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Closing the innovation cycle in lightweighting compressor pistons technology

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Summary:

What started out as an exercise in exploring the weight reduction potential of those allegedly “heavy recip crossheads”, turned out to be a fast leap towards implementation of a new hybrid material concept for very lightweight pistons. This was enabled by a next phase in the EFRC R&D group research project which has been subject of this conference before.

The 2014 paper was technical in nature, addressing the context and requirements and defining the solid polymer concept (SPP) as an exciting solution, as well as the characterization of polymer composite materials in fatigue. Building on these foundations, the current paper focuses on the challenge of turning the obvious good idea into a readily available technology under the restrictions of pre-competitive research. Therefore it identifies the things that should be done, how to do it and also which things are best left until later.

Bypassing the extensive volume of technical work that had to be done to demonstrate feasibility and develop key materials and testing technology, the results of the full scale validation experiments are presented as well. Following an earlier 1:10 scale piston fatigue test, a full scale test demonstrated a residual strength – after accelerated fatigue – of 400 kN.

Comparing against commonly encountered designs based on steel and aluminium, a 30 – 70% mass reduction is found for typical larger size pistons.

Enabled by the full scale validation of the concept, the technology readiness is enhanced to a level that by 2016, the technology seems ready for validation in an actual compressor. As a matter of fact, the results of the R&D project are industrially applied, witnessed by the emergence of a spin-off company and plans by major compressor manufacturers to design and/or launch new and significantly improved machines.

The authors argue that the EFRC R&D project may be seen as a model case in efficacious creative innovation, where the time between idea generation and industrial application is less than 3 years. A brief discussion of why we believe this was possible is included. It explains what is required to achieve success – in spite of a rather odd idea introducing

an unknown 'plastic' material into a self-declared conservative industry – to get a disruptive innovation like the solid polymer piston accepted so quickly.

1. Introduction

Lowering the reciprocating mass has been a continuous activity over the past decades because of the associated improvements in machine capacity, durability, efficiency and vibration behavior. While the application of conventional metals has supported the current state of the art in recip machinery, the returns of these efforts have been diminishing. A previous paper introduced and explained an initiative by the R&D group to explore the potential offered by other materials than have normally been applied in the recip world. The present paper describes how over the two years since then the feasibility of one candidate material and structural concept has been investigated and technology has been developed. In doing so, the master plan as outlined in [1] has been essentially followed and implemented.

Focus on the piston

To summarise, in [1] it was argued that there was good reason to put emphasis on mass reduction of the piston rather than of the crosshead because of two major reasons: First, the piston is typically significantly heavier than the crosshead (and piston rod); this applies especially to the low pressure stages where the piston mass may even limit the machine capacity directly. Second, the crosshead is structurally more complex, limiting the potential mass reduction from the outset.

Most manufacturers have obtained some experience with investigating the potential of other materials for pistons. For example, ceramic pistons and fiber composite materials have been investigated to some extent in scattered research efforts. Whereas no major applications have resulted from such studies, it may be argued that the effort spent, scope and expertise was insufficient to result in a breakthrough. This was the background and rationale for the joint research in the EFRC R&D group. In doing so, the master plan as outlined in [1] has been essentially followed and implemented in a three phase project.

From requirements versus the state of the art to a new design concept

In the early study phases, a careful compilation of requirements was made and an exploration study was done against a background of data from materials science and similar developments in other industries. For example, it was seen that automotive suspension springs were successfully made much lighter under severe fatigue requirements using fiber composite materials. In general however, it seemed that high manufacturing cost, design complexity and even more severe (very high cycle) fatigue (VHCF) requirements would jeopardise the competitive potential of CFRP[1].

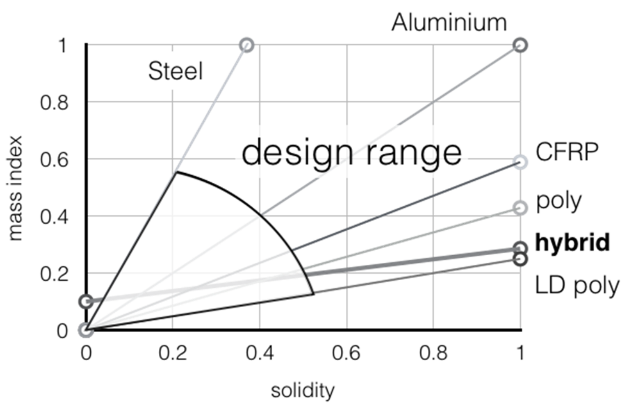

Figure 1 Basic mass-solidity-density (MSD) diagram

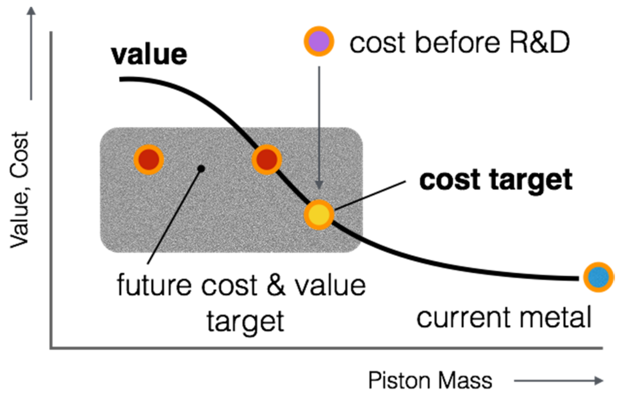

Figure 2 Tentative saturation sketch for mass reduction

It was concluded that a radically new approach had to be taken to the design and material selection. Thus, the so-called *Solid Polymer Piston* (SPP) concept was conceived and presented in [1], a hybrid combination of metal and composite polymer (CCPC: Controlled Cavity Polymer Compound) which derives its potential competitiveness from three key factors:

[1] CFRP: Carbon Fiber Reinforced Polymer

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- low density core material allows efficient transfer of gas pressure loads to piston rod using a solid or pseudo-solid core;
- relative ease of consistent manufacture from one-offs to series production;
- an affordable engineering development sufficient to guarantee infinite fatigue life.

With a mass reduction potential of typically 50% or more relative to both steel and aluminium baseline, it was apparent that efforts had to be focused on this concept during the remainder of the project. The SPP is discussed under the corresponding header, allowing the reader to become familiar with its basic tenets which already allow dramatic mass savings (Figure 1). Moreover, it was felt that the drive for even further weight reduction would disappear as mass contributions of crosshead and piston rod would become of comparable magnitude and an S-curve saturation would be approached (Figure 2).

From precompetitive research to innovation

A vital aspect that was considered from the outset is what can be called the valorisation of the idea/invention. This is a challenge for the pre-competitive EFRC research group. An idea may be good in itself, but in practice many obstacles can and do prevent its implementation. This is true especially in an industry where any perceived risk may be too much and which has relied extensively on metals technology for structural components. Therefore the transfer of the idea of using a hybrid polymer concept toward actual application was built into the project using concepts of disruptive innovation theory. This means that the conditions were to be promoted for implementing the new technology if and when the specified success criteria had been met. This involves aspects of pre-competitive development and follow-up competitive activities, which were formulated and concretised during the project, as will be discussed under the heading *Innovation Concept*. Members of the R&D group would then have a choice, to embrace and extend the technology either as their own proprietary development from a common background, or to adopt the technology more passively by involving a supplier – be it from a knowledgeable perspective enabling a truly *smart-buyer* position.

On a technological level, it was essential to demonstrate the feasibility by experimentally validating the concept, again going as far as the precompetitive nature would allow to do so. Under the heading *Validation*, some results are presented of materials and scaled and upscaled experiments which cover manufacturing feasibility and structural integrity.

requirement item	**requirement**	**SPP compliance**
mass	significant saving	from ~30% to ~70% depending on size and allowable cost
structural integrity	resistant to environmental attack (lubrication oil and process gas)	polymer inherent resistance very good; elimination of metal surface as a factor in fatigue life.
	infinite fatigue life	low stress and good testability and predictability
	thermal boundary conditions satisfied	proper polymer selection allows elevated temperature operations
	condition monitoring	can be built-in,
economic value	affordable	price comparable to metal for very small series
development feasibility	3 years, < 1M€ investment	qualitative compliance; 2 years pre-development with core technologies
industrial requirement	no mandatory single source dependence	SPP as open-ended concept allows multiple implementations
	limited industrial risk	by retaining metal hub and sleeve, many aspects remain unchanged and success is promoted

Table 1 Evolved requirement overview for the lightweight piston.

Requirements

In the original article [1], the set of requirements was presented and discussed, which should guarantee that the developed idea would be both techno-economically feasible and near-optimum. Such a set of requirements is subject to gradual evolution in a process called requirement discovery. Some of the most important evolved requirements, together with an assessment for the SPP concept, are listed in Table 1.

2. The Solid Polymer Piston (SPP) concept

Anatomy of the SPP

In its most basic form, the SPP consists of three elements as illustrated in Figure 3. By being solid, the low density core offers a simple load path from pressurised faces to the piston rod. Corresponding shear stresses (discussed below) are relatively low because the load transfer area (via the shaft or hub) is large.
The sleeve, being well-supported by the core, can be shaped as desired from considerations of weight and manufacturing. A choice for metal such as stainless steel or aluminium would be obvious for several reasons, but not required in itself.

For lower values of the piston length-to-diameter ratio of the desired piston design, a fourth element may be introduced, namely a piston pressure face liner which could be metal and could be integrated with the sleeve.

As a solid element, the core would be subject to the square cube law, implying that its mass contribution would become large for the larger size pistons. For such cases, there exists an obvious possibility to design a core with cavities which would counteract this trend. We may designate such a concept with the abbreviation CSPP (Cavity-SPP).

Variations could be applied throughout. For example, one could be in the assembly on the interfaces: these could be smooth and adhesively bonded or with a form-fit in combination with adhesive bonding. In all cases, the common feature is the low density core of the CCPC type. The possibilities to conceive such a core is discussed next.

Low density materials

Typical polymer densities are in the range of 0.95 to 1.25 kg/dm3. In order to transfer these into CCPC materials of even lower density, they should be mixed (compounded) with low density fillers, but this is not a straightforward issue. The reason is that many desirable polymer properties lead to high viscosity which inhibits proper mixing. To promote easier processing, the polymer is best chosen to be of a thermosetting type. Then, in combination with the fillers and depending on the compound composition, a density in the range of 0.4 to 0.8 kg/dm3 can be achieved.

In the previous article [1] it was argued that the mechanical performance (e.g. fatigue strength) does decrease due to the fillers, but if done properly will maintain a sufficient level to sustain the applied stress typical for piston application. It was also remarked that comparison of our project data and literature suggests that achieving an outstanding manufacturing quality is essential for good fatigue performance. The ideal would be to produce defect-free cured compound, as VHCF performance is especially susceptible to minor flaws.

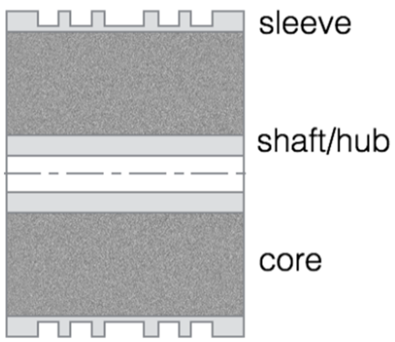

Figure 3 The generic SPP

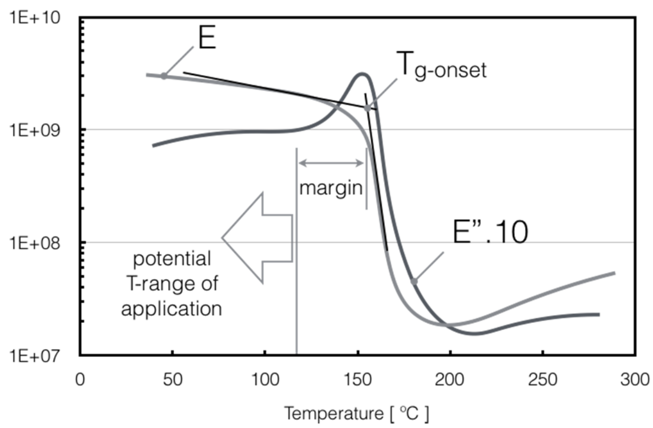

Figure 4 Stiffness and damping as a function of temperature for a medium temperature thermosetting polymer.

For any elevated temperature application of polymers, temperature is a driving requirement.

For the present project, a high temperature curing epoxy was selected to support also intermediate temperatures. A tentative equilibrium temperature requirement range was formulated pending a full measurement or validated computation of the temperature distribution through the piston. On the low end, a 90ºC requirement was considered to be on the safe side. On the upper side, a value of 140ºC seems to be representative. Figure 4 shows how stiffness of a typical thermosetting polymer is a function of temperature. Also, the internal damping of the material is seen to increase as the glass-to-rubber transition (Tg) is approached in this so-called DMTA test diagram. While it is typically good practice to maintain a 30ºC margin between the Tg onset and an operational temperature under load, it is probably even more important to consider the fatigue performance under elevated temperature. The corresponding fatigue limit is a property which cannot be computed, but is only accessible through empirical research. As discussed in the next section, this was beyond the scope of the precompetitive work and only room temperature data were generated for the VHCF range, although [1] also presents data up to 120ºC in the HCF range.

Stress levels and fatigue performance prediction

The core material will be loaded in a three-dimensional state of stress, especially near the critical areas. Therefore we have stress concentration (reduction) and multi-axial fatigue performance as our main challenges. Moreover, stress will arise due to imposed strain (from the preload on the shaft) as well as from alternating (gas and inertia) loads. In addition, residual stress from manufacturing will be present depending on the processing that has been applied. Figure 5 shows typical computed stress components for the shaft to core interface. We may consider the situation as an average shear stress ($P/(\pi.D_s.L)$) with stress concentrations, superimposed on a compressive stress distribution. The average cyclic shear stress will for low pressure stages be of the order of 1 or 2 [MPa], according to:

$$\tau = \Delta p\ \pi/4\ D^2/(L.D_s) = \Delta p\ \pi/4\ (D/L)\ .\ (D/D_s)$$

, where Δp is gas pressure difference, P is maximum piston rod force, D and L are piston diameter and length and D_s is shaft diameter. The imposed (axial) compressive stress in the polymer will depend on the shaft stiffness, i.e. modulus and cross sectional area. It will also be of this order of magnitude especially if aluminium alloy is chosen. Even in this case, there is an option to reduce this stress field if desired by performing the bonding operation under load. In addition, elevated temperature curing may be used to tune the core stress levels at the operational temperature to a desired value.

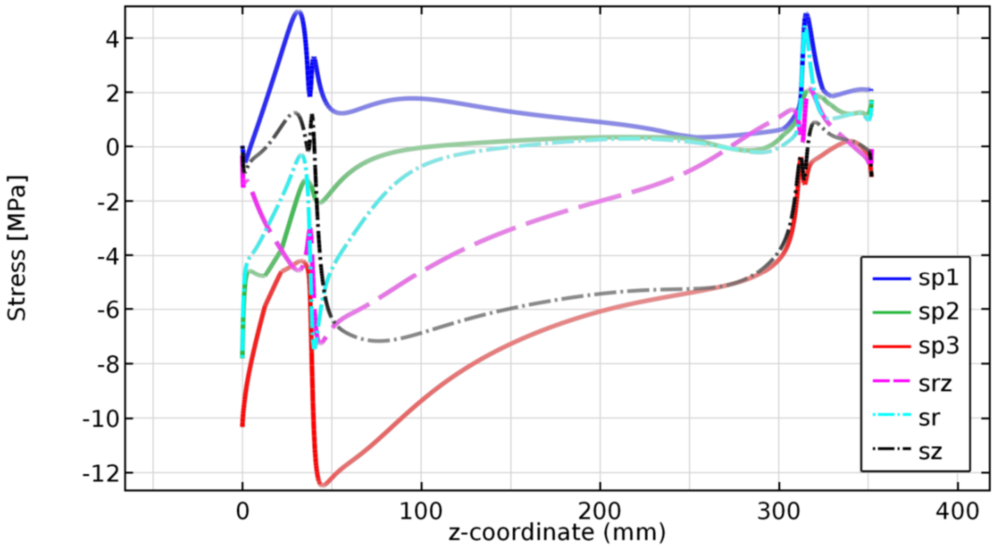

Figure 5 Representative stress components along a simple (straight) shaft-to-core interface; sp1, sp2, sp3 are principal stresses; sr and sz are radial and longitudinal stress, srz is shear stress.

When designing the piston using the SPP concept, a fatigue evaluation for the core material should be enabled by a database obtained from experimental work. In [1], results from a uniaxial test into the High Cycle Fatigue (HCF) domain of 10 Mcycles was presented. The uniaxial stress condition was obtained by using a 3 point bending test. In order to better represent the three-axial stress condition from Figure 5, a unique shear strength test for the VHCF domain (Very High Cycle Fatigue, 1 up to 10 Gcycles) was developed especially for the SPP application. This biaxial test could be combined with an axial load to achieve the desired tri-axial state of stress. Table 2 shows the possibilities using this technology, together with the limitations of scope as applied in the present project. The last column contains the “Final” requirement which would apply to an actual application where such a material characterisation would be part of a risk reduction effort as required. The 100ºC test temperature used in the table would cover many applications such as API-618 machines, but would have to be increased for cases where the piston local equilibrium temperature is expected to be higher. To clarify this, the section about *critical aspects* contains a discussion of the thermal behavior.

test method	**stress type**			**temperature**		*** test - frequency**	**N_{max}**	**EFRC R&D**	**Final**
	uni-axial	**bi-axial**	**tri-axial**	**RT**	**~100ºC**	**[Hz]**	**[-]**		
3P bending	x			x	x	< 25	2. 10^6	phase 2	
torsional shear		x		x		< 300	3. 10^9	phase 3	
torsional shear		x			x	< t.b.d.	1. 10^9	–	✔
residual strength		x		x			n/a	–	✔
pre-stressed torsional shear			x	x			0.1 10^9	–	✔

Table 2 Overview of applicable material test methods related to fatigue performance (RT = Room Temperature), to be applied to CCPC materials (indicates achieved or allowable frequency). Nmax is the maximum number of load cycles.*

Hybrid Elements

From the outset, the SPP is conceived as a hybrid structure, allowing for the best materials to be applied locally to achieve the best compromise for performance and cost. In particular, metal is initially retained in the inner and outer zones so that the best of both worlds may be combined and transition would be easier and risk severely reduced. Table 2 presents a brief overview of options and design considerations.

	materials options	**optional features**	**baseline SPP**
shaft	aluminium alloy; stainless steel; fiber composites	straight or form-fit; interface to torque-nut; recess for collar	straight where sufficient, Al 7075-T6
sleeve	stainless steel; aluminium alloy; filled polymers	full castellation contour	straight, modestly staggered
face	metal sheet; filled polymer gelcoat	-	no face cladding
core	thermoset polymer and controlled cavity filler compound	stress concentration reducing features, gradient zones, macro cavities	

Table 3 Specification of basic SPP components

Critical aspects for the SPP and research efforts

General concerns about potential shortcomings of polymer composites and several specific to the SPP concept and CCPC (Controlled Cavity Polymer Compounds) are listed in Table 4 below, together with a brief discussion on the relevance and criticality. The major aspects have been addressed in the current project and are discussed more extensively below.

The most important design driver which is decisive for the feasibility of the SPP concept is the fatigue strength. It was argued in [1] that for a polymer one cannot simply assume the existence of a fatigue limit, one will have to test it into the VHCF domain of 1 Gigacycles. However, at the normally allowable testing rates (below 10 Hz), such an effort would take much too long. The first concern then is to find or design a material that will allow accelerated testing without introducing failure due to non-representative internal heating. On this subject, the section on *Validation* presents some results that have been generated with the testing methods mentioned in Table 2, as an essential start of the materials data. Given a dataset for any particular CCPC compound, a design can be based on these data and appropriate design margins (on stress, not on life[2]) and this should be sufficient if: (a) product quality is reproducible on every level, and (b) if the behavior on a product level has been successfully related to material level test data. The latter condition is also discussed in the *Validation* section where both scaled and full scale SPP testing is presented.

A second critical factor is the thermal behavior and the thermal load itself. Because of its importance, work was done to predict the temperature. This is not a trivial task however, since it involves complex heat transfer phenomena of a non-steady flow – which is at present beyond the state of the art (see for example the discussion in [2]). Nevertheless, one can apply an empirical combination of heat transfer coefficient and average temperature to result in an educated guess through a stationary computation. It should be noted that the value obtained from experience or direct measurement as such on a steel or aluminium piston cannot be used as a requirement, because the SPP's much lower thermal conductivity will cause a quite different and inhomogeneous temperature distribution. Therefore, the code "Compressor 3D" as developed for the EFRC R&D group [3], which enables to compute estimated heat transfer coefficients, was used. An example of a temperature distribution calculated from these heat transfer values and also others, is given in Figure 6.

It is seen that for this particular estimation, temperatures of 90ºC to 110ºC are representative. Because of the insulating property of the CCPC material, the result is highly dependent on heat transfer through the piston rod; this effect may be cooling, especially for a rod which is specifically designed to cool (see for example, the EFRC project described in [4]). One contributing factor has yet to be implemented: the heat generation due to hysteretic heating by the stressed polymer itself. A computational procedure has been devised and work is ongoing to assess the total effect of this phenomenon and heat transfer from the gas. This is done in conjunction with efforts to experimentally measure the temperature transient on the piston itself, but this is beyond the scope of the original EFRC project.

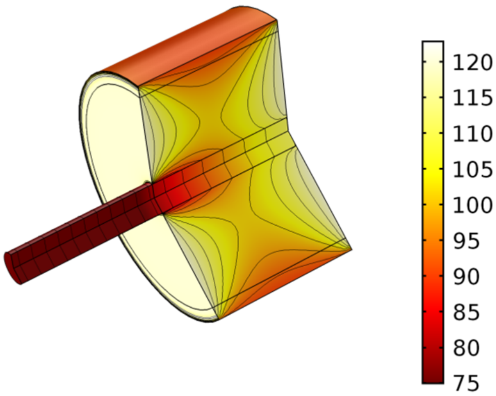

Figure 6 Stationary temperature distribution within the SPP based on estimated heat transfer coefficients.

Thermal expansion of a hybrid piston and its components is a factor that should be well recognised. In itself, thermal expansion behavior of the piston as a whole is sometimes of concern, but in general it can be said that it is only necessary to know the final geometry, so therefore the main criterion is predictability. More relevant and also more subtle is the structural integrity issue that is related to differences in thermal expansion, both during manufacture and in operational life. With steels having expansion ratios in the order of 10, aluminium alloy 25 and polymers in the range of 30 to 60 [µstrain/K], the effect can only be assessed with consideration of stiffness, i.e. modulus and geometry. In general, the consequence is:

[2] The mistake is sometimes made to use a design margin on life; for brittle materials especially, the low slope in the S-N diagram makes this an inappropriate approach which is too sensitive for scatter, outliers and manufacturing error.

- incorporate the thermal state relative to the stress-free condition (from manufacturing) as a load case in stress computation;
- there may be resulting constraints on heating rates as applied during manufacture and also heating rates during operation should be checked; this can result in detail design changes to guarantee structural integrity.

The material class (CCPC) which has been presently explored, is a brittle material. Lacking ductility, construction needs to be done with care since design mistakes will certainly result in unexpected premature failure. Such care starts in the conceptual design phase, where architecture should be such that load paths and deformations may utilise the material's load bearing capability under compressive loading. Under tension it will be more prone to fracture. This principle implies that, when the material is contained, it can transfer high shear loads while even impact loading can be absorbed, for example due to liquid slug[3] ingestion. The highest regular design loading occurs near the interface to the shaft and is in shear. As argued before, compressive stress will dominate in the axial direction. What will happen in the radial direction depends on detail design features and also the temperature distribution relative to its as-manufactured state, which can be considered a design variable besides being a manufacturing issue. In general, the desired containment is an implicit property of the SPP with metal shaft and sleeve at the extremities.

A final major concern that was addressed/screened in the project was the corrosive effect or other susceptibility to either gaseous components or lubrication oils. In general, the resistance of thermoset polymers to corrosive gases is good and similarly to oil as well. In the aerospace world, the most challenging test for polymers is to expose them to hydraulic fluid (e.g. Skydrol) and observe residual properties. For one particular candidate polymer (pdcpd), there was concern about potential absorption of a-polar oil types. Subsequent exposure to various oil types at 90ºC however, did not result in any significant uptake, so the concern was dropped. Even so, it will be prudent to apply oil exposure before or during fatigue testing as part of any qualification effort.

#	aspect	assessment	#	aspect	assessment
1	fatigue prediction	solved in project	8	corrosive gas	good resistance
2	temperature resistance	solved by proper material selection	9	static charge build-up	t.b.d. (avoid by design)
3	brittleness	requires good engineering	10	UV resistance	not applicable to enclosure
4	stiffness	sufficient in SPP concept	11	condition monitoring of core	candidate technologies exist if desired
5	bonding to metal	solved industrially by surface treatment	12	development time	potentially fast, as demonstrated in current project
6	creep	in control for thermosetting polymers	13	marginal benefits	high mass reduction demonstrated
7	decompression damage	not-susceptible; Helium used	14	economical competitiveness	moderately expensive materials, favorable processing; but expensive engineering effort for generating data

Table 4 Overview of 14 compiled potential aspects of concern and their assessment for piston application.

The SPP as an open ended concept

Combining a product improvement challenge with philosophy, we may refer to the ground-breaking theory about cognition, concerning concept formation from Ayn Rand [5]. Concepts are viewed as an abstraction based on essential properties using measurement emission. We may recognise this in the current SPP concept where the elements, material classes and topology have been specified, but the dimensions and specific materials are omitted. The concept is open

[3] it is interesting to tentatively consider the behavior under slug loading: rather than overloading the piston rod (with large scale damage as a consequence), the surface may be *indented* at relatively low repeated local loads, supporting a '*graceful degradation*' failure mode allowing a regular shut down and repair to be done.

ended in that variations can be conceived which involve a specialised application. Such extensions of the concept are valuable for the R&D partners involved as these allow a proprietary, competitive edge to be achieved.

The idea of the precompetitive research effort becomes clearer when one considers these opportunities. They build on a common technology level among the R&D members, which itself would cover TRL6[4] at the most. A number of potential variations of the concept have been listed in Table 5. Both the missing technology to achieve (TRL9) application of the SPP and these variations are discussed next under the header *Innovation Concept*.

variation	feature	application
large pistons	size up to t.b.d. with special core features	Large API-618 machines
disk type pistons	with L/D < 0.4; introduce integrated facing	certain types of compressors
trunk type pistons	different type of structural concept	even combustion engines
high temperature pistons	For example for T > 130ºC	high pressure ratio and T_suction
graded density core SPP	one way to achieve a lighter core for large pistons	large very lightweight pistons
integrated piston rod piston	eliminating the pre-stressed joint	t.b.d.
high pressure piston	high strength and pressure resistance	specialties
aggressive environment piston	special inert polymer compounds	t.b.d.
flexible revamp	fully flexible manufacturing for arbitrary size and high mass reduction, e.g. increasing piston diameter.	revamping existing machinery, solving an acute problem
unlubricated, ringless piston	close tolerance piston with thermal control	e.g. laby-seals
pressurised cavity piston	extra light weight reinforced piston with floating piston potential	e.g. floating pistons

Table 5 Open ended lightweight SPP concept offspring examples

3. Innovation Concept

Precompetitive versus competitive elements in the SPP invention

This section is concerned with the demarcation line between the competitive area and the common ground of precompetitive research. This line was continuously explored as the project progressed and further phases were defined within the overall master plan. For the sake of discussion, the degree of technology maturity towards an actual application will be indicated by a measure of *technology readiness level* (TRL) as defined by NASA [6].

Competitive development elements	reasons	status*
high temperature fatigue properties database	high investment required; proprietary knowledge of materials	pending
multiple CCPC material screening	optimum material formulation is application specific and is beyond generic demonstration	ongoing
extensive building block testing	beyond generic demonstration	partially ongoing
in-machine demonstration of piston	high investment required	imminent
advanced shaft to core integration	beyond generic demonstration	–

*Table 6 Competitive elements of SPP technology development towards TRL 9; * status refers to known follow-up initiatives.*

Obviously, the precompetitive parts addressed those questions which involved the feasibility evaluation as such. Clearly, a minimum level of demonstration was necessary of the fatigue performance as well as the means for testing them in an economical way. Also, some of the concerns listed in Table 5 were addressed such as the potential

[4] TRL: Technology Readiness Level, refer to next section

mechanical capabilities at elevated temperatures and the resistance to oils. Also, the manufacture of the demonstrator hardware (at the level of a mock-up) was essential in illustrating the feasibility of the SPP concept. Finally, both the scaled and the full scale (room temperature) fatigue test into the HCF domain were considered suitable technology demonstration stepping stones to TRL6 status.

The parts that were agreed to be outside of the precompetitive domain were agreed on the basis of a few common sense criteria, refer to Table 6. In general, the precompetitive elements are concerned with essential feasibility demonstration and the remainder supports some degree of optimisation towards specific applications as well as risk reduction.

Radical innovation theory applied to the piston project

There is a question how good new ideas can be brought to the market. Looking at the academic literature on this subject, this is ultimately done by so-called *‚First-movers’*. Schilling [7] describes these as the first market players that bring a product or service to the marketplace. As such, they typically experience additional disadvantages, the so-called ‘First-mover disadvantages’. These involve high costs for Research en Development with a long break-even period, patenting concerns, absence of a distribution channel and all the factors listed in Table 7 up to the absence of applicable standards. The development of own proprietary standards may even worsen the risks when these standards are not adopted by the industry at a later stage (examples: Philips with the V2000 video standard, Microsoft with the .doc standard). Also in general, standards which are too far ahead of the industry contribute to problems due to the difficulty of communicating with the ‚external world’.

An analysis of so-called success factors is presented in [9]; here the definition of disruptive – and radical – innovation was enhanced from Abetti [8], resulting in the following:

> *A radical innovation is an innovation with a unique and original product , system or business model, that will make other already existing ones unnecessary or obsolete and has a high uncertainty of success because of the level of newness and obscurity of the needed design effort, technology, knowledge and market.*

This definition takes into account that radicalism is accompanied by a high level of uncertainty, newness, risk, differentness and market impact. More literature background can be found in the original article of Groenewegen [9]. We proceed with considering some related questions and making a link to the hard core technology and market context of the present case. We do this because studying these issues makes us better able to make a success of the idea.

> *Why is it so hard to be successful with a radical innovation?*

A shortlist of the problems when dealing with radical innovations was found in the literature [9], see Table 7.

Financial	**Organisational / Market**	**Technological**
High costs of R&D and long payback period;	**Resistance, fear and uncertainty** of potential **customers;**	Non existing **‘enabling’ technologies** and supporting products;
Defensive behavior of the established order;	Uncertainty how to manage a radical innovation (R&D and businesswise);	Not matching existing legislation and current **quality norms**;
Largely unknown size of market and **customer needs**;	Difficulty of getting feedback from potential interested parties due to secrecy because of competition threats	Struggle about the use of **standards** and agreements upon them
	Non existing distribution channel	

Table 7 Innovation obstacles inventory (categorised, from [9]).

Some of these factors can be influenced by properly incorporating these considerations in the development work; these have been printed in bold. For example, the “fear and uncertainty” will be mitigated by performing and presenting technological work meeting the highest standards and making use of world class expertise. The high cost issue has in our case been tackled by first joining forces/funds and then choosing a technology with cost as a main driver. Enabling technologies could mean for example the existence of test methods for extremely long durability, which were developed here as a necessity.

What are the success factors of a radical innovation?

After the extensive literature study [9] a conceptual model was designed in which three main factors determine the success of growth: the uniqueness of the advantages of the innovation, the startup organisation characteristics and the person of the entrepreneur.

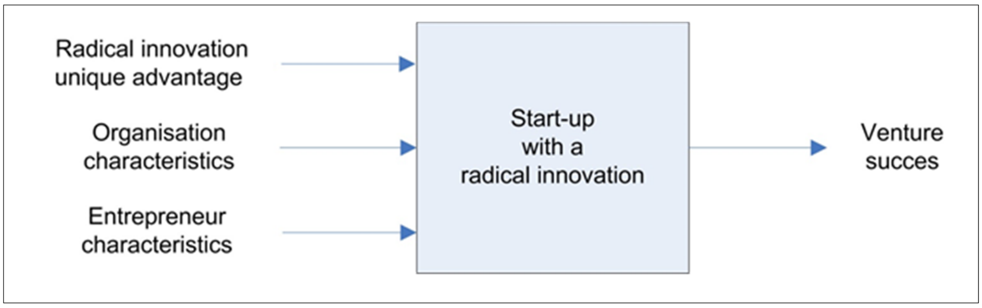

Figure 7 Conceptual model for the First Mover, towards success in the start-up scenario [9].

Abetti [8] concluded first and foremost that a radical innovation should have unique advantage to existing other solutions which is sufficiently big, so that it helps potential customers and companies to overcome their resistance and fear for the unknown because of the attractiveness of the new solution.

	Variable	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1.	Thoroughness Business plan	3,75	1,96	1,00																				
2.	Member of formal networks	0,56	0,50	0,35	1,00																			
3.	Intensity external advice	3,69	2,37	0,26	0,25	1,00																		
4.	Customer Proactiveness	12,23	4,02	0,20	-0,04	0,25	1,00																	
5.	Degree of structure innovation process	3,51	1,49	0,31	0,12	0,21	0,43	1,00																
6.	Degree of expertise	4,79	1,73	0,04	0,00	0,10	0,12	0,15	1,00															
7.	Application of investors money	0,35	0,48	0,33	0,25	0,15	0,04	0,11	-0,04	1,00														
8.	More then 75000 seed capital	0,25	0,44	0,12	0,08	0,06	0,31	0,09	0,04	0,09	1,00													
9.	Multiple owners	0,51	0,50	0,08	0,09	0,03	0,08	0,14	-0,06	0,16	0,02	1,00												
10	Uniqueness advantage of the innovation	9,77	2,44	0,17	0,02	0,16	0,32	0,34	0,25	0,15	-0,07	0,17	1,00											
11	Willingness to take risk	11,55	1,79	0,29	0,15	0,10	0,23	0,17	0,21	0,11	0,11	-0,06	0,14	1,00										
12	Years of industry-experience	5,52	6,60	-0,14	0,01	0,18	0,12	0,22	0,32	-0,14	-0,03	-0,16	-0,08	0,10	1,00									
13	Years of management experience	5,40	6,56	0,05	0,11	0,05	0,25	0,25	-0,20	-0,03	0,39	-0,15	-0,14	0,03	0,24	1,00								
14	Relevant social network	5,23	1,62	0,05	0,23	0,19	0,25	-0,02	0,11	-0,03	0,13	0,11	-0,01	0,13	0,08	0,06	1,00							
15	Higher education (BSc or higher)	0,83	0,38	0,07	0,09	0,03	0,11	0,01	0,31	0,04	-0,06	0,18	-0,01	0,12	-0,07	-0,27	0,28	1,00						
16	Previous jobs	3,20	2,09	-0,19	-0,07	-0,04	-0,09	-0,07	0,15	0,00	-0,03	-0,14	-0,29	0,04	0,23	0,01	0,14	0,13	1,00					
17	Years of previous working experience	11,47	8,39	-0,08	0,23	-0,03	0,17	0,19	-0,05	-0,18	0,14	-0,24	-0,18	0,19	0,50	0,51	0,13	-0,12	0,51	1,00				
18	Years of earlier entrepreneur experience	2,35	4,77	-0,01	0,02	0,14	0,28	0,12	0,07	0,21	0,18	-0,10	0,11	0,07	0,12	0,39	0,16	-0,19	-0,12	-0,01	1,00			
19	Degree of radicalness	25,12	5,09	-0,02	0,12	0,07	0,36	0,22	0,33	-0,06	0,10	0,06	0,53	0,05	0,02	0,03	0,05	0,06	-0,30	0,00	0,07	1,00		
20	Turnover growth in %	493,37	879,81	0,24	0,01	0,15	0,20	0,01	-0,03	0,24	0,09	0,27	0,36	0,04	-0,21	-0,10	0,22	0,15	-0,21	-0,26	0,05	0,08	1,00	
21	Employment growth in %	132,12	332,70	0,21	0,07	0,18	0,09	0,00	0,09	0,16	0,20	0,09	0,14	0,11	-0,05	0,06	0,12	0,09	-0,02	-0,04	0,12	0,11	0,57	1,00

Table 8 Correlation matrix of success factors [7]; mean, standard deviation and correlations.

In Table 8 an overview can be found with all the variables measured to operationalise the main question. Some are related to the uniqueness of the innovation, some to market & organisational approach and others to the personal treats of the inventor/entrepreneur.

With the help of Table 8 some additional observations were done: A very high correlation (>0.5) exists between degree of radicalness and uniqueness of advantage of the innovation. This is also true between working- experience, industry-experience, management experience and previous jobs. And also true for turnover growth and personal growth. The percentage of employment growth turned out to be a factor 4 smaller than the turnover growth.

What are the conclusions?

The study [7] tried to expand the existing theory of the success factors of a radical starter (Table 8). In the other empirical research on success factors of starters, we have seen the importance of specific organisational and entrepreneurial traits. This we combined with the success factors of a radical innovation within an established firm, which added innovation characteristics (unique advantage), organizational traits (customer pro-activeness) and confirmed entrepreneurial traits. This was combined further with the success factors found for innovative entrepreneurs in general which added specific organisational (use of seed capital) and entrepreneurial traits (willingness to take risks).

All these factors were combined in a model for starters with a radical innovation. This model states that to succeed, there are three relevant factors. The starter has to be an entrepreneur (with specific personal traits and human capital), the organization has to have certain characteristics (business plan, seed capital, etc.) and the innovation has to have some unique advantages for the (potential) customers.

Testing this model through a questionnaire, we see a statistical relevance for each measurement of success. The general findings do support the idea that growth is determined by the uniqueness of the advantage of an innovation, specific organizational characteristics and entrepreneurial traits. The results however are clearer for turnover then for employment growth and not all the factors identified in the existing literature were found statistically significant or positive.

From the outcomes of this study an image of the radical start-up with the most turnover growth in the first 3 years can be drafted. The start-up exist of a team of founders with not too much working experience and with a relevant social network. There is a thorough business plan that is executed with at least 75,000 euro seed capital. By a pro-active customer approach the start-up is able to bring to the market, successfully, a radical innovation with enough unique advantages (compared to other existing possibilities) to overcome initial customer and market resistance.

The EFRC R&D connection

The connection with the Light Weight Piston is obvious. Because of the significant unique advantages of a lighter weight piston, many people and companies are willing to test and use this radical innovation. Obstacles such as listed in Table 7 can be removed. Companies associated with the EFRC R&D group are in a position to either choose to develop the last technology elements themselves, or to adopt a specialised supplier from a knowledgeable position, thus enabling a proper requirement set to be formulated. Because of the open-ended nature of the SPP concept, there is a multitude of possibilities to develop proprietary installments or contributions for EFRC members.

4. Validation

Test and verification philosophy

Test and verification is an essential part of the feasibility assessment, development and implementation for two reasons:

- the properties that are decisive for the feasibility (e.g. fatigue and a favorable manufacturing concept) are accessible only through empirical work (and not by simulation);
- introducing a novel concept into an industry that relies heavily and successfully on metals requires experimental evidence.

A strong emphasis was therefore put on experimental work, after careful early theoretical analysis and synthesis. This even involved developing a new test method for VHCF life of polymers under stringent requirements of low budget and decimated testing time. Figure 8 illustrates the elements supporting the feasibility assessment and the transition to full scale verification, also including manufacturing. It must be emphasised at this point that in a good practices approach of composite materials, processing (i.e. manufacture) and materials should be an integrated whole[5]. This leads to the incorporation of the manufacturing concept in the materials and building block testing. In this respect, it is important to mention that it was chosen to apply pre-cured polymer blocks and investigate its particular performance level.

Scaled testing approach

In developing the technology, it is desirable to apply an approach where for each project phase the complexity and predictability of the outcome is under control. In combination with the factors listed in Table 4, this leads to the scaled testing overview in Table 9.

[5] This is not unlike the area of cast metals where material quality is entirely dependent of the casting process. With the current CCPC materials, there is an option to choose an in-situ curing or a machined pre-cured route; this can be expected to have impact on performance which should be investigated.

SPP Full scale fatigue trials result

Figure 8 shows the test setup used for the full scale test. This test rig was specifically designed to withstand high fatigue loads and allow the (adjustable) application of prestress on the loading rod. Full load reversal could be applied, while even simultaneous testing of two specimens is possible. Also, elevated temperature testing is foreseen while diagnostics mainly concern the evolution of the pretensioning force in the rod. This feature allows the monitoring of an anticipated failure mode along the core to shaft interface. A second technology involving continuous fiber optical strain measurement was prepared but was not applied.

	Fatigue RT	Fatigue HT	Core shaft shear load	pre-stress	Manufacturing induced defects	Lube oil	T transient	Gas Attack	Gas Flow	Boundary layer effects	T distribution, heat flow	Full environment
Material level	x	x				x		x				
Building block								x				
Scaled SPP	x		x	x	x		x					
Full scale SPP	x		x	x	x							
Compressor piston					(x)	x	x		x	x	x	x

Table 9 Assignment of research aspects to scaled testing elements (RT, HT: Room and High Temperature respectively)

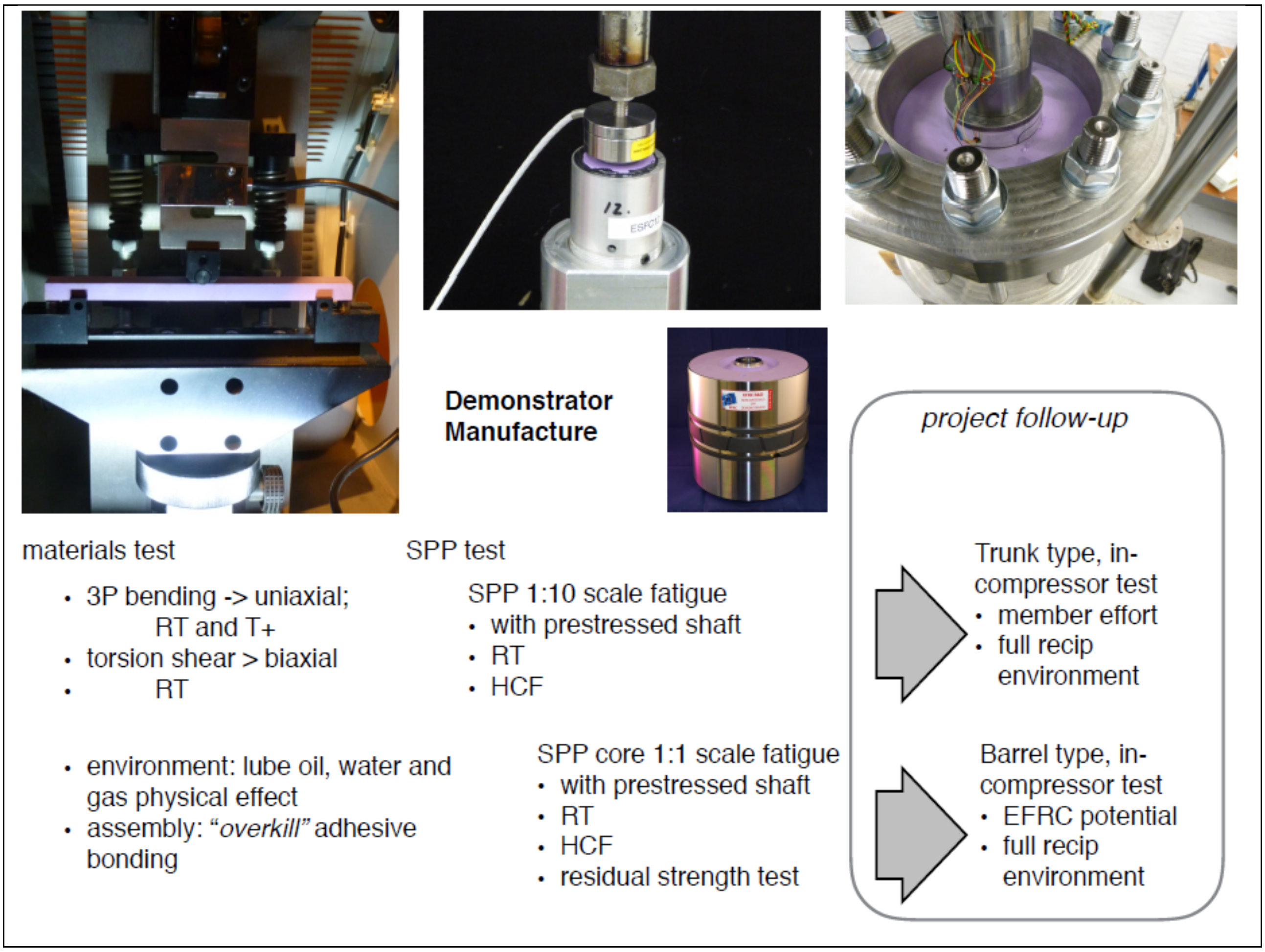

Figure 8 Illustration of the test and verification philosophy supporting the SPP concept road to implementation.

The result of the test is presented in Table 10 together with the result of the 1:10 scaled *"mini-piston"* test. In terms of failure mode and residual strength, it was surprising to see that with a maximum sustained load of 400 kN (equivalent to 800 kN design), the failure behavior involved stable damage extension up to the maximum load and finally core pull-out at a load of 65 kN (LF=1). This was in contrast with the behavior usually observed for brittle materials and indicates a mechanism involving radially compressive stress in confined configuration as discussed before.

	mini piston	**full scale piston core**	**comment**
Design piston rod load P_d	1.3 kN	± 130 kN	130 kN scaled down to 65 kN by length reduction
Demonstrated maximum fatigue life/loadfactor	N = 3.50 10^6, LF = 4	N = 0.82 10^6, LF = 2	at shaft prestress factor 3: F_{pre} = 3 x 1.6 x P_d
Residual strength	n/a	LF_{max} = 6.1	after crack growth at LF=2.5

Table 10 Scaled and Full Scale test results (load factor LF=P/P_d).

In-machine validation

While it is difficult to explicitly project what kind of "things could go wrong" after full scale fatigue testing such as described above, it is equally obvious that any application would first be preceded by a test of the actual piston in a testbed compressor. First and foremost this would involve the actual manufacture of the full piston, complete with required manufacturing tolerances for installation etcetera. Subsequent testing may take days or even weeks or even longer where on-site application is foreseen with the presence of a back-up machine. Among the variables to be monitored are the temperature (distribution) and the specimen stiffness. On-piston temperature measurement is not trivial. Periodic inspection may be labor intensive and hence costly, but its frequency could be minimised by proper instrumentation. Final tear-down inspection may be done as a last step or even destructive testing (residual strength).

While such a competitive activity will be an expensive exercise, an application to a much smaller machine might be a useful intermediate step. This would for example allow already the quantification of the actual effective thermal load, which is most difficult to access by theory as discussed above. One initiative of this kind is already being implemented based on an 11 [kW] two stage machine, 35 [bar] air compressor and a hybrid low pressure piston of the trunk type [10]. Other applications will be able to benefit significantly from the insights which will result from such an exercise.

5. Conclusions

This paper describes the final outcome of a successful project initiated by the EFRC R&D group with the aim to investigate the potential for weight reduction by using non-conventional materials and subsequently develop the technology for implementation. The work started with a creative phase which was well grounded in reality by studying the state of the art as well as working on the requirements. The outcome was a concept coined the Solid Polymer Piston (SPP) which stood out among any other competing concepts such as those based on CFRP material.

Faced with multiple challenges in inventing a new affordable configuration as well as precompetitive considerations, three project phases were construed which each confirmed the expectations of feasibility towards a typical 50% mass reduction. Not only does this mass reduction enable a more than gradual improvement of machines (it can be considered a *disruptive innovation*), but technology readiness can be obtained in a short period of time and at a modest cost associated with the hybrid SPP concept making use of the CCPC class of materials.

Validation of the technology was obtained as far as precompetitive research could take it. Starting with an SPP demonstrator (for manufacturing), a materials database was obtained confirming good "infinite life" fatigue strength and yielding also statistical data. Finally, scaled and full-scale fatigue testing confirmed the ability to resist enhanced fatigue loading up to 1 million cycles.

Extensive effort has been spent on adopting the right approach and cooperative model to allow valorisation of the present development. Implementation by several EFRC members can be foreseen in the near future. Among the anticipated machine improvements are efficiency improvement, capacity increase and the reduction of vibrations.

6. Acknowledgement

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