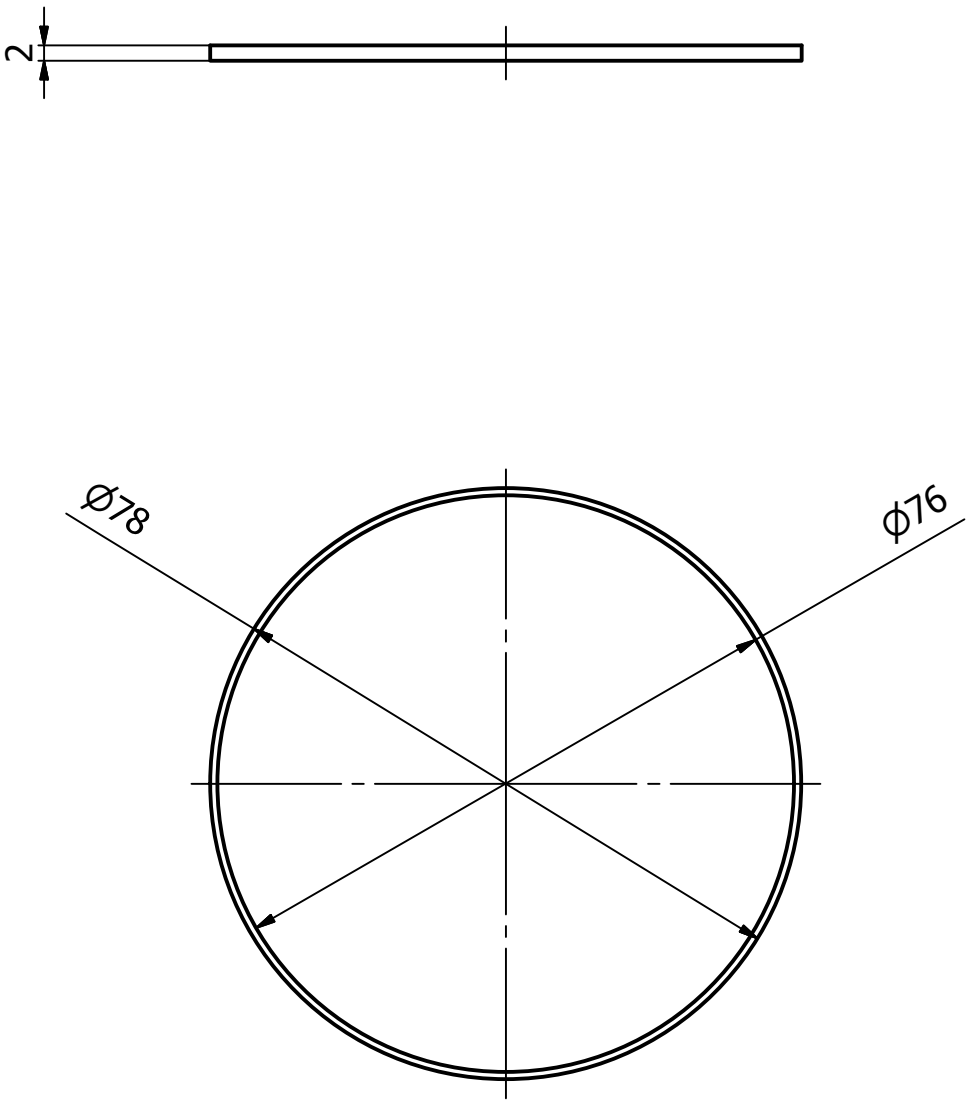
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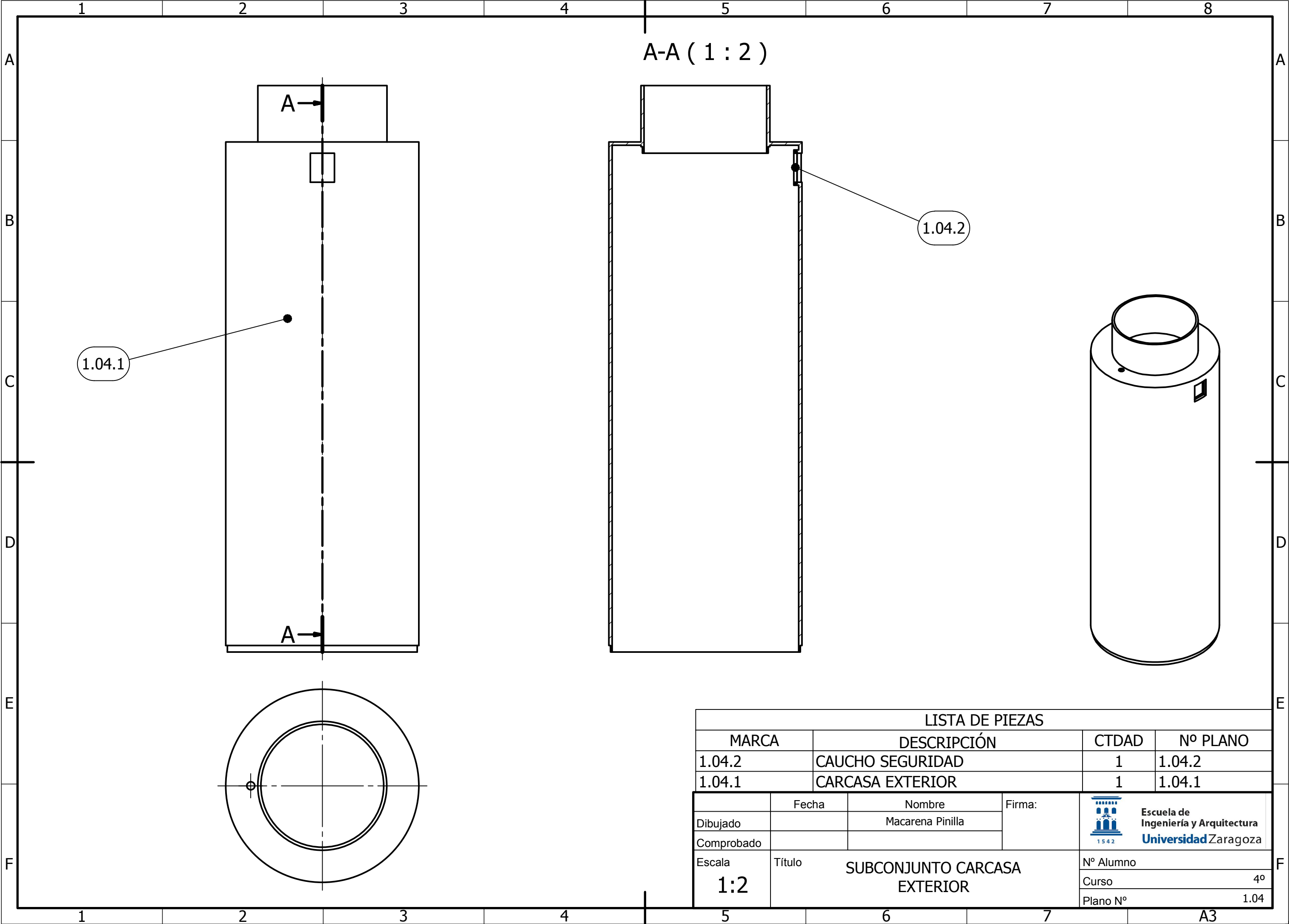
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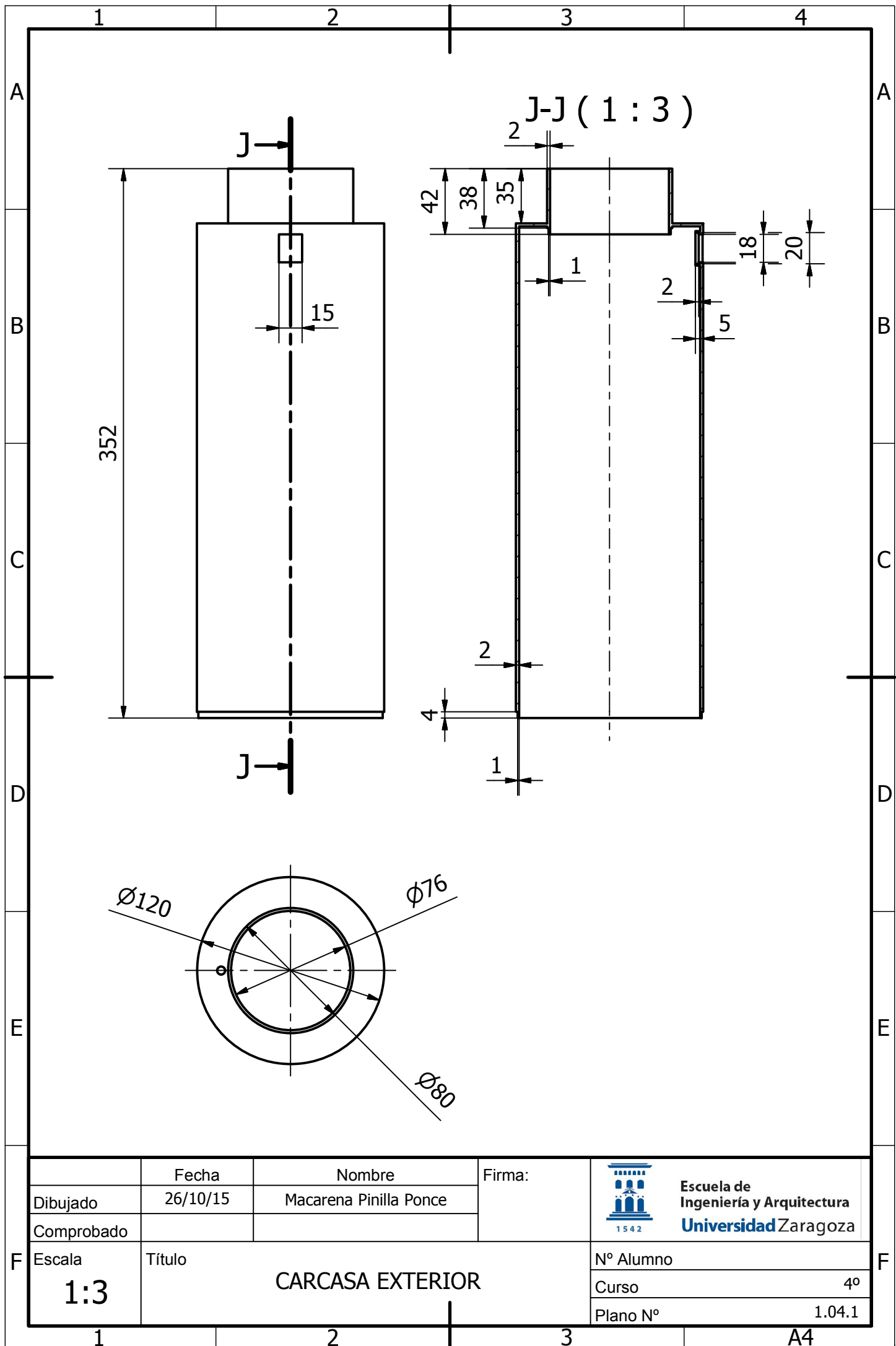
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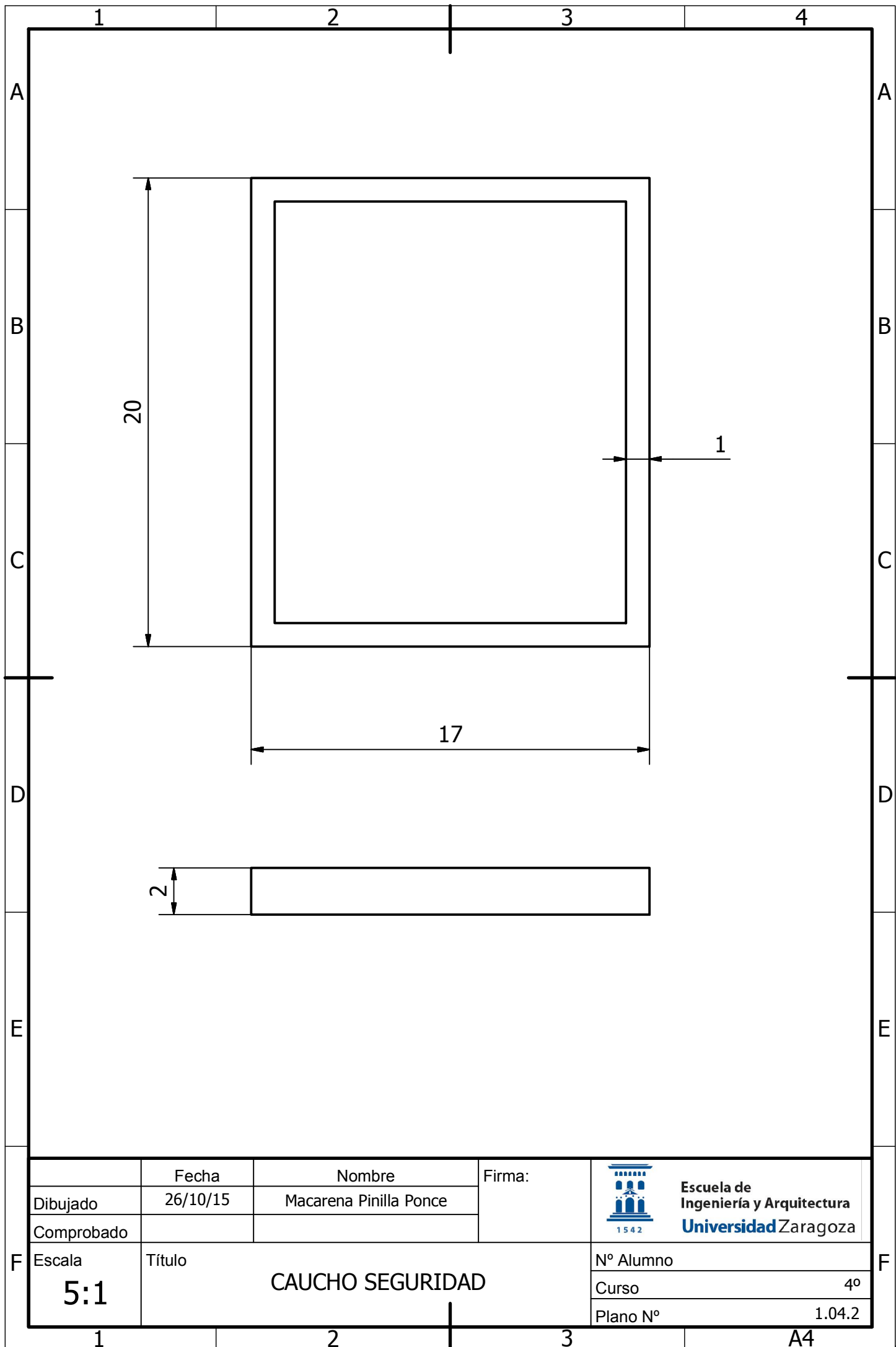


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Dibujado		Macarena Pinilla			
Comprobado					
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Dibujado	26/10/15	Macarena Pinilla Ponce		
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ANEXO METODOLOGÍA BIÓNICA 2.....



Universidad Zaragoza

TEMA 04: Metodología de diseño basada en Biónica II



Escuela de
Ingeniería y Arquitectura
Universidad Zaragoza

GRADO EN DISEÑO INDUSTRIAL Y DESARROLLO DE PRODUCTO.

ASIGNATURA: BIÓNICA 25828

FEBRERO DE 2013 – Profesor: IGNACIO LOPEZ FORNIES

Departamento de Ingeniería de Diseño y Fabricación.

Área de Expresión Gráfica en la Ingeniería.

OBJETIVOS

El objetivo principal es que el alumno identifique los dos grandes grupos metodológicos y reconozca su aplicación, de modo que comprenda como afrontar un proyecto y sepa desarrollar acertadamente el proceso.

También se pretende que asimile una parte teórica que necesitará para desarrollar ejercicios y proyectos.



INTRODUCCIÓN

En este bloque metodológico se pretende explicar dos formas de trabajo que se corresponden con las vistas anteriormente pero están directamente relacionadas con la forma de trabajo que se aplicara en los ejercicios y proyectos del curso.

Se detallan las fases de trabajo y se explican por medio de algunos ejemplos.

La innovación funcional de producto puede utilizar la biónica y biomimética, haciendo que forme parte del proceso de diseño, se plantean nuevas formulas y métodos para encontrar funciones diferenciadas y soluciones alternativas.

La mejora en la metodología se obtiene gracias a la integración de fases intermedias, en las que se establecen los criterios para buscar esas funciones clave, para después aplicar investigación biomimética con la búsqueda de referentes naturales que aporten soluciones de éxito.



METODOLOGÍA BIÓNICA. PLANTEAMIENTOS BÁSICOS



METODOLOGÍA BIÓNICA.

PROCESO DE DISEÑO



A large orange arrow pointing to the right, containing two rectangular buttons. The first button is green and labeled 'SOLUCIÓN EN LA NATURALEZA'. The second button is blue and labeled 'DEFINICIÓN DE UN PROYECTO'.

**SOLUCIÓN EN LA
NATURALEZA**

**DEFINICIÓN DE UN
PROYECTO**

Proceso de Diseño

1. Identificación del ser vivo a estudio. (individuo o grupo / sistema)
2. Definición del criterio o rasgo característico del ser vivo
3. Selección. Estudiar, analizar y dar conclusiones según los principios y procesos , analogía ingenieril.
4. Traducción al objeto a diseñar, emulación, tratar de conseguir superar lo ya existente.
5. Aplicación y diseño del objeto.



METODOLOGÍA BIÓNICA. PROCESO DE DISEÑO

Proceso de Diseño

1. Identificación del ser vivo a estudio.
(individuo o grupo / sistema)



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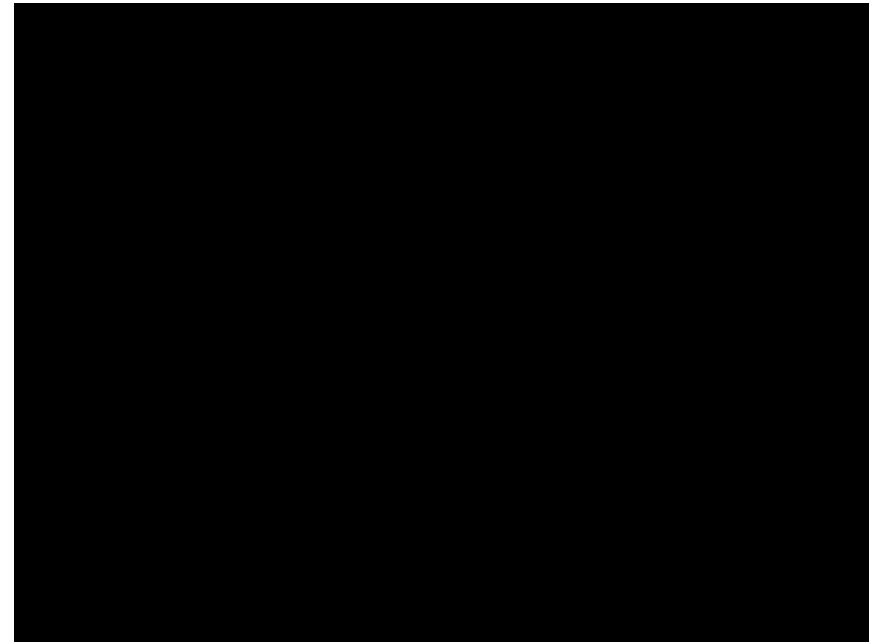
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METODOLOGÍA BIÓNICA.

PROCESO DE DISEÑO

Proceso de Diseño

2. Definición del criterio o rasgo característico del ser vivo



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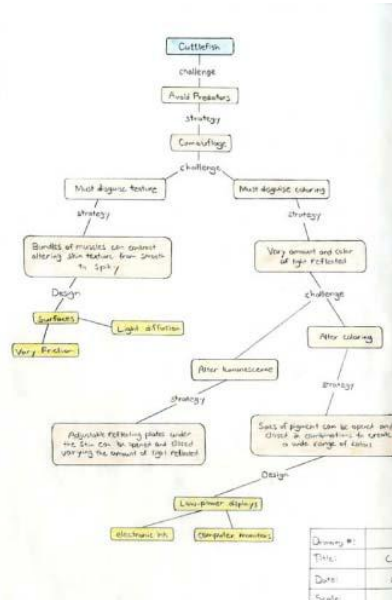
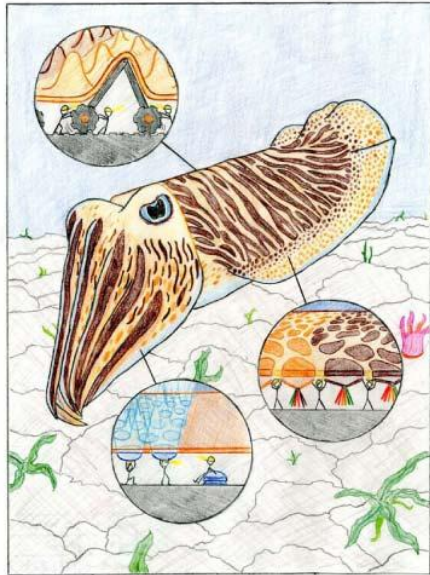
PROCESO DE DISEÑO

Proceso de Diseño

- Selección. Estudiar, analizar y dar conclusiones según los principios y procesos , analogía ingenieril.

SOLUCIÓN EN LA
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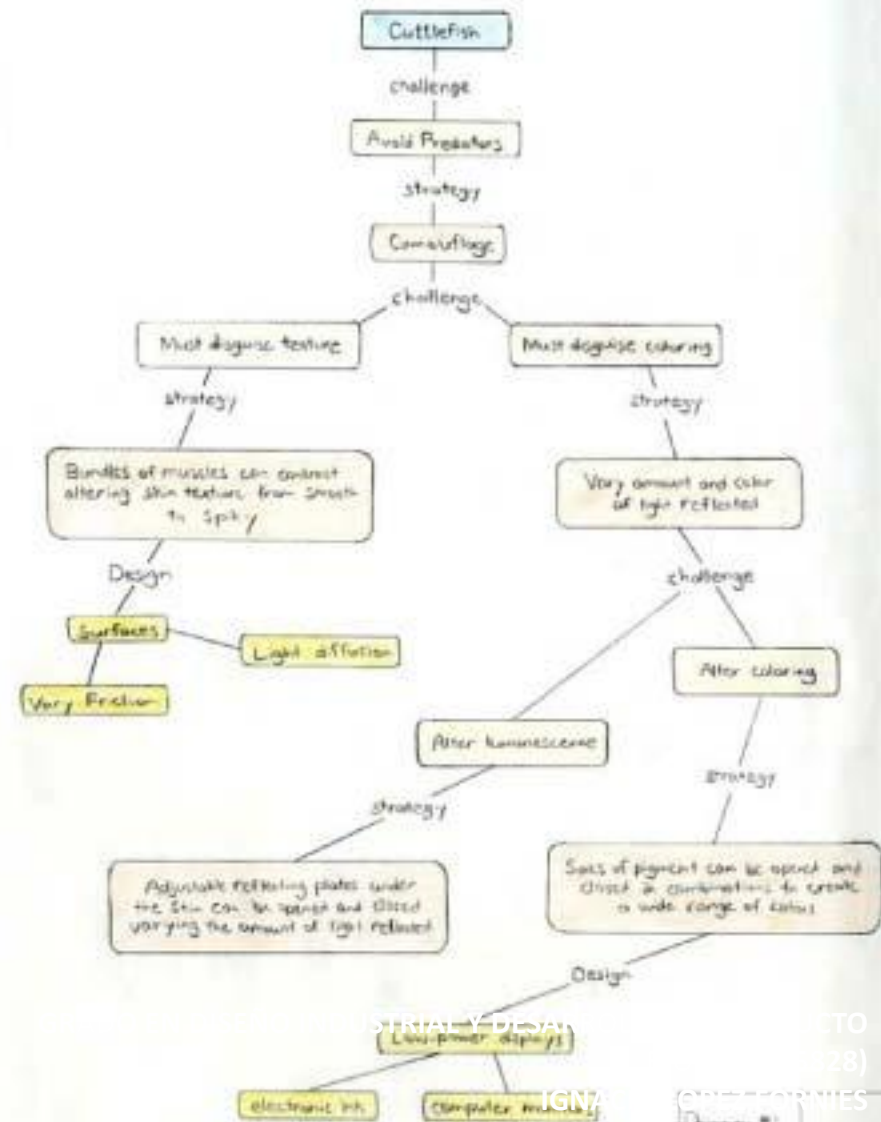
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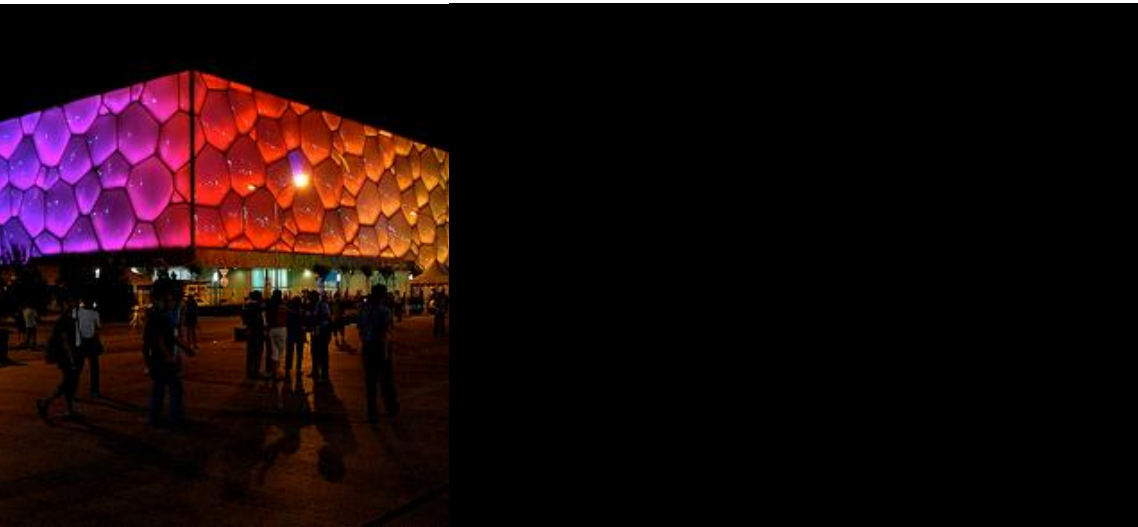
METODOLOGÍA BIÓNICA.



METODOLOGÍA BIÓNICA. PROCESO DE DISEÑO

Proceso de Diseño

4. Traducción al objeto a diseñar, emulación, tratar de conseguir superar lo ya existente.

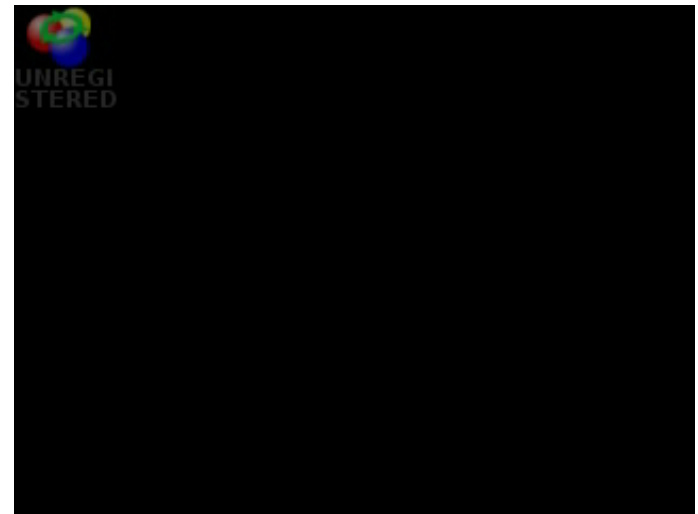


Ideas de aplicaciones: pantallas de vídeo biodegradables en dispositivos electrónicos. Eliminar pigmentos tóxicos en los revestimientos y productos comerciales, incluidas las pinturas. Textiles, papel y productos de construcción, protección solar flexible o revestimientos de edificios.

METODOLOGÍA BIÓNICA. PROCESO DE DISEÑO

Proceso de Diseño

5. Aplicación y diseño del objeto.



METODOLOGÍA BIÓNICA. PROCESO DE DISEÑO

SOLUCIÓN EN LA
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BIOMIMICRY

YiWei Liao

IDES 202

Daniel Michalik / Jonas Milder

METODOLOGÍA BIÓNICA. PROCESO DE DISEÑO

**PROBLEMA
TÉCNICO**

**INVESTIGACIÓN
BIONICA**

**DEFINICIÓN DE UN
PROYECTO**

Proceso de Diseño

1. Establecer el marco de trabajo
2. Definición las funciones clave / oportunidades de innovación
3. Estudio del estado del arte, en lo biológico como en lo industrial
4. Traducción de la soluciones naturales a funciones clave
5. Definición conceptual del producto
6. Diseño de detalle

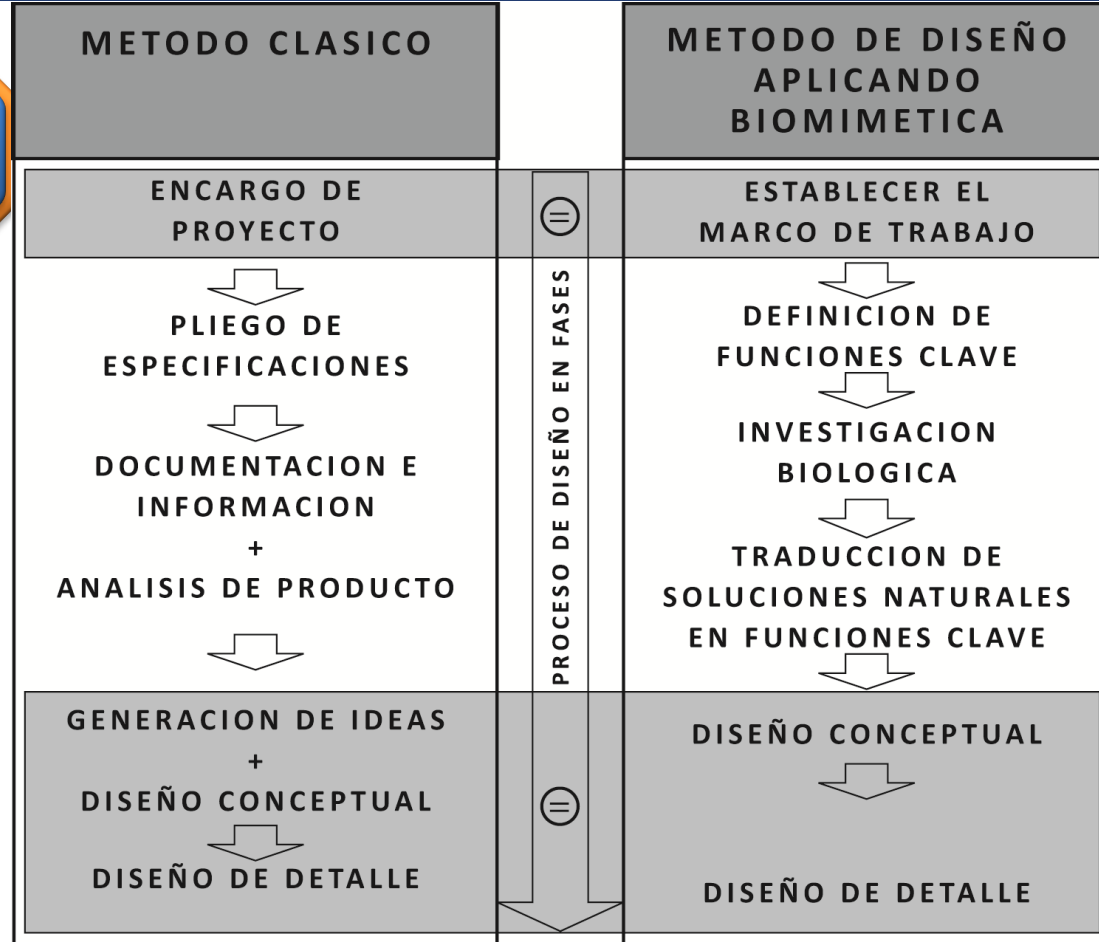
METODOLOGÍA BIÓNICA.

PROCESO DE DISEÑO

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Condiciones de la metodología

1. Normalmente no hay un encargo. Es necesario establecer un marco de trabajo
2. Las funciones clave o rasgos que pueden crear innovación pertenecen a un grupo de productos, son aplicables a todos dentro del grupo
3. Las innovaciones se pueden plantear por la investigación biónica o por el análisis del estado del arte.
4. Es necesario hacer investigación biónica y detectar fuentes de información de calidad.



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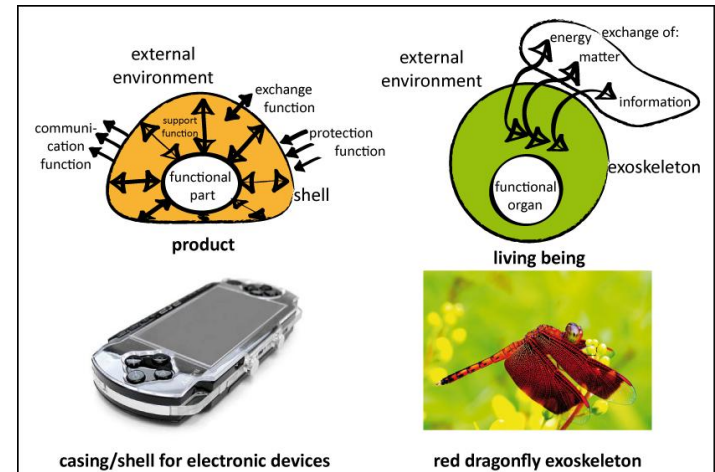
DEFINICIÓN DE
UN PROYECTO

Proceso de Diseño

1. Establecer el marco de trabajo

- Búsqueda de un grupo amplio, sector industrial o similar
- Establecer unas características a desarrollar y buscar innovación

PRODUCT CATEGORY	Electronic devices with touch, etc...	Litter bins or recycling bins	Packaging for food, disposable packs	Elements for body protection, helmets, bicycle or motorcycle armour, gloves, boots, goggles and masks, etc...	Suitcases and travel bags
IMAGE					



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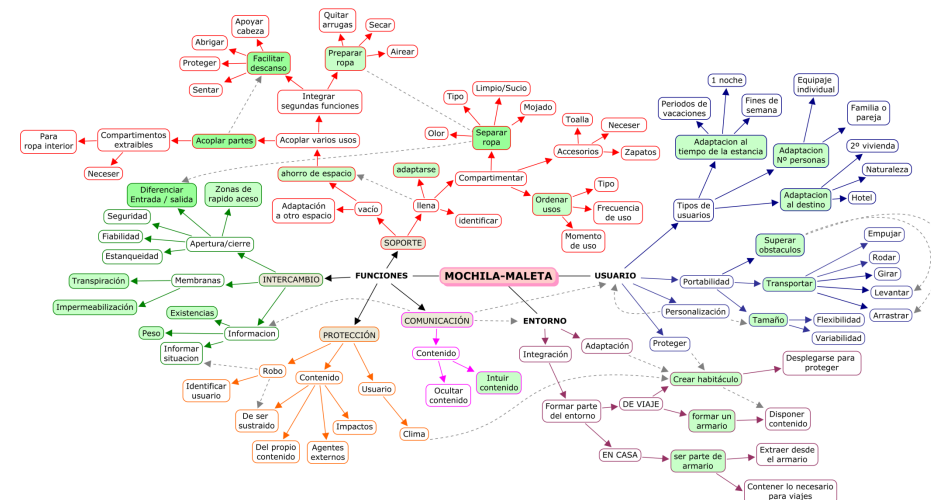
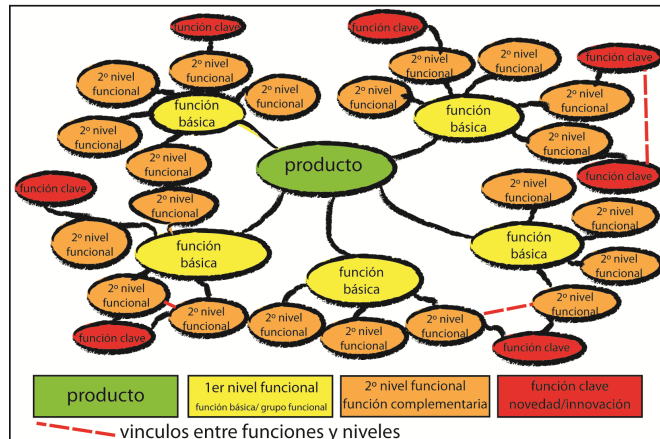
Proceso de Diseño

2. Definición las funciones clave / oportunidades de innovación

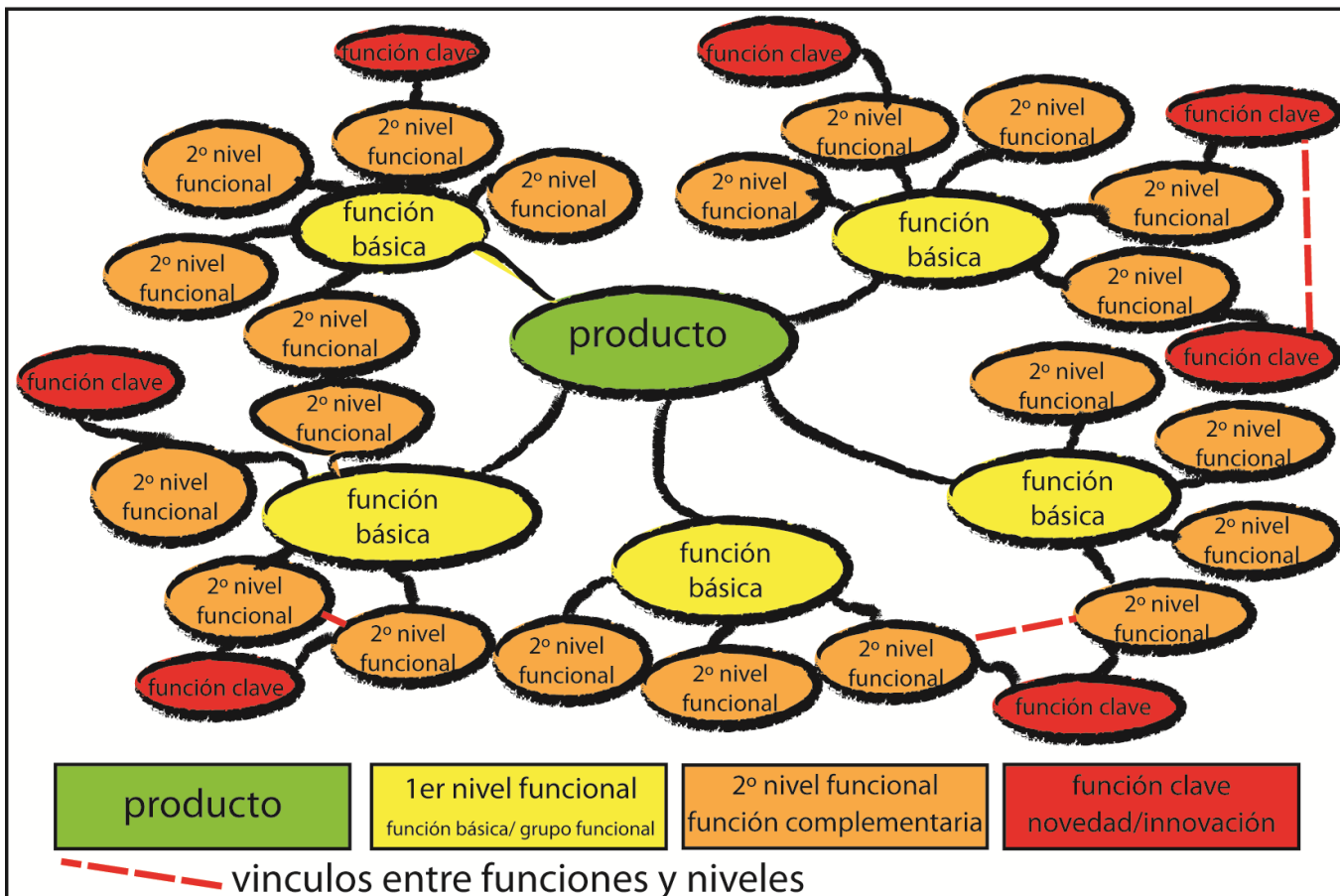
a) Utilización de técnicas de análisis, funcionales u otros

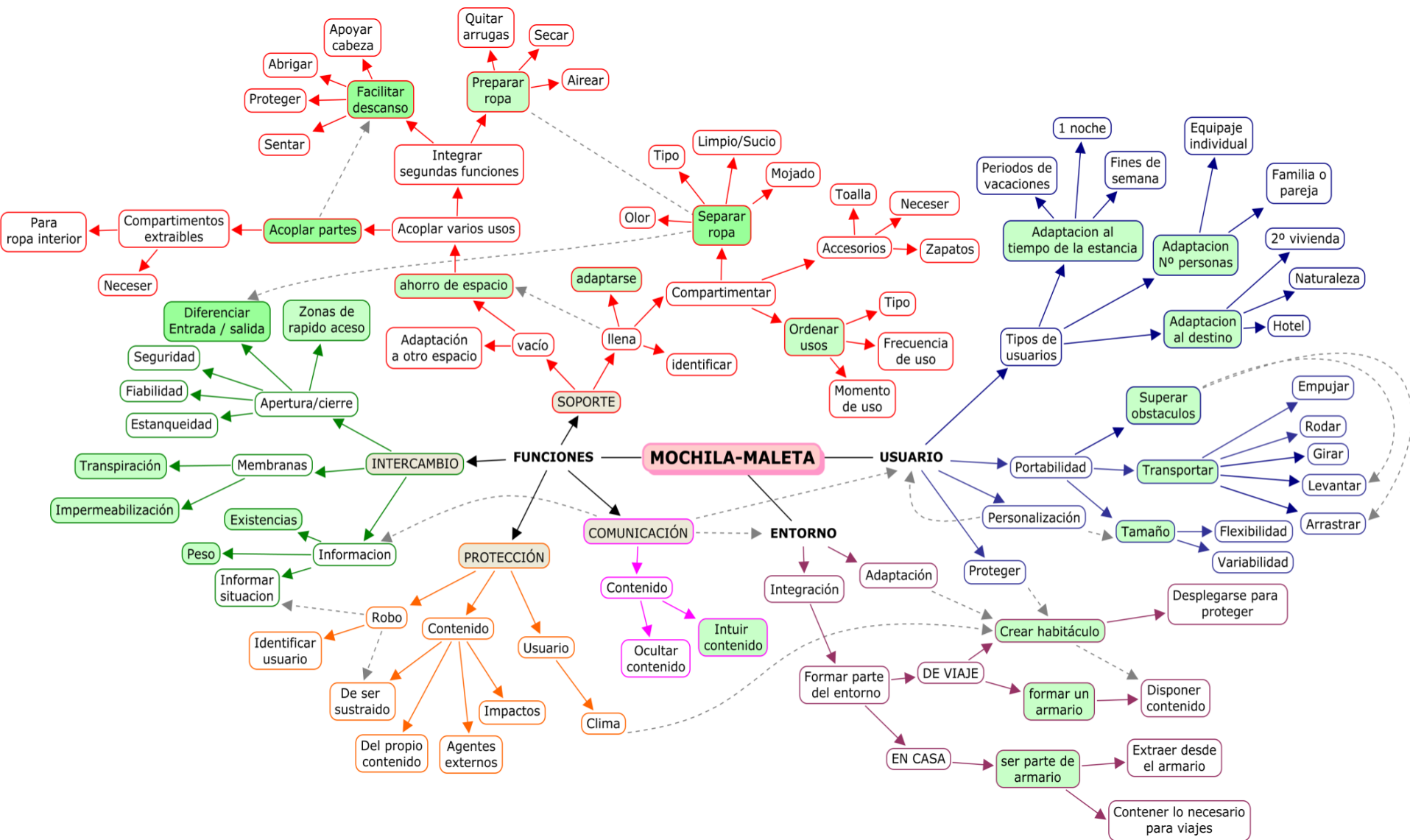
b) Utilización de técnicas de creatividad

FUNCIONES DEL PRODUCTO	1st LEVEL	2º NIVEL	3rd LEVEL	n LEVEL
FUNCION PRINCIPAL	Subfunción 1 (grupo funcional 1)	Subfunción 1.1	Subfunción 1.1.1 Subfunción 1.1.2	Subfunción 1.1.1.n
		Subfunción 1.2		
		Subfunción 1.3		
	Subfunción m (grupo funcional m)	Subfunción m.1 Subfunción m.2	Subfunción m.1.1 ...	Subfunción m.1.1...n ...



FUNCIONES DEL PRODUCTO	1st LEVEL	2º NIVEL	3rd LEVEL	n LEVEL
FUNCION PRINCIPAL	Subfuncción 1 (grupo funcional 1)	Subfuncción 1.1	Subfuncción 1.1.1	Subfuncción 1.1.1.n
			Subfuncción 1.1.2	
		Subfuncción 1.2		
		Subfuncción 1.3		
	Subfuncción m (grupo funcional m)	Subfuncción m.1	Subfuncción m.1.1	Subfuncción m.1.1...n
		Subfuncción m.2	...	...





METODOLOGÍA BIÓNICA.

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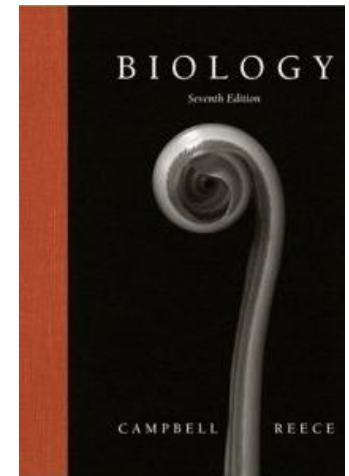
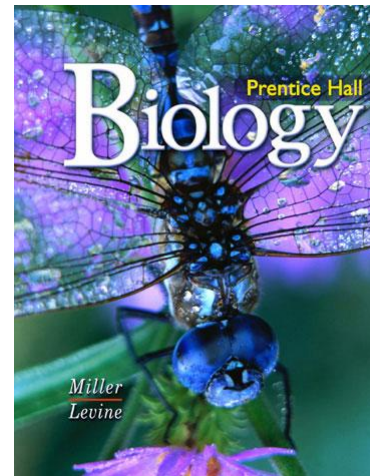
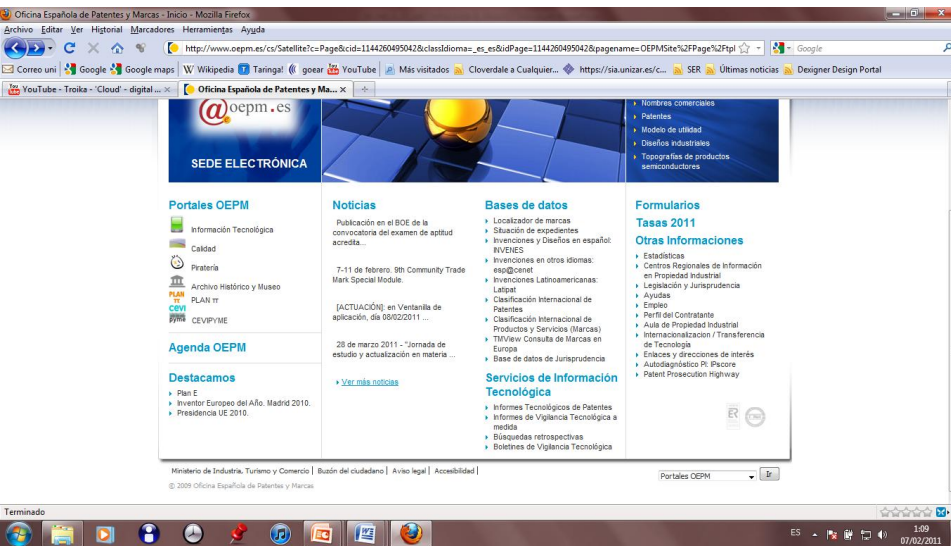
DEFINICIÓN DE
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Proceso de Diseño

3. Estudio del estado del arte, en lo biológico como en lo industrial

a) Analizar el estado del arte para evitar el hacer lo ya hecho

b) Analizar las características mas interesantes del medio vivo



KEY FUNCTION (PROJECT OBJECTIVES)	RESEARCH GUIDELINES (HOW TO ACHIEVE THE KEY FUNCTIONS)	NATURAL REFERENCE (BIOMIMETIC RELATION)
KEY FUNCTION 1	HOW COULD...? WHO COULD...? WHY SHOULD...? WHAT STRUCTURE COULD...? WHAT MATERIAL COULD....? WHAT IS NEEDED TO? WHERE COULD?	LIVING BEING 1 LIVING BEING 2 LIVING BEING 3 LIVING BEING 4 LIVING BEING 5
KEY FUNCTION 2	QUESTIONS FOR KEY FUNCTION 2	LIVING BEING x
KEY FUNCTION 3	QUESTIONS FOR KEY FUNCTION 3	LIVING BEING y
KEY FUNCTION 4	QUESTIONS FOR KEY FUNCTION 4	LIVING BEING z

OBJETIVOS	LINEAS DE PROYECTO/ COMO CONSEGUIR EL OBJETIVO	NATURALEZA/ REFERENTE BIOMIMICO

REQUISITOS (FUNCIONES DE LAS CARCASAS)			SOLUCIONES (ANALOGIA CON FUNCIONES DE LOS EXOSQUELETOS)		
1er NIVEL (GENÉRICO)	2º NIVEL	3er NIVEL	FUNCIONES	EJEMPLO EN LA NATURALEZA	
FUNCION BASICA DEL PRODUCTO O GRUPO FUNCIONAL	FUNCION DETALLADA DE ALGUNOS DE SUS COMPONENTES O PARTES	FUNCION ESPECIFICA, FUNCION QUE REALIZA UN OBJETIVO CONCRETO	FUNCION DESARROLLADA POR EL EXOSQUELETO	EJEMPLO DE SER VIVO QUE DESARROLLA LA FUNCION	IMAGEN
PROTECCION (MANTENER LA INTEGRIDAD FISICA)	RESISTIR IMPACTOS	DISIPACION DE ENERGIA	RESISTIR IMPACTOS/ DISIPACION DE ENERGIA DE CHOQUE	"La estructura del tejido de las patas del grillo amortigua el choque del salto debido a un exoesqueleto de cutícula flexible y fibras densas. (Stanislav Gorb Instituto Max-Planck-Institut Metallforschung) "	
		ABSORCION DE ENERGIA	RESISTIR IMPACTOS/ DISIPACION DE ENERGIA DE CHOQUE	El exoesqueleto de la ibélula le protege durante las colisiones con la presa al ser duro pero lo suficientemente flexible como para absorber los golpes (Harun Yahya 2002 Diseño en la Naturaleza Londres: Ta-Ha Publishers Ltd.)	
				en las pulgas el recubrimiento de su exoesqueleto protege durante los impactos: (Harun Yahya 2002 Diseño en la Naturaleza Londres.: Ta-Ha Publishers Ltd.)	
	PROTECCION ANTE AGRESIONES EXTERNAS	PROTECCION ANTE LA HUMEDAD	PROTECCION ANTE FACTORES ABIOTICOS / PERDIDA DE HUMEDAD	una espuma proporciona un control térmico y de humedad. Las larvas están protegidos de las fluctuaciones de la temperatura y la humedad gracias a la cobertura de savia de la planta.	
				La cutícula de las cucarachas permite una variación de temperatura controlada y pérdida de humedad a través de una capa cerosa. (Wigglesworth, VB 1945 transpiración a través de la cutícula de los insectos Journal of Experimental Biology 21 (3):... 97-114.)	
		PROTECCION ANTE LA LUZ	PROTECCION ANTE FACTORES ABIOTICOS / FILTRADO DE LUZ	Los exoesqueletos de carbonato de calcio de los corales podría ayudar a proteger sus simbiontes fotosintéticos mediante la absorción de los rayos UV. (Arrecife I; Kaniewska P; Hoegh-Guldberg O. 2.009 esqueletos de coral defensa contra la radiación ultravioleta PLoS One 4 (11):... e7995)	



METODOLOGÍA BIÓNICA.

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4. Traducción de la soluciones naturales a funciones clave

KEY FUNCTION (PROJECT OBJECTIVES)	RESEARCH GUIDELINES (HOW TO ACHIEVE THE KEY FUNCTIONS)	NATURAL REFERENCE (BIOMIMETIC RELATION)
KEY FUNCTION 1	HOW COULD...? WHO COULD...? WHY SHOULD...? WHAT STRUCTURE COULD...? WHAT MATERIAL COULD....? WHAT IS NEEDED TO? WHERE COULD?	LIVING BEING 1 LIVING BEING 2 LIVING BEING 3 LIVING BEING 4 LIVING BEING 5
KEY FUNCTION 2	QUESTIONS FOR KEY FUCNTION 2	LIVING BEING x
KEY FUNCTION 3	QUESTIONS FOR KEY FUCNTION 3	LIVING BEING y
KEY FUNCTION 4	QUESTIONS FOR KEY FUCNTION 4	LIVING BEING z

Bibliografía y fotografías:

Archivo propio

Apuntes propios

www.google.com/videos



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