The radiation shielding cloth was developed by coating tungsten powder on polyethylene cloth with the SilicaTech® coating technique in order to guard Fukushima children from radiation after the TEPCO (Tokyo Electric Power Holding Corp.) Fukushima Daiichi NPP (Nuclear Power Plant) Accident. The glass film was reliably adhered to both the cellulose of cloth and tungsten powders by the siloxane bond. Shielding ability was found to be more than two times compared with same weight lead in the experiments. The cloth is so softer than the other materials for shielding cloth that even woman can easily wear and move.

**KEYWORDS:** Radiation, Shield, Cloth, Wear, Tungsten, Glass, Sol-Gel Method, Siloxane Bond

1. **Introduction**

In March 2011, four Reactors of the TEPCO (Tokyo Electric Power Holding Corp.) Fukushima Daiichi Nuclear Power Plant were damaged by core melting and hydrogen explosion. Environments of east Japan were also contaminated by radioactive isotopes and the residents in Fukushima prefecture became heavily afraid of radiation exposure. Iwamiya, originator of Mizuhiki-art[1-3] that was characterized by decorative Japanese code made from twisted paper, decided to guard them from radiation by using the SilicaTech® coating technique[4] based on the sol-gel procedure by developing radiation shielding cloths and wears. The cloth was invented[5] by coating tungsten powder on polyethylene cloth. It can be easily cut and sewed into a wear. The radiation shielding ability was examined.

2. **Sol-Gel Procedure in Present SilicaTech®Coating Technique**

The SilicaTech® coating technique is based on sol-gel processing. The sol-gel processing is beneficial in the formation of ceramic and glass films of various functions and applications. The sol-gel process consists[6] of a series of hydrolysis and condensation reactions of an alkoxide. Here, alkoxy silanes are used as an example but all of the metal alkoxides react similarly. While hydrolysis is initiated by the addition of water to the silane solution in ordinal sol-gel method, any water is added to the mixture solution of main alkoxy silanes, metal alkoxides as catalysts, functional auxiliaries and solvent in the present SilicaTech® glass coating technique; hydrolysis is initiated by
using water contained in the coated objective or in the environment in the present method. This method induces a slow sol-gel reaction and results in a perfect glass to be expected.

A convenient way to modify ceramic and composite materials with polymeric structures is through the use of Organically Modified Silicates (ORMOSILs). ORMOSILs are derived from tetrafunctional silicon alkoxides such as Tetraethyl Orthosilicate (TEOS), as shown in Fig. 1, where \( n \) is representative of the number of organic moieties connected to the silicon atom and \( f \) is representative of the number of reactive alkoxy groups connected to the silicon. \( R, R', \) and \( R'' \) are the functional group(s) on an organically modified silicate such as methyl, vinyl, or benzyl. Often, the present SilicaTech® glass coating technique adopt mono- to tri-functional alkoxy in stead of TEOS.

While silicon atom is fixed by oxygen in case of a ordinal glass that is made of TEOS with the sol-gel procedure and is hard, the present glass film is soft, because one more bonds of the silicon has a degree of freedom due to other functional alkoxy than tetra-one as shown in Fig. 2.

![Fig. 1. Functionality of ORMOSILs](image1)

![Fig. 2. Structure of Glass.](image2)

Sol-gel reactions do not employ extreme reaction conditions. The reactions take place at room temperature and require only moderate temperatures to ‘cure’ the gel, removing the solvent and water/alcohol that the reaction generates. Through sol-gel processing, homogeneous, high-purity inorganic oxide glasses can be made at ambient temperatures conventional approaches. Various products, such as molded gels, spun fibers, thin films, molecular cages, and xerogels can be developed for utility in such areas as gas separations, elastomers, coatings, and laminates.[6]

Mixture solution has low viscosity and high wettability to material. After coating the objective material which should be coated with the solution, the solution diffuses on the material and penetrates into pin hole or narrow gap (if it exists) and vitrifies around the cellulose fiber in case of cloth and the tungsten powder through the Sol-Gel procedure. The glass film chemically bonds to both of the organic and inorganic material by the siloxane bonds through dehydration reaction.
3. Development of Tungsten-Coated Cloth for Radiation Shielding

Tungsten is harmless and good shielding material because of its large density of 19.3 g/m³. Accordingly, the SilicaTech® coating technique was initially tried to coat uniformly tungsten powder on a Japanese craft paper. Selected alkoxysilane solution was that had properties of dispersing uniformly the tungsten powder of 3.5 micrometer diameter in the liquid to make a very thin silica glass film with a few micrometer thickness, and good bonding a silica glass film to both cellulose fiber of the paper and the tungsten powder. The mixture of the solution and the tungsten was coated on the paper and drying process was made at high temperature above 100 degree in Celsius[3].

Fig. 3 shows the optical microscopic pictures of the paper. Uncoated paper in Fig. 3(1) indicates that it is made of a collection of cellulose fiber and ten micrometer sized gaps. Thick-coated paper of Fig. 3(2) shows that the tungsten powder coated with a glass film is in the gaps between the cellulose fiber and on the fiber surface. They are connected via a glass film and also stick to the cellulose fiber. The appearance will be resemble to the Japanese cookies “Kaminari Okoshi” that the grains of baked rice are connected to each other by the sugar candy. Of course, each connection is very strong due to the siloxane bond. Fig. 3(3) shows a cross sectional view of a tungsten-coated sheet with about 60 micrometer thickness. The sheet is composed of a cluster of tungsten powder coated with glass film on the paper. The results coating on the paper clarified that the SilicaTech® coating technique had sufficient possibility to realize radiation shielding cloth by substituting the craft paper with a polyester cloth. The thick-coated paper can be easily cut with scissors and folded.

The same coating process was made on the polyester cloth. Final content of cloth

![Optical microscopic picture of the uncoated and tungsten powder coated craft papers](image1)

**Fig. 3.** Optical microscopic picture of the uncoated and tungsten powder coated craft papers

![Optical microscopic observation of tungsten-powder coated cloth.](image2)

**Fig. 4** Optical microscopic observation of tungsten-powder coated cloth.
was 740 g/m² (87.5% in weight) of tungsten, 85 g/m² polyester and 105 g/m² thin glass film. Fig. 4 shows Optical microscopic observation of outer surface and cut plane: both figures indicate that the tungsten powders are well covered with the glass film like the case of the craft paper.

3.1 The characteristics of the cloth

- Averaged volume density: 2.58 g/cm³, Thickness: 0.36 mm and weight: 930 g/m²
- Extension strength was longitudinal 698 N (71.2 kgf), laterally 438.7 N (44.7 kgf)
- The growth rate was in the longitudinal direction 26.0%, laterally 21.8%
- Wear strength was 870 times in A-1 method (planar method): A method of evaluating the wear strength against the plane, such as elbows, knees, buttocks, etc. when wearing mainly fabric and knitting clothing.
- Glass liquid was safe as getting USA Food and Drug Association (FDA) standard and Japanese F4 star indicating the highest standard of formaldehyde grade which is obliged to be displayed on JIS (Japanese Industrial Standard) products produced at JIS factory.
- The cloth was excellent in moving, strength and water repellent because unique crystal of the silicon oxide with free functional groups formed by organic moieties connected to the silicon atom (shown in Fig. 2) gave softness.
- It is possible to cut in size according to the application, and to sew with a sewing machine
- Additive crepe process to the cloth makes it fluttering.
- The present tungsten adhesive cloth can provide a radiation shielding wear that is easy to wear and move easily.

3.2 Radiation shielding Properties of tungsten coated cloth

1) Flat and crepe cloth against mono-energetic X-ray and thermal neutron

The radiation shielding experiments for the flat and the crepe cloths were performed by taking a radiation transmission image with a combination of an X-ray or neutron scintillator and a CCD camera at Kyoto University Institute for Integrated Radiation and

![Fig. 5](image)

150 keV X-ray transmission rate

| 0.406 | 0.532 |

Thermal neutron transmission rate

| 0.980 | 0.989 |

Fig. 5 150 keV X-ray and thermal neutron transmission image through the tungsten- powder coated cloth. The values in the figure are the transmission rates averaged over the cloth area.
Table I  Comparison of shielding properties between tungsten cloth and lead plate

| Specimen | Thickness (mm) | Shielding property | Equivalent Pb Thickness (mm) | weight of 100 cm² W cloth (g) | weight of 100 cm² Pb plate (g) | weight ratio to lead |
|----------|----------------|--------------------|-------------------------------|------------------------------|------------------------------|---------------------|
| Flat     | 0.36           | 46.8%              | 0.264                         | 9.5                          | 29.8                         | 0.32                |
| Crepe    | 0.36           | 59.4%              | 0.377                         | 20.2                         | 42.6                         | 0.47                |

N.B. Half width of lead for 150 keV X-ray: is 0.29 mm (from ICRP Pub. 21)

Nuclear Science (KURNS). 150 keV X-ray was produced by the X-ray generator TRIX-150WE-OC made by TORECK Co., Ltd.

The X-ray transmission results are shown in the two figures on the left hand sides of Fig. 5. Table I gives shielding properties of the cloth derived from the measured transmission image. Averaged transmission rates are 0.532 and 0.406 for 150 keV X-ray through the flat and crepe cloth, respectively. Those shielding abilities are equivalent to that of the 0.264 mm and 0.377 mm thick lead. The X-ray shielding property (i.e., radiation attenuation rate) of the flat cloth is 46.8% and fairly high. However, that of the crepe is 59.4%, not so much considering their weight ratio, factor of two.

Neutron transmission data were also taken by measuring thermal neutrons from the beam port E2 for neutron radiography of Kyoto University Research Reactor at KURNS. Averaged transmission rates are 0.989 for the flat cloth and 0.980 for the crepe. Their neutron attenuations of 1.1% and 2.0% are small, and the value seems to be nearly proportional to the shielding weight.

2) Flat and crepe cloths against Cs-137 gamma-rays

The other shielding experiments were made for different number of folds of cloths, up to 10 folds for the flat and 4 folds for crepe, by using Cs-137 gamma-ray source at Tokyo Metropolitan Institute of Industrial Technology (TMIIT) using the Ionization Chamber, of RAMTEC-1000d type made by Toyo Medic Co., Ltd. The detector was located along the central axis of the cloth. The results for radiation attenuation of both flat and crepe cloth are shown as a function of the total shielding weights per 100 cm² area in Fig. 6. Attenuation factor increases to 8% as weight. It seems that the factor of the crepe cloth is some tens percent higher than that of the flat cloth with the same weight, but its tendency may be occasional within the experimental errors due to single
detector measurement and difficulty to make a crepe structure uniform in size and density.

3.3 Radiation shielding property of Flat paper against Cs-137 gamma-ray

Shielding properties of the tungsten-powder-coated craft papers and tungsten metal were also measured at TMIIT by using a Cs-137 gamma-ray source. The results are given in Table II. Shielding properties per weight is the largest in case of the tungsten metal but its difference between the metal and the thick-coated paper is 8.9%. Shielding rate of the paper depends on a thickness of coated layer on the craft paper: The reason seems to be that coated tungsten layer thickness may be un-uniform due to influence of cellulose fiber distributions.

Table II  Comparison of shielding factors of tungsten coated papers and its metal

| Specimen         | Number of papers | Total thickness (mm) | Weight (kg/mm²) | Shielding rate (%) | Shielding rate per weight |
|------------------|------------------|----------------------|-----------------|--------------------|--------------------------|
| Thin-coated paper | 60               | 9.3                  | 22.9            | 12.7               | 0.55                     |
| Thick-coated paper | 11              | 6.5                  | 21.6            | 13.9               | 0.64                     |
| Tungsten metal   | 1                | 1.0                  | 19.3            | 13.9               | 0.72                     |

3.4 Radiation Shielding property of wear against scattered gamma-rays

The experiment for the shielding wear was made in the radiation exposure room of Nagoya University with the JAAP Ionization Chamber C-110 made by Applied Engineering Inc. Shielding wear will be used at the nuclear reactor and radiation facilities. The radiation works there are mainly done at the places where the direct radiations from the source are shaded by walls and especially designed shields. Accordingly, in the present experiments, the lead blocks were located to shield direct gamma-rays from the cobalt-60 source and built-up the scattered gamma-rays in the room. The wear to be tested was made of 3 fold crepe cloths and totally weighted 10.5kg which was about a half of the conventional lead wear. Eight detectors were placed on the front, back, left and right hand sides of a mannequin’s body for a dress hung as shown in Fig. 7. The measurements were made for both a bare and dressed mannequin. The experimental
results are given in Table III. The attenuation factors are ranged from 35% to 55%, except for the front breath below the neck. Average shielding rate of all position was 42%. This value seems to be within the range expected by user.

Lower value of the front breath, 13.7%, can be explained as insufficient radiation shielding because a part of the detector was protruding from the collar of the shielding wear.

4. Discussions

4.1 Shielding properties of flat and crepe cloths

In Fig. 5, the transmission image of the crepe cloth is composed of dark (black) ridges giving strong shield where the crepe is folding and wide gray valley showing weak shield, while that of the flat is uniform. Gray valley indicates slightly higher attenuation factor than that of the flat. Against 150 keV x-ray, shielding property of a flat tungsten coated cloth was 46.8% and equivalent to 0.264 mm Pb. On the other hand, the crepe cloth with a double weight of the flat indicated radiation attenuation factor of 59.4% that is equivalent to only 0.377 mm Pb. In this case, the ridge was too slim to supplement weak shields of wide valley as shown in Fig. 5.1. As a whole, average shielding property of equivalent Pb thickness became 0.377 mm and lower than that to be expected, 0.528 mm. Accordingly, it can be said shielding property of the crepe is not so high to be expected against X-ray and scattered gamma-ray. However, multi-fold crepe cloths may supplement weak points of a crepe to make shields.

On the other hand, it should be noted that there are many dark ridges of thermal neutron attenuation given in Fig. 5.3 and low attenuation of a few percent. As a whole, shielding effects at the ridges surpassed weak shielding effect in the valley. Accordingly, shielding property of the crepe became nearly double of the flat. The similar results are observed in Fig. 6 in case of the experiments of cesium-137 gamma-ray source: attenuation factors are below 8%.

4.2 Tungsten cloth and sheet for low energy gamma-ray shields

There is a new shielding material of tungsten sheet[7] taking place of lead produced by Nippon Tungsten Co. Ltd. as like the present tungsten cloth for low energy gamma-rays including X-ray. Their properties are compared in Table IV. Major difference is in the density of material: 2.58 g/cm3 of SilicaTech® tungsten cloth and more than 11.5 g/cm3 of Nittan tungsten sheet. Next important common property is soft and to be processed in a free form: SilicaTech® tungsten cloth can be tailored into a shielding cloth such as a shielding wear and a soft-and-tight shields for delicate electric devices, while thermoplastic Nittan tungsten sheet can be easily molded with a certain degree of heating, and kept its shape at room temperature. For example, it is molded in
advance a roll which is convenient to perform the detachment to the pipe with one touch.

Nittan tungsten sheet having the nearly same weight and shielding property as lead can take place of lead shields. On the other hand, higher specific shielding property of the SilicaTech® tungsten cloth per weight than lead can make shields light.

**Table IV** Comparison of properties of SilicaTech® tungsten cloth and Nittan tungsten Sheet

| Items               | SilicaTech® tungsten cloth | Nittan tungsten Sheet |
|---------------------|-----------------------------|-----------------------|
| Production method   | tungsten powders coated on polyester with SilicaTech® method. | mixing tungsten powders and elastomeric resin at high temperature. |
| Characteristics     | soft cloth, low density as like Al (light), excellent in moving, strength and water repellant, easy to be cut and sewed into any shaped shields, wide (1,300 mm x 10,000 mm) | soft sheet, high density (heavy), maintaining a certain shape as like tape, bendable, good mechanical strength, wide (800 mm x 1,000 mm) |
| Density             | 2.58 g/cm³                  | more than 11.5 g/cm³  |
| Hardness            | -                           | 95.6.                 |
| Extension strength  | longitudinal 71.2 kgf, laterally 44.7 kgf. | 44.9 kgf. |
| Elongation          | longitudinal direction 26.0%, laterally 21.8% | 25.6 % |
| 150 kV X-ray shielding property of 1mm thick specimen relative to the same weight Pb | 0.73 mm Pb. 3.0 (near to metal tungsten). | 1.11 mm Pb. 1.09. |
| Applications        | shielding wear, glove, hat etc., shielding for electric devices, and radiation detectors, wide shields as a curtain and standing for radiation rooms. | shielding sheets, shield mats, roll-molded shields, tape-like molded shields for pipes. |

4.3 Example of shielding wear

The tungsten coated cloth must be useful to shield both scattered gamma-rays and X-rays. Such radiation exposure will be occurred not only in the nuclear power plant accident but also in working areas of radiation fields such as the rooms for the radiation experiments, the medical diagnosis and therapy with radiations. Especially, ordinary person and child will encountered in the medical field. The present shielding wear is softer, lighter and more-easily-to-wear than the conventional one.

**Fig. 8** shows a shielding wear of 10.5 kg that can be applicable enough to a woman. It will make a child reassure because of giving tight shield of body. Flexible shielding cloth will be also applicable to shield sensitive electronic apparatus used in the radiation field. Even in the case of large or complicated geometry, the wide cloth will be able to
cover apparatus. The cloth can be build up to adjust the geometry by cutting and sewing. Any shielding thickness can be realized.

5. Conclusion

SilicaTech® glass coating technique produced well a tungsten-powder coated cloth which is soft and about two to three times lighter than an equivalent shielding lead in case of 150 keV Xray. The shielding wear was 10.5kg in weight easy to wear and move. Its shielding performance was found to be of 40% in average against scattered gamma-rays that radiation workers frequently encounter. The result seems to be enough to use the actual radiation work. The shielding cloth and wear will be also useful to both medical diagnosis and therapy for doctor and patient. Especially, the shielding wear will be favorite to guard child by gently and firmly wrapping his body with an associated cloth.

Soft and broad shielding cloth can envelope any shaped apparatus and equipment and is widely applicable as a radiation shield to guard the tools sensitive to radiation in case of the radiation experiments.

Acknowledgment

Authors are grateful to Dr. Kohmei Harada of Sustainable Design Institute for his valuable idea of crepe cloth that realized a fluttering movement of the cloth.

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