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# Optical Fibers in Pressure Sensor Textile Fabrics

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*Abstract-* **In this paper we report the successful development of pressure sensitive textileprototypes based on flexible optical fibres technology. Our approach is based on thermoplastic silicone fibres, which can be integrated into woven textiles. As soon as pressure at a certain area of the textile is applied to these fibres they change their cross section reversibly, due to their elastomeric character, and a simultaneous change in transmitted light intensity can be detected. We have successfully manufactured two different woven samples with fibres of 0.51 and 0.98 mm diameter in warp and weft direction, forming a pressure sensitive matrix. Determining their physical behaviour when a force is applied shows that pressure measurements are feasible. Their usable working range is between 0 and 30 N. Small drifts in the range of 0.2 to 4.6%, over 25 load cycles, could be measured. Finally, a sensor array of 2 x 2 optical fibres was tested for sensitivity, spatial resolution and light coupling between fibres at intersections. This procedure also applies to all Hospital and Health Services. This procedure specifically applies to Hospital and Health Service employees who prescribe compression garments to adults with lymphedema and the facilities which provide these garments and/ or which are responsible for the purchase of these garments. The procedure does not include recommendations regarding the clinical care of clients with lymphedema beyond the selection and supply of compression garments. New applications in the field of so-called smart textiles for health monitoring are having a high demand of new techniques to successfully miniaturize and embed electronics, optics and sensors into fabrics and garments. The benefit of close to the body measurements are numerous e.g. enhanced comfort and ease of movement for the wearer, reduction of loose connecting wires between sensors.**

## ELIGIBILITY TO RECEIVE COMPRESSION GARMENTS FREE OF CHARGE

Clients meeting all of the following criteria should be provided with compression garments free of charge:
A diagnosis of lymphedema has been documented by a medical practitioner or a Level 1 lymphedema therapist who has a Level 1 Lymphedema Training Certificate (accredited by the Australasian Lymphology Association). The diagnosis should be documented in a referral letter, prescription/order form or a Queensland Health medical record. Aged 16 years or over Outpatient holding one of the following cards.Centrelink Pensioner Card.Centrelink Health Care Card. permanent resident of Queensland. Medicare eligible.

The HHS may determine local compression garment provision arrangements for clients not meeting all of the above criteria.

Ineligibility for free garment provision does not exclude clients from accessing other services from a Hospital and Health Service including lymphedema assessment, assessment for compression garment, therapy intervention, prescription, fitting and problem solving for self-funded garments.

## CARE PROVISION

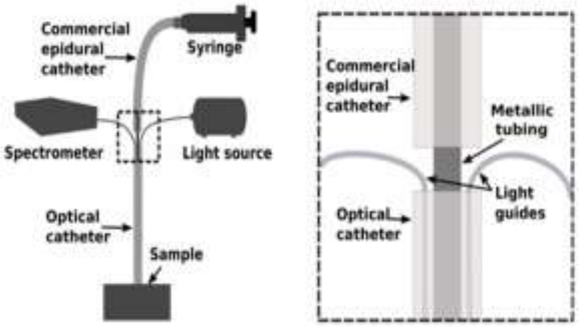
If relevant, a patient with a current episode of care requiring compression garment prescription will have the costs of the products/consumables (garments) met by the treating Hospital and Health Service/Cancer Centre as part of that episode of care . On discharge from a Hospital and Health Service Cancer Centre or Lymphedema Service care should be transferred to the local service, i.e. the facility closest to the patient's residence, through a documented referral process. The referral should include details of the most recent medical referral, clinical prescription, garments provided, and the recommended interval for next review. When a patient/consumer is transferred or referred from one service to another, the receiving clinician who provides compression garment care will organise an assessment for compression garment prescription, fit and review with the patient/consumer at an interval negotiated with the referring clinician. The local service is responsible for receiving, reviewing, and processing the garment prescription form as well as ordering and paying for the garment.

Electronic circuits and energy sources. Textile integrated sensors could measure a large variety of variables, e.g. physical dimensions like pressure, stress and strain [5-10] applied to the textile or biomedical dimensions such as heart rate, electrocardiogram (ECG), sweat rate and sweat composition (salts, pH), respiration rate or arterial oxygenation ($SpO_2$) of the monitored subject [11-16]. Most of these sensors are based on microelectronic devices or conductive polymers which are integrated into the fabric structure, or are part of the fibrous structure themselves. Optical fibres made of polymeric materials have the advantage of high flexibility a low stiffness compared to glass fibres, therefore they are receiving more and more attention in the field of smart textiles and will complement electrical wires and sensors in the near future. A couple of advantages make their application very attractive: they produce no heat, they are insensitive to electromagnetic radiation and they are not susceptible to electrical discharges. Several types of textile sensors already have been developed using optical fibres based on grating or micro bend principles

However, standard plastic optical fiber (POF) materials like polymethylmethacrylate, polycarbonate and polystyrene are rather stiff compared to standard textile fibres and therefore their integration into textiles usually leads to stiffen of the woven fabric and the textile touch is getting lost. Alternative fibres with appropriate flexibility and transparency are not commercially available; few examples are mentioned in the literature, among them silicones.The manufacture of these flexible silicone POF has been laborious, because two-component thermoset materials have been used. These materials had to be mixed first, and later filled into adequate soft tubing materials and cross-linked inside finally (by heat or catalysts). This method allows only the production of rather short fiber lengths with large diameters. Furthermore, the procedure is error-prone to air bubbles, material shrinkages and tubing in homogeneities. To overcome these disadvantages, we are reporting in this paper about our approach to manufacture silicone fibres made of thermoplastic material and their application as textile integrated pressure or touch sensors. Goniometry, a rather new block copolymer made up of soft and hard segments (siloxane/urea) was chosen, due to its elastomeric properties, suitable optical transparency and flexibility – combined with the thermoplastic characteristic induced from urea units. Our goal was to establish a new fiber optic sensor type, where the fiber itself shows a fully reversible elastic deformation. The application of pressure would lead to a squeezed fiber profile where light could not propagate further, or at least part of it would leave the light guide (back reflection, side emission). By integrating several fibres into a fabric sensor arrays could be established as basic touch transducers (on/off switch, or for input devices like keyboards) or more sophisticated pressure and activity monitors in e.g. beds for geriatric care (nursing homes), decubitus prevention of patients (beds or wheel chairs), prevention of sudden infant death syndrome, but also for sports (rehabilitation) and many industrial applications.

## EXPERIMENTAL SECTION

Figure 1:



FEATURES:

1. Highly reliable and secure due to immunity of the sensed signal to electromagnetic interference.
2. Safe in explosive and nuclear environments free from risk of fire and sparks.
3. More suitable for remote sensing and telemetry.
4. Corrosion resistant.
5. Small size and weight.
6. High accuracy and weight.

SENSORS CONSIST OF:

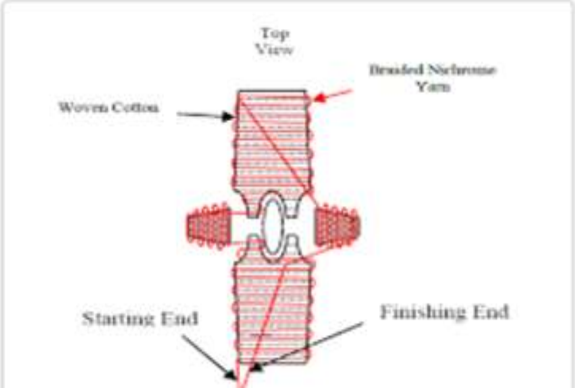
a. Miniature of all silica fibre optic extrinsic fabric pirate interferometer (EFPI)
b. An encapsulated fibre brag grating (FBG) for temperature sensing.

Figure 2. Extruded silicone fiber of 0.51 mm core diameter.

## LIGHT ATTENUATION MEASUREMENT

Light attenuation was measured according to the cut back method The silicone fibres were glued into F-SMA connectors (Precaution, Switzerland) with standard epoxy; fiber ends were cut with a scalpel (no polishing is possible, due to the rubbery character). A medicinal laser LC PDT 652-2 (652 nm; AOL Medical Instruments, USA) was used as a light source, having a FD-1 fiber (Med light, Switzerland) and a proprietary F-SMA coupler attached as an interface to the silicone fiber. The light energy was measured with an Ulbricht integrating sphere (RW-3703-2; Gigahertz Optic, Germany). Attenuation at a wavelength of 652 nm has measured 9.3 ± 0.8 and 5.5 ± 0.9 dB/m for the 0.51 and 0.98 mm fiber, respectively. However, we assume that at least 1 dB results from the poor quality of the untreated fiber ends

Figure 3: shows the light attenuation measurement



## MANUFACTURING OF WEAVE

Two woven samples were produced with a hand loom (ARM AG, Switzerland) of cotton multifilament fiber of 0.75 mm (Leibundgut, Switzerland) and with the 0.51 and 0.98 mm silicone POF respectively. We have chosen a so-called atlas pattern with a 1/4 repeat (see Fig. 3) because, compared with the standard canvas pattern, only few fiber dislocations from bottom to top (or vice versa) occur – therefore a minimum light attenuation, caused by micro bends within these dislocations, is expected when the fabric is in its unloaded state.

For our forthcoming experiments a 2 x 2 POF matrix has been appointed. Due to low fiber density in warp direction (one POF and four cotton fibres per 1.5 cm) two adjacent POF have been connected to the light sources and detectors. In weft direction a much higher fiber density is reached (8 POF and 32 cotton fibres per 1.5 cm), therefore only every 8th POF was connected. The four POF of this 2 x 2 matrix therefore defined a square of 1.5 x 1.5 cm (see Fig. 4).

Figure 4. Canvas and atlas weave patterns (top and front view); blue = cotton fibres,orange = optical fibres. The atlas pattern has the weft POF always over the warp POF (top and bottom positions).

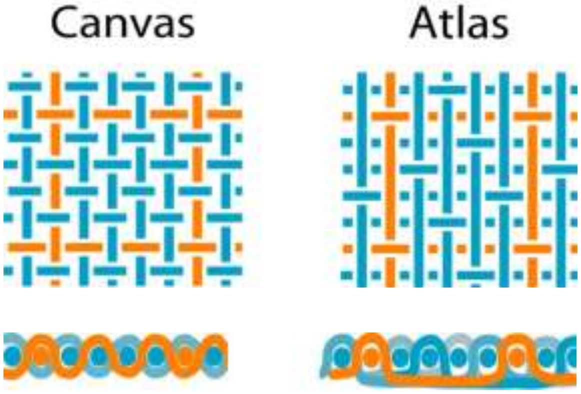
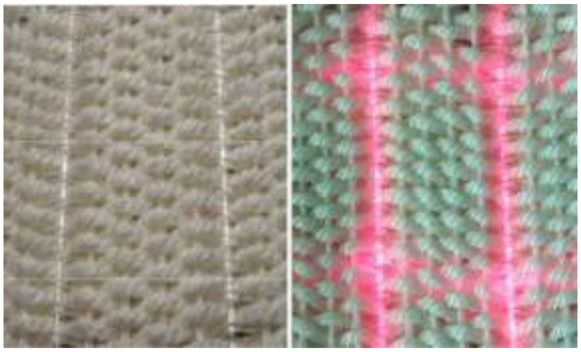


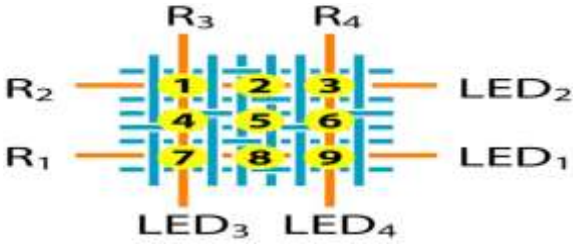
Figure 5. Atlas pattern weave of 0.51 mm silicone POF and cotton multifilament fibersin warp and weft direction (left picture). Four POF in a distance of 1.5 cm have been chosen to define a 2 x 2 matrix with four optical fiber intersections (right picture).



## MEASUREMENT SET-UP LIGHT IN-COUPLING AND DETECTION

A proprietary breadboard set-up has been used with four 660 nm light emitting diodes (LED; SFH 756V; Avago, USA) and four phototransistors (SFH 350V; Avago, USA) in a design according to Fig.5.The detector signals were recorded with an analog/digital converter board (USB-6009; National Instruments, USA) at 14 bit resolution with 10 Hz data acquisition rate. Data from the converter board was transferred to a standard personal computer using dedicated software (developed with LabVIEW8.2; National Instruments, USA). For data analysis Origin 8 (Origin Lab, USA) and SPSS 14 (SPSS, USA) has been used.

Figure 6. Location indices1to9(where pressure gauge head was placed). Led= lightemitting diodes; Rx = light receiver (phototransistors). In weft direction, the graph shows only the POF (orange) which were used to define the 2 x 2 matrix (7 POF in between are not connected to a LED or R and are neglected in the graph).



## FORCE MEASUREMENTS

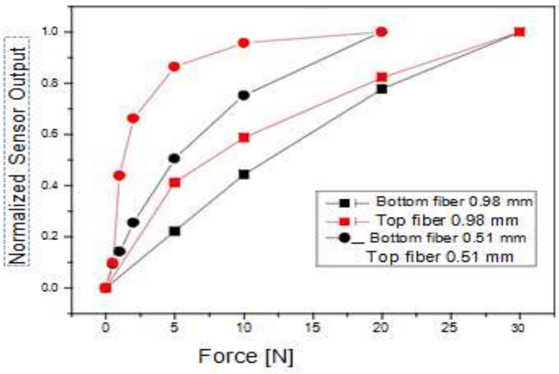
Pressure has been applied onto the fibres by means of a pressure gauge (Stopping, Switzerland); diameter gauge head = 10 mm. The samples were placed onto a flat metal surface which was covered with a thin sheet of black cardboard. Five different experiments have been conducted (for location index see Fig. 5), with three repetitions in each case:

a. measuring the relation of force versus sensor signal for 0.51 (0-20 N) and 0.98 mm fiber fabric (0-30 N) just at a single POF intersection
b. measuring the signal drift behaviour for both weaves, when a cyclic load (20 N) was applied
c. measuring the location sensitivity of the 0.98 mm fabric when pressed at POF intersections 1, 3, 7 and 9 and also at non-intersections 2, 4, 5, 6 and 8 (20 N)
d. measuring the sensor response of the 0.98 mm weave when contacted (20 N) at locations 1, 3, 7 and 9 – with all four LED ON
e. and measuring the same sensor response when contacted at locations 1, 3, 7 and 9 – with LED no. 1 and 2 ON, 3 and 4 OFF, respectively.

## MEASUREMENT OF APPLIED FORCE VERSUS SENSOR SIGNAL

Measurements of applied pressure versus sensor signal were performed for the 0.51 and 0.98 mm weave, and in particular the response of POF in top and bottom position at the intersection has been studied. The comparison of 0.51 and 0.98 mm weave generally showed that thinner POF have a very sensitive response for small forces, but a small measuring range before equilibrium was reached (see Fig. 6). The 0.51 mm weave could already detect forces of 0.5 N, with a resolution (defined as three times noise level) of 0.1 N, but reached already sensor signal saturation at 10-15 N. One reason for this finding could be the limited accessibility of the thin fibres, because the surrounding textile threads will carry from a certain point on the main part of load. Thicker POF have a lower signal resolution at small forces (0.25 N), but show a practical measuring range up to 30 N (with 1 N resolution). In both cases, the top fiber showed a much pronounced sensor signal for small forces, probably due to the fact, that the top fiber bends and squeezes first when pressure is applied.

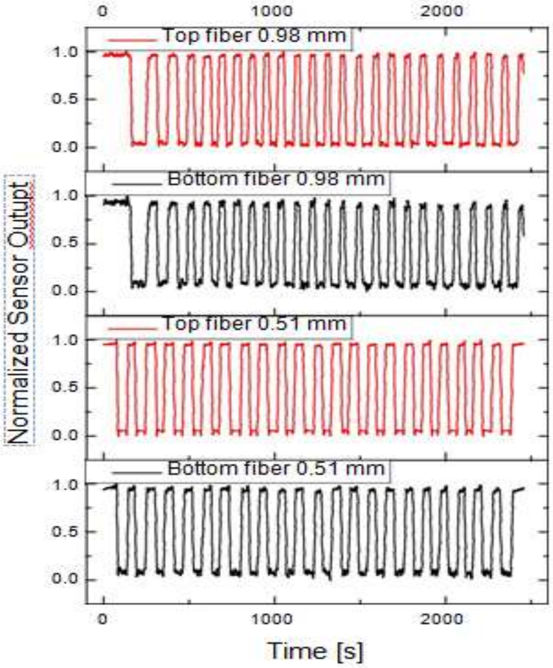
Figure 7. Measurement of force versus normalized sensor signal for POF fabric made of0.51 mm diameter (round markers) and 0.98 mm (square markers) fibres, subdivided in top (red) and bottom fiber (black) response.



## MEASUREMENT OF DRIFT

To determine short time drift or hysteresis of the sensor, which could be the result from inelastic POF or weave properties (or a combination of both), 25 load cycles have been recorded over about 45 seconds. Elastic behaviour of top and bottom fibres has been monitored, for 0.51 and 0.98 mm weaves, the results are displayed in Fig. 7 and Table 1.

Figure 8. Drift behaviour of POF fabric during 25 load cycles (applied force 20 N). Top(red) and bottom fiber (black) response given for 0.51 and 0.98 mm weave.



Clearly there can be seen a difference between both weaves, and also between the top and bottom POF. Signal drift of top fibres is small for both weaves (when pressure applied and textile relaxed, respectively), but the corresponding bottom POF showed a significant drift. The value received for the 0.98 mm weave was 2.5 to 4.5 times higher than for the 0.51 mm weave. We assume that a possible reason for this behaviour is the enhanced shielding of the thinner POF as a result of the thicker surrounding textile threads.

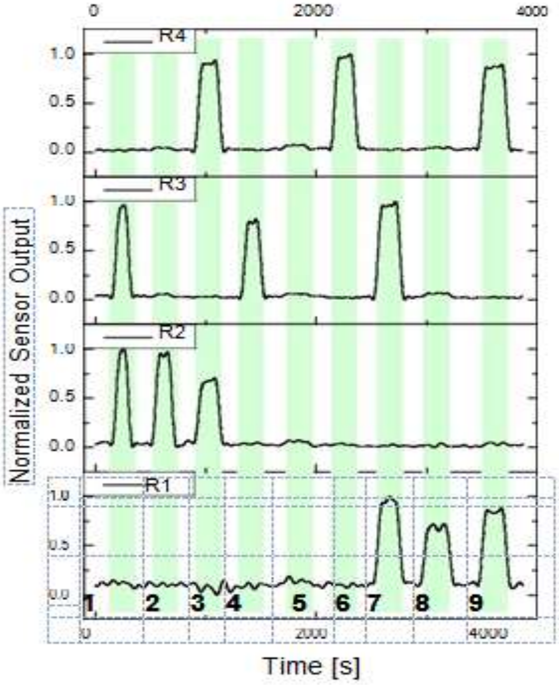
Table 1. Drift behaviour of 0.51 and 0.98 mm POF weaves during 25 cycles of appliedforce (20 N) and complete release.

| | 0.51 mm Top | 0.51 mm Bottom | 0.98 mm Top | 0.98 mm Bottom |
|---|---|---|---|---|
| Drift [%] pressure applied | 0.6 ± 0.2 | 1.8 ± 0.3 | 0.2 ± 0.1 | 4.6 ± 0.6 |
| Drift [%] no pressure | 0.2 ± 0.1 | 0.6 ± 0.1 | 0.5 ± 0.2 | 2.8 ± 0.5 |

## SPATIAL RESOLUTION

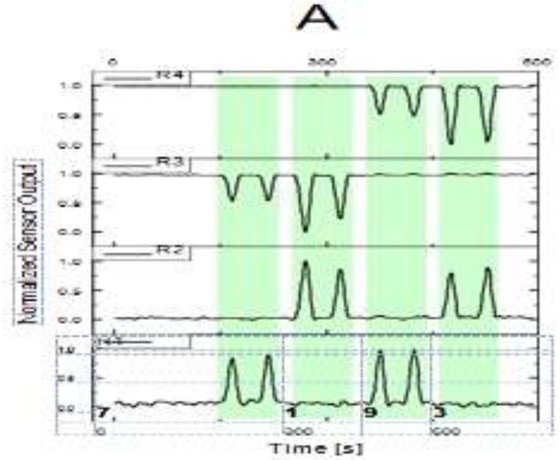
To quantify the spatial resolution of the POF fabric a force of 20 N was applied at 9 different fabric locations, four of them at POF intersections (1, 3, 7 and 9), four at single POF locations (POF in weft direction: 2 and 8; POF in warp direction: 4 and 6) and one in a POF free area (5). Fig. 8 shows an overview of the normalized sensor signals received. It is obvious that hardly any cross-sensitivity exists in the present sample (none of the interfering signals is > 5%) for all nine locations, and also no noteworthy difference for POF in weft (R1 and R2) or warp direction (R3 and R4) could be noticed. Therefore, the 2 x 2 POF matrix produced has a resolution of 9 pressure sensitive locations inside an area of 1.5 x 1.5 cm. Though, as mentioned in section 2.2, only every 8th POF in weft direction was used to define the matrix – hence, an apparent potential for higher resolution is available.

Figure 9. Force of 20 N applied through pressure gauge on locations1to9of the 2 x 2POF matrix with corresponding normalized sensor signals (R1 to R4).



## LIGHT COUPLING BETWEEN FIBERS

For an explicit allocation of where pressure has been applied not necessarily every fiber has to be connected to a light source. We found, that it is also possible to detect light decrease in weft and light increase in warp direction when pressure is applied, due to light coupling between two POF at every intersection. The following cases A and B illustrate this behaviour (see also Fig. 9). In case A (LED 1 and 2 were ON; weft fibres) R1 and R2 showed a positive signal change (equals less light on the phototransistor) when POF intersections 1, 3, 7 or 9 were pressed. However, R3 and R4 indicated that Small amounts of light have been coupled into the weft fibres (a smaller signal indicates more light on the phototransistors). Case B, where all four LED were ON, showed only decreasing light intensities at all detectors as already demonstrated in the former section. The amount of light transferred between POF (case A) could be increased probably by reworking the POF intersections to facilitate light emission and light reception. A potential modality would be the removal of cladding polymer (chemical, thermal or mechanical procedure), the supplement of index matching materials or optical components between the POF. Or on the other side an optimization of the textile pattern in a way, where one or both POF are more exposed to an external load (and not partially hidden inside the fabric). However, we assume that the small amount of light coupled between fibres could not be used in a quantitative way since textile structures are typically not rigidly coupled. Therefore the fiber touching points are dynamically moving and the quality of light coupling changes continuously.



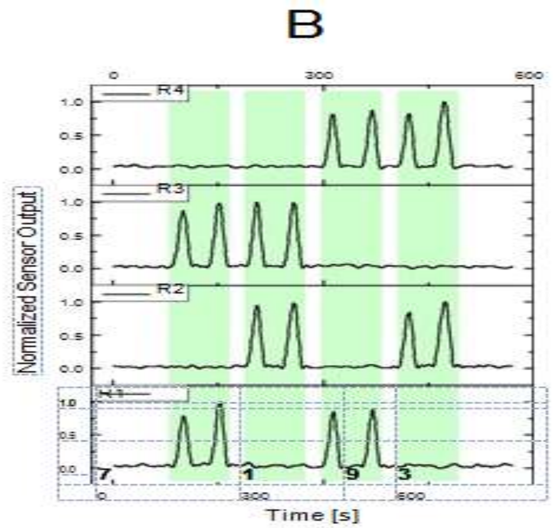


Figure 10. Force of 20 N applied through pressure gauge on locations1,3,7and9of the2 x 2 POF matrix with corresponding normalized sensor signals (R1 to R4). Case A having LED1 and LED2 ON, and case B having LED1 to LED4 ON.

## CONCLUSION

In the present report, we have demonstrated a pressure sensitive sensor array which is based on flexible optical fibres in pressure garments integrated into woven textiles. At first, we developed an easy route to get new optical fibres from merchantable thermoplastic silicones. They showed excellent flexibility and could be manufactured with diameters in the range of 0.2 to 1 mm in an undemanding extrusion process. Their light transmission, compared to standard optical polymers, is poor, but sufficient for short distances. Materials with lower light attenuation are needed however for future applications. Secondly, these silicone fibres were integrated into woven fabrics and their use as pressure or touch sensors was Evaluated. A 2 x 2 sensor matrix was able to clearly distinguish between forces applied with a lateral resolution of 10 mm. The design of the sensor matrix however does not allow shape recognition of an object or multi-touch sensitivity, because the sensor and the signal transmission element are combined in one entity. A more complex approach would be needed for such requirements

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