Essential Readings in Light Metals: Cast Shop for Aluminum Production.
Edited by John F. Grandfield and Dmitry G. Eskin.

10. SAFETY

The industry has steadily improved its safety performance through better systems, engineering, and fundamental science. Much emphasis has been given to the risk of molten metal water explosions. In this section there are a number of papers on the science and prevention of molten metal water explosions. Other hazards are also covered.

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PERSONAL PROTECTIVE CLOTHING : FROM FUNDAMENTALS TO A GLOBAL STRATEGY OF PROTECTION IN THE CASTHOUSE ENVIRONMENT

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ABSTRACT

Among potential casthouse hazards, water/aluminum explosions are the major ones.
To face this risk, personal protective clothing is a significant element of a safety program, at the same level as design of equipment or training of casthouse workers.
Therefore, within the framework of our experimental casthouse, we have tried to select the best suitable protective clothing for our personnel.
This paper presents a classification of fibers which have a potential application in casthouse protective clothing. The resistance of these fibers is evaluated in the case of molten metal splashes and the results, in particular sticking of metal to protective clothing materials, are analyzed within the context of burns.
The other fibers properties which are required in the casthouse environment are also examined. A strategy for the choice of personal protective clothing is proposed, taking into account the properties available and the specificity of the casthouse requirements.
This strategy is applied to the case of primary clothing, secondary clothing and gloves.

PROTECTIVE CLOTHING WITHIN OUR GLOBAL SAFETY APPROACH

In our experimental casthouse, the objective to continuously make the personnel benefit from the highest performance in individual protective clothing is one of the four major themes of our safety approach. As described in a previous paper [1], the other themes are the design of equipment, the training of personnel and communication. Within this context, studies about casthouse clothing have been carried out.
While undertaking this endeavor, we were confronted to difficulties, notably due to the lack of knowledge about commercial fabrics. We therefore felt the need to determine appropriate evaluation means in the field of fabric properties and to set up a methodology for the selection of these fabrics.
For several reasons we wish to present our approach and the solutions retained to the casthouse community :

- safety is one of our permanent concerns and we believe that progress in this field is not worth anything if not shared,
- the collection of existing documents, data and synthesis of the knowledge on the subject that we carried out aims at facilitating the access to information and relevant parameters ; we hope that this source of information will be considered as a contribution to prevention,
- a global safety approach requires a permanent, unabated improvement and we are convinced that the contribution of any unit aiming at protecting the casthouse personnel against major risks such as molten aluminum splashes is needed.

This study deals with personal protective clothing in an aluminum casthouse : secondary clothing, primary clothing, gloves.
It is based on the role of human beings within their working environment : with the knowledge of the industrial fibers provided for a potential use in casthouse, we have examined their elementary properties and - by comparing these properties to each worker's objectives, according to their use for a given function - set up an analysis methodology.
This strategy enables to define the types of equipment which take into account the various elementary risks linked to working conditions.

The plan of this article directly stems from the approach described earlier :

- classification of industrial and commercial textile fibers
- characterization of fabrics according to their reaction to molten metal splashes
- study of fabrics behaviour and consequences in terms of burns
- determination of other fabric properties to take into account
- strategy for the protection of casthouse personnel.

To begin with, we would like to warn the reader that all tests and results mentioned in this article aim solely at emphasizing trends and enabling an objective analysis intended to make choices easier. They are not in any way a substitute to existing standardized tests to which the user must refer as much as possible.

CLASSIFICATION OF INDUSTRIAL AND COMMERCIAL TEXTILE FIBERS

One of the difficulties to select protective clothing is to sort out among the large variety of commercial brands with a potential use in casthouse (Figure 1).

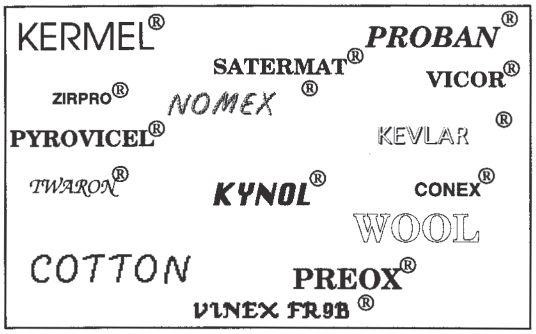

Figure 1 : A few examples of fabrics proposed to casthouse- often leading perplexity.

Despite this apparent complexity, fibers may be classified into two generic groups [2-6] :

- natural fibers
- synthetic fibers.

Each of these categories can be further divided into sub-groups. Natural fibers break down into :

- animal fibers : wool, silk, ...
- vegetable fibers : cotton, flax, hemp, jute, ...
- mineral fibers : asbestos, ...

Synthetic fibers break down into :

- man-made fibers : fibers extracted from a natural polymere. E.g. : cellulose fibers from cotton linter or wood cellulose = viscose, polynosic, rayon
- organic fibers : fibers originating from a synthetic polymere : acrylic, polyamid, aramid, polyester fibers ...
- inorganic fibers : glass, metallic, ceramic fibers, carbon fibers ...

Synthetic fibers have considerably developed during the last thirty years. Given the interest they generate within trade, the case of aramid fibers has to be mentioned. These fibers belong to the following commercial brands :

NOMEX®, KEVLAR®	Du Pont de Nemours (United States)
KERMEL®	Rhône-Poulenc Fibres (France)
CONEX®	Teijin Ltd (Japan)
TWARON®	Enka (The Netherlands)

They feature very good properties in the field of mechanical resistance, fire and heat protection. As will be seen later on, these properties may lead to confusion in case of too quick and simple extrapolation.

Finally, with regard to the categories of fibers mentioned above, two complementary options are possible :

- flame retardance processing providing the fabric with a resistance to flame ignition and propagation,
- surface aluminization processing to protect against radiative heat transfer.

Flame retardance (FR) processing

Flame retardants incorporated into the fabrics to modify their inflammation act in three different manners [3, 7] :

① **in the vapor phase** : at this stage, they have an inhibitory action on the flame, especially on combustion free radicals. Halogen derivatives, notably bromine derivatives, act in this way ($HBr + OH^{\bullet} \rightarrow H_2O + Br^{\bullet}$), thus unsettling the flame and capable of going as far as its extinction.

Sb_2O_3 and Sb_2O_5 antimony oxides, phosphorus and bore derivatives are also found in this category.

② **in the condensed phase** : They disturb the combustion of the material by reacting with it in the solid state. In this category, the case of tri-hydrated alumina ($Al_2O_3,3H_2O$) must be mentioned : at a temperature above 250°C, it loses its water through endothermal reaction, thus consuming the thermal and radiating energy of the flame and slowing down the pyrolysis speed of the fabric.

Furthermore, the water vapor dilutes and cools the flame and the residual alumina acts as a thermal screen.

The necessity to use large quantities of flame retardant (up to 60-70 %) likely to reduce the properties of the material (notably, the mechanical properties) is a drawback.

Other agents acting in the condensed phase : magnesium hydroxide (same principle as tri-hydrated alumina), calcium carbonate and talc (inert loads).

③ **by forming a protective layer** isolating the fabric from air oxygen. The intumescent systems (i.e. which swell while reacting) create an expanded carbon structure at the surface of the material, representing a true thermal shield. These materials (often inorganic phosphates) are under development. Their drawback consists in the fact that they do not modify the intrinsic inflammability of the fabric.

Generally, it is very difficult to know, for a commercial FR fabric, which is the type of flame retardant incorporated into it.

The main commercial brand names [9, 10, 15, 23, 29] will however be mentioned :

• cotton :	PROBAN® (Albright and Wilson Ltd) PYROVATEX® (Ciba Geigy) CALIBAN® (White chemical corporation) PYROSET® (American cyanamid) INDURA® (Westex, Inc.)
• cotton/polyester :	FLAMEX® (Galey and Lord)
• wool :	ZIRPRO® (International wool secretariat)
• rayon :	VISCOSE FR (Lenzing) DANUFIL CS® (Hoechst)

The aluminization treatment of fabrics

The two main aluminization processes are [8, 28] :

① **vacuum transfer** of an aluminum coating a few microns-thick (either sheet or spray) onto the fabric. The advantage resides in the fact that the aluminum layer is bound with the fabric fiber, thus guaranteeing a good resistance.

② **the thermal bonding** of an aluminum sheet (or of an aluminized polyester film) on the fabric. This process is a priori less efficient than the first one as it may result in possible problems of adherence, incidence of blisters, premature wear, or of a lesser reflectivity.

Aluminization of various fabrics is possible. The most common ones encountered are :

- aluminized glass fabric
- aluminized PROBAN®
- aluminized KEVLAR®
- aluminized KEVLAR®-PREOX®, also named KEVLAR®-Carbon : It associates KEVLAR® fibers (generally 30 %) to polyacrylonitrile oxide fibers (70 %), a blend between polyacrylonitrile, providing it with its textile properties, and carbon which gives its thermal resistance properties [6].

The whole set of commercial fabrics may be described by using the classification just mentioned : we focused on those that are generally proposed for casthouse uses. They are grouped inside the table of Figure 2.
Even if it is not a fiber, leather has also been studied as it is often used in the confection of casthouse personal protective clothing.

Generic name	Class	Name	Flame retardance treatment	Aluminization treatment
Natural fibers	Animal	Wool	Zirpro®	
	Vegetal	Cotton	Proban®	Aluminized Proban®
Man-made fibers	Rayon		Pyrovicel® [1] Satermat® [1]	
Organic fibers	Aramid	Kevlar® Nomex® Kermel®		Aluminized Kevlar®
	Polyvinylic		Vicor® [2] Vinex® [3]	
	Acrylic			Aluminized Préox®-Kevlar®
	Phenolic	Kynol®		
Inorganic fibers	Glass			Aluminized Glass fiber
	Ceramic	Zetex®		Aluminized Zetex®

[1] FR Viscose blended with wool and polyester
[2] FR Polyvinylic fiber on FR cotton substrate (on one face)
[3] 85 % Vinal 15 % Polynosic fiber

Figure 2 : Classification of fabrics proposed for a casthouse use.

With this classification and considering it as globally satisfactory, the next step of our approach consisted in characterizing these fabrics with regard to molten metal splashes.

CHARACTERIZATION OF THE FABRICS ACCORDING TO THEIR REACTIONS TO MOLTEN METAL SPLASHES

In order to characterize the fabrics, the conventional test, consisting in pouring a given amount of molten metal on a fabric sample that inclines has been used. The major reference, in this field, is the British BS 6357 test known as the "British Standard Method for assessment of resistance of materials used in protective clothing to molten metal splash". This test is indeed described in a very precise manner [12] and has been used in other publications on this subject [10, 13].

Description of the test : A crucible containing molten metal is placed on a base capable of revolving around an axis (Figure 3) (manual rotation using a handling wheel). The pouring conditions remain identical, thanks to the measurement of the molten metal temperature with a thermocouple. During the rotation of the crucible, the molten metal falls in a counterslope manner on a sample of fabric inclined at 45°. It is then collected inside a tank. A protective screen shields the operator from possible metal drop splashes.

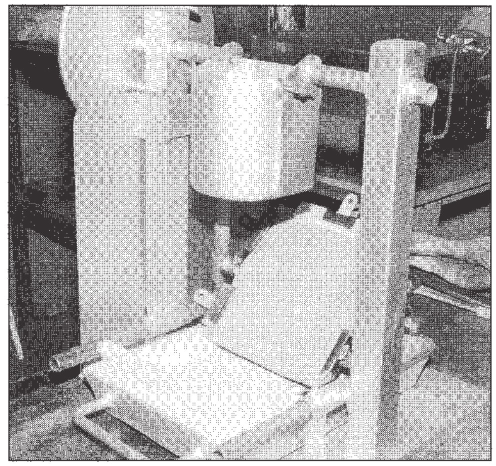

Figure 3 : Fabric testing (characterization of the fabrics according to their reactions to molten metal splashes).

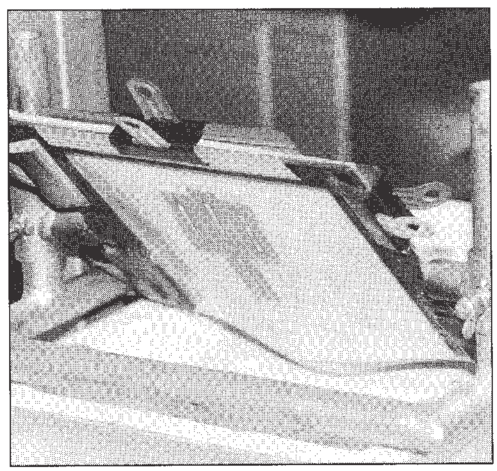

Figure 4 : Measurement of the temperature on the reverse side of the fabric using a thermo-sensing tape. The PVC sheet acts as a cushion.

The main test parameters are the following :

- molten metal : pure aluminum
- pouring temperature : 750°C
- metal falling height : 300 mm
- fabric slope with regard to the horizontal plane : 45°
- rotation of the crucible : 110° within 3 seconds
- counterslope pouring
- amounts poured : from 250 g to 500 g depending on the tests.

The inclination angle of the fabric is of 45°. Some articles mention a greater angle : 70° [11, 25] or 60° [14]. It should be noted that the closer the angle to the horizontal plane is, the harder the conditions of the test are.
Three modifications were introduced as compared to the BS 6357 test :

- ➡ reduction of the pouring temperature (750°C instead of 780°C) in order to be closer to actual workshop conditions ;
- ➡ measurement of the temperature on the reverse side of the fabric using thermo-sensing tapes (Figure 4). The British test recommends the use of a PVC sheet with very specific grammage and thermal properties, supposed to behave like a human skin and to indicate the various degrees of burns.

Only one reference giving a precise description of the plastic sheet that should be used to simulate the skin was found in the literature. The plastic sheet, though essentially made of PVC has a composition much more complex than PVC. A precise calibration intended to correlate the surface aspect of the sheet with the different degrees of burns is described [26].
Given the uncertainties related to the representativeness of PVC alone, we have opted for a direct measurement of the temperature of the fabric, connected to a mathematic simulation in order to estimate the skin temperature. This will be seen in the following paragraph.
However, a PVC sheet was kept to simulate the mechanical behaviour of the skin (absorption of the metal stream impact) ;

➡ the quantities of metal needed were generally of 250 g for fabrics used as part of secondary clothing, 500 g for fabrics used as part of primary clothing. In the case of fabrics that are resistant to 250 g of metal, intermediary quantities were required.

Our objective being to emphasize trends, we did not try to determine from which quantity of metal the fabric starts to fall apart (Molten Metal Splash Index (MMSI) defined in the protocol of the BS 6357 test).
Approximately 60 tests were performed on fabrics which, according to the suppliers, are likely to be part of the confection of secondary or primary clothing.
For each test a video tape was recorded. The temperatures reached at the reverse of the fabric and, in case of sticking, the amounts of metal involved were measured. A series of photographs, before and after the test, were carried out.
In a synthetic manner, the classification of the various fabrics tested with molten aluminum splashes enables to reveal the following hierarchy (Figure 5) :

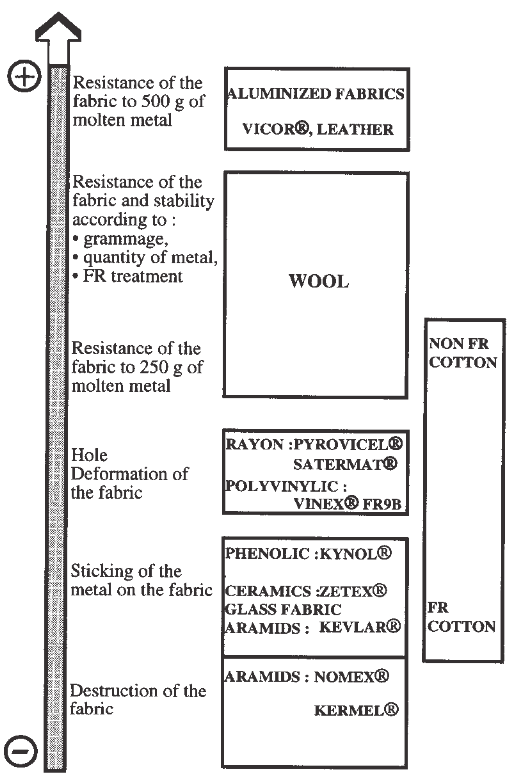

Figure 5 : Characterization of the fabrics according to their reactions to molten metal splashes : hierarchy of behaviour on test setting.

A short comment about the fibers tested, is now presented in order of increasing performance.

Aramid fibers : The fibers tested in this category do not resist to molten aluminum. Their behaviour range from total destruction (NOMEX®, KERMEL®) to metal sticking to the fabric (KEVLAR®, Figure 6). In that case, temperature on the reverse side of the fabric is above 300°C.

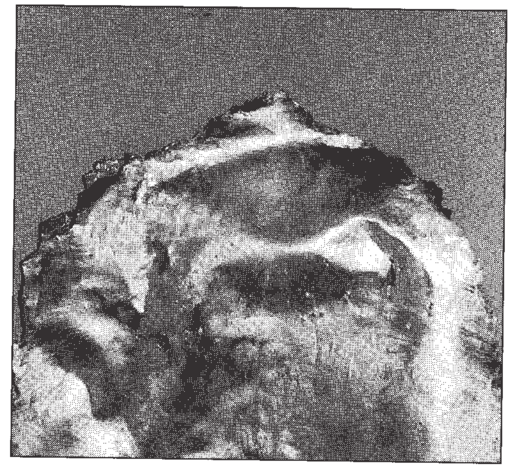

Figure 6 : Metal sticking on aramid fiber.

Phenolic fibers : We have only tested Kynol® in this category. It is used by firemen to protect themselves against flame waves. This fabric is subject to molten metal sticking (reverse side temperature above 300°C).
Glass fibers and ceramics : For the two fibers tested (one in each category), molten metal sticking can also be noted (reverse side temperature above 300°C).
Polyvinilic fibers and rayon : In this category the fabrics tested feature a different behaviour as compared to the previous ones : the metal does not stick but it slips on the fabric. These fabrics are nevertheless subject to a deformation likely to result in a puncture or in a tear. In this category, VICOR® (FR PVC on cotton substrate, which looks like leather) resisted well to molten metal, up to 500 g.
Cotton : Untreated cotton presents a good resistance to molten metal even if the amount of poured metal is increased (up to 300g) or if grammage is decreased (to 300 g/m^2). On the other hand, when it is FR treated, metal sticks to the fabric and the temperature on the reverse side is above 300°C (Figure 7).

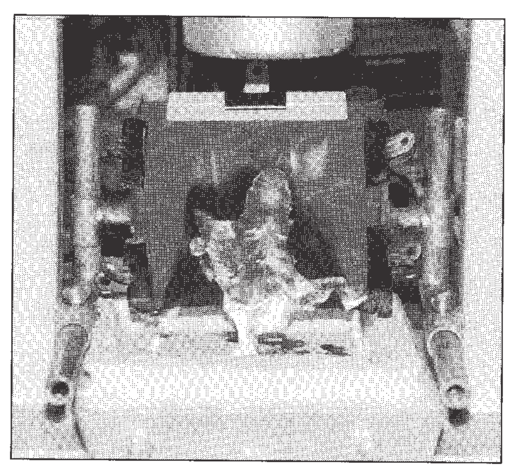

Figure 7 : FR cotton (PROBAN®). Metal sticks to the fabric.

Wool : Wool demonstrates a very high stability when parameters vary. Within the investigated field (grammage variation from 700 g/m^2 to 300 g/m^2, amount of liquid metal from 250 g to 400 g, effect of the ZIRPRO® FR treatment), wool resists to the contact of molten metal which slips on it.

Aluminized fabrics : All the aluminized fabrics tested resist well to 500 g of liquid metal (investigation carried out from 850 g/m^2 to 300 g/m^2). However, slight differences of behaviour can be noted depending on the fabrics, notably in terms of thermal insulation or resistance of the aluminized coating. The aluminum layer appears highly protective : a fabric such as PROBAN® cotton which did not resist to 250 g of molten metal resists to 500 g when it is aluminized ; same observation for the glass and ceramic fibers tested.

Leather : Leather also resists well to 500 g of molten metal, with, however sometimes, metal sticking points according to roughness of the material.

Fibers blend : For blended fibers, it was noticed that the weakest in terms of reaction to molten metal confers to the blend the same level of weakness - observations made on wool-rayon (weaker than wool) aramid-rayon and aramid-wool blends (featuring the same behaviour as aramids alone).

These results are in agreement with previous studies on the subject summarized Figure 8.

L. Benisek et al [14, 27, 28] (International woolsecretariat) : . sticking of metal on glassfiber and aramid fibers. . harmful effect of FR treatment on cotton (PROBAN® or PYROVATEX®). . good resistance of wool (FR treated or not), untreated cotton and aluminized fabrics (with variations according to the aluminization process). . behaviour of fiber blends identical to the weakest componant of the blend.
The Foundry Industry Advisory Committee [10] : . molten metal does not stick to wool (MMSI > 400 g), and not or little on leather (MMSI > 400 g also). . it does not stick very much on untreated cotton. . its sticks on FR treated cotton (MMSI of PROBAN® < 30 g). . CALIBAN® FR cotton relatively better than PROBAN® (MMSI = 110-180 g) with nevertheless a slight sticking (CALIBAN® has been developed to improve other FR cottons (PROBAN®, PYROVATEX®) [15].
J. Coughlan (NZAS) [13] : (tests run with 50 g of metal at 820°C). . very good results with wool (ZIRPRO® treated or not, doubled or not, washed or dry - cleaned) and VINEX®. . very bad results with NOMEX® and FR cotton (metal sticking). . intermediary results with untreated cotton.
R. Sharkey (ALCOA) [24] : (tests run with 1 kg of molten metal). . bad behaviour of FR cotton, aramid fibers (NOMEX®, KEVLAR®) and VINEX®. . good behaviour of untreated cotton but inflammation if there is a fold. . very good behaviour of ZIRPRO® wool.
B.J. Sasser (REYNOLDS) [25] : (tests run with two pounds of molten aluminum). . sticking of molten metal on FR cotton. . no sticking of molten metal on untreated cotton but tendency to catch fire if there is a fold. . no change with molten aluminum-magnesium or aluminum-zinc alloys.
P.N. Mehta et al [26] (International wool secretariat) : (tests run with 640 g of molten metal). . good results with wool (ZIRPRO® treated or not). . unsatisfactory results with FR cotton fabrics (PROBAN®, PYROVATEX®). . bad results with aramid fibers.

Figure 8 : Summary of main studies on fabrics

At this stage of our study, we wish to reposition these results within the real context of molten metal splashes, that is to say, in terms of burns.

BEHAVIOUR OF THE FABRICS IN REACTION TO MOLTEN METAL SPLASHES : CONSEQUENCES IN TERMS OF BURNS

The role of personal protective clothing is to avoid burns during a molten metal splash. To start with, let us remind that the skin is made up of three layers :

- **the epidermis** : a superficial thin and transparent layer of approximately 0.1 mm. It constitutes the protective envelope of the human body in accordance with the external environment. At the surface, pores enable the flow of sweat (internal thermal regulation) and hair enables external thermal protection.
- **the dermis** : in the order of one mm, it ensures the elasticity and resistance of the skin. It is also the center of the sensory organs : pain, touch, pressure, heat, cold.
- **the hypodermis** : fatty tissues, shock absorbers in case of high pressure. It is a tank of energy crisscrossed by cutaneous arteries, veins and nerves that irrigate the upper layer. It also contains the sudoriferous glands and hair follicles.

Burns are classified in two categories :

- **partial skin thickness burns** : The epidermis is completely affected, together with a lesser or greater part of the dermis. The skin may however regenerate itself at the location of the injury if the cells from the membrane located between the epidermis and the dermis (epithelium cells) are preserved.
- **full skin thickness burns** : all layers of the skin are affected. The nervous terminations are destroyed. A surgical treatment is required.

Studies on the subject show that the importance of the burn varies as a function of :

- the temperature or heat flux reached at the skin level
- the duration of the exposure (Figure 9) [11, 18-22].

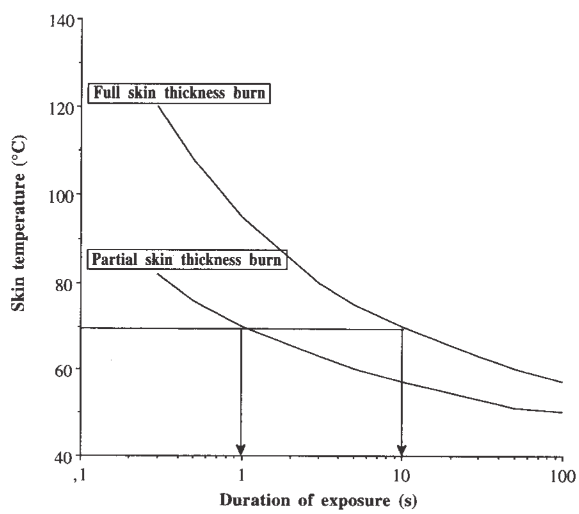

Figure 9 : Burns : skin temperature/duration of exposure relationship. (According to [20]).

For instance, a temperature of 70°C at the skin level leads to a partial skin thickness burn after one second and to a full skin thickness burn after ten seconds.

Consequently, the two requirements in terms of safety are : avoid a prolonged exposure to high temperatures, but above all, make sure that the skin temperature, in case of splash, is as low as possible.

The molten metal splash tests performed shows that there is a significant temperature difference, at the reverse side of the fabric, depending on whether the metal sticked to it or not (Figure 10).

	Temperature on the reverse side of the fabric
Metal sticking to the fabric	> 300°C
Slipping of the metal on the fabric	80 to 100°C

Figure 10 : Temperatures on the reverse side of the fabrics.

To try to foresee the corresponding temperature at the skin level, we carried out a simple numerical simulation (monodimensionnal calculation taking into account thermal properties of successive layers : molten metal, fabric and skin). We focused on three cases :

- fabric on which the metal sticks
- fabric on which the metal slips
- double protection (primary and secondary).

The increase in the skin temperature over time was determined (Figure 11).

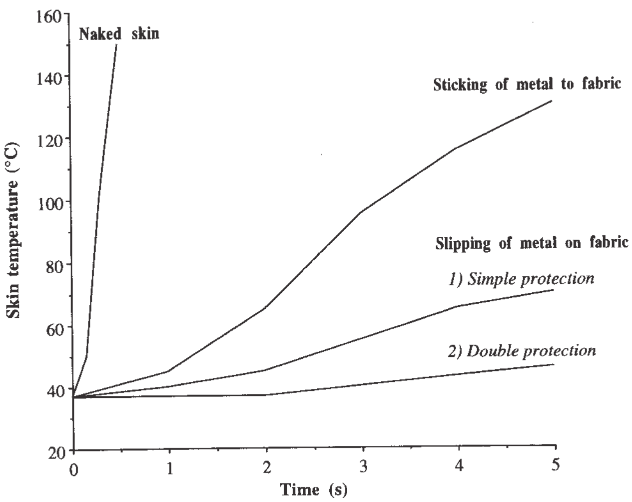

Figure 11 : Skin temperature according to the behaviour of the fabrics during a molten metal splash.

To start with, let us notice that if the skin is put into direct contact with the molten metal, it almost instantly reaches a very high temperature (150°C in half a second).

As far as fabrics are concerned, the following behaviours can be observed :

- whenever the metal sticks to the fabric, the skin temperature increases rapidly. It reaches 130°C in 5 s and keeps on increasing thereafter,
- if the metal does not stick to the fabric, the rise in temperature is lower : 70°C after 5 s with a maximum of 72°C reached after 7 s,
- finally, with a double protection, the increase in skin temperature is even lower : 46°C after 5 s and the maximum reached is only 64°C (after 20 s).

This difference of behaviour depending on whether the metal sticks or not to the fabric, may be at the origin of significant differences in terms of burns. The reporting of temperatures stemming from the simulation (Figure 12) on the burns diagram shows that : with a fabric on which sticking occurs, after a 5-second exposure, a molten metal splash may result in a full skin thickness burn. With a fabric on which sticking does not occur, the burn may only be a partial skin thickness one. Finally, with a double protection, it is possible to remain under the burn threshold.

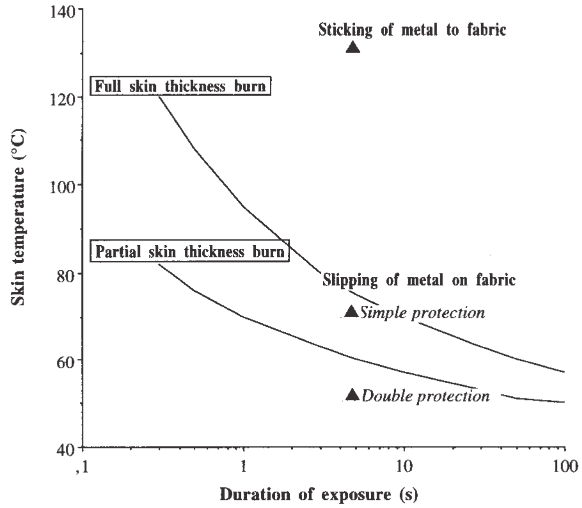

Figure 12 : Influence of the behaviour of fabrics on burns.

This simple simulation enables to confirm that :

- it is imperative to protect all parts of the body in order to avoid direct contact between the metal and the skin
- for hazardous operations (start-up of casting for example), wearing a primary clothing over the secondary clothing permits to considerably reduce the risk for burns
- in all cases, the fundamental criterion for the choice of a fabric exposed to molten metal splashes is the non sticking of the metal to the fabric.

If this criterion is taken into account for the results obtained during the splash test, it is already possible to select the fabrics that may be suitable for a casthouse worker and eliminate those that do not fit (Figure 13).

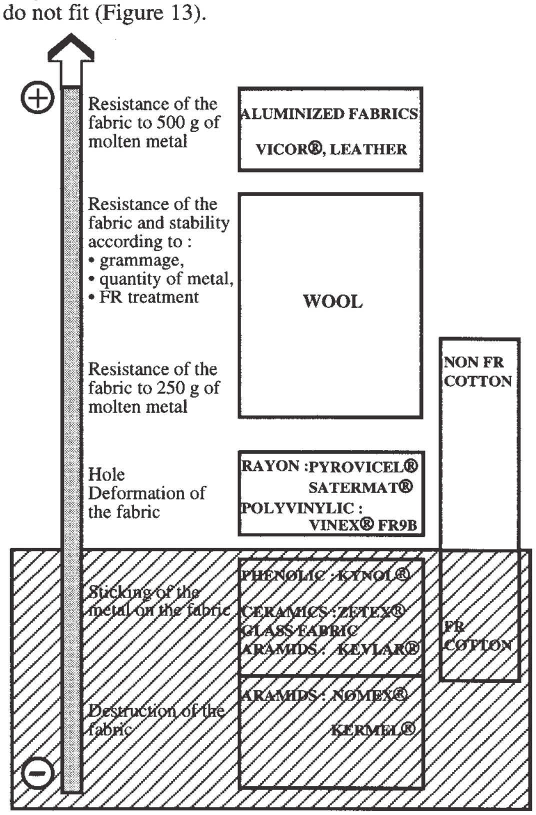

Figure 13 : Dismissal of the fabrics to which the metal sticks during a splash.

The next stage of our approach consists in completing this first analysis by taking into account other properties enabling to develop a rational selection strategy.

OTHER FABRIC PROPERTIES TO TAKE INTO ACCOUNT

With the resistance to molten metal splashes, the other features to take into account are :

- inflammability
- thermal insulation
- mechanical resistance
- regulating properties of perspiration : moisture regain, permeability
- conservation of properties according to wear, maintenance
- global comfort : dimensional stability, touch.

Cost requirements are not considered at this stage : once the fabrics meeting the use and safety criteria have been selected, non technical data can be taken into account.
Let us review each of these properties.

① **Inflammability** : The resistance of a fabric to the propagation of flame appears to be the second property to take into account after the resistance to molten metal splashes.
The inflammability of a fabric can be characterized by its ignition temperature and the Limiting Oxygen Index, LOI, which is the minimum percentage of oxygen necessary to maintain the flame :

- if LOI < 22 %, the flame propagates until the total deletion of the fabric,
- if LOI > 26 %, the flame dies out by itself in the air. The fabric is self extinguishing.

Figure 14 (according to 2, 4, 5, 9, 35) gives the LOI and ignition temperature values for the most common fabrics.

Fabrics	LOI (%)	Ignition temperature (°C)
Non treated cotton	18	400
Non treated rayon	20	420
Non treated wool	25	600
FR rayon	29-30	-
FR cotton	31-32	-
Aramids	29-32	-
Phenolics	30-34	-

Figure 14 : Inflammability features of the main fabrics.

This table highlights the natural qualities of aramid (Nomex®, Kermel®, Kevlar®) and phenolic (Kynol®) fibers, demonstrating an outstanding flame retardance behaviour. To a lesser degree, wool naturally features a good LOI.
At the end of this classification, untreated cotton demonstrates a very bad LOI and a low ignition temperature : it ignites easily, the flame propagates quickly and is difficult to stop. Combustion proceeds slowly even after the extinction of the flame.

Coupled with resistance to molten metal, this property turns out to be important if, for example, metal is trapped into the fold of a cloth. For the sake of experiment, we ran again the splash test on untreated cotton, by creating a fold on the fabric. Contrary to the conventional test, the cotton in this case caught fire under the action of the metal (Figure 15). This results in the elimination of cotton for the secondary clothing.
Under the same test conditions (splash test with a fold), wool does not burn and the metal properly slips on the fabric. A hole may be noticed after the splash only at the location where the metal stayed longer.

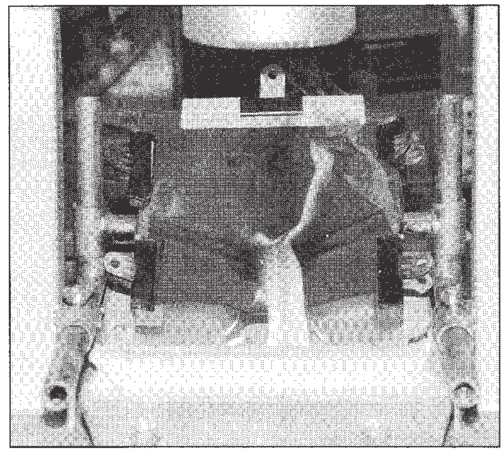

Figure 15 : Ignition of untreated cotton during a metal splash over a fold.

The paradox and the essential difference between the flame retardance behaviour and the behaviour toward molten metal can be noted :

- aramids do not propagate the flame but, in case of molten metal splash, the metal sticks to the fabric with a potential for causing serious burns,
- untreated cotton resists to the splash test but, in case the molten metal gets trapped, it catches fire and is completely destroyed,
- FR cotton does not propagate the flame but does not resist to molten metal (sticking).

Only the fabrics achieving a good performance for these two criteria (resistance to molten metal and uninflammability), wool for example, could be used for the confection of a casthouse clothing. It is noted, here, that a single test (the test of resistance to molten metal splashes) is not sufficient to select a fabric. On the contrary, taking into account several properties enables to reach this goal. This is the basis for our methodology.
② **Thermal insulation** : The thermal properties of the fabrics must also be taken into account : one of the functions sought out is indeed the protection of the casthouse workers against heat. We can try to classify the different fabrics using their usual thermal properties (thermal conductivity, specific heat, diffusivity) but reality may appear different due notably to the thickness of the fabric which is a primary parameter [31, 32], to its weaving, etc ...
A few studies on the topic enable to highlight some trends, summarized Figure 16.

Convective heat transfer : (decreasing order in performance)
wool > Kynol®, FR rayon, glass fiber, aramid fibers > FR cotton
(L. Benisek et al. [27, 28])
wool > cotton > aramid fibers > FR cotton
(R.M. Perkins [31])
FR wool > aramid fibers > FR cotton
(W.P. Behnke et al. [17])
Radiative heat transfer :
aluminized fabrics feature the highest performance.
(L. Benisek et al [27, 28])
Heat transfer, through contact, with a hot object :
wool > aramid fibers, FR rayon, phenolic fibers > FR cotton.
(R.L. Barker et al. [32])

Figure 16 : Insulation performance of main fabrics

The good behaviour of wool and, to a lesser degree, of aramids, phenolics and FR rayon fibers can be noted. FR cotton features a lower performance.

③ **Mechanical resistance** : This property is important for the aging of clothing in general or for specific use (gloves for example).

We have tried to classify fibers by using the breaking tenacity which is the breaking load related to the lineic density of the yarn before tensile test. Breaking tenacity is expressed in N/Tex where Tex is the mass in grams for a yarn of 1000 m.

Without any surprise it will be noticed (Figure 17) that Kevlar® features a mechanical resistance of an order of magnitude greater than the other fibers. Those are relatively grouped around 0.15-0.5 N/Tex except for wool which presents a discrepancy by comparison with the other fibers.

Fabric	Breaking tenacity N/Tex
Wool	0.03-0.3
Kynol	0.12-0.16
Kermel	0.15-0.35
Rayon	0.2-0.35
Cotton	0.2-0.6
Nomex	0.4-0.5
Glass	0.9-1.3
Kevlar	1.9

Figure 17 : Mechanical features of main fabrics. (According to [2-5]).

④ **Regulation of perspiration** : The two parameters chosen in order to best describe this property are :

- the moisture regain of the fabric (its ability to accumulate perspiration),
- the permeability of the fabric (its ability to ensure the draining of perspiration toward the outside).

The values relevant to the moisture regain property can easily be found among the usual data about fabrics. Figure 18 shows the main values encountered. Moisture regain is the weight of water uptaken at equilibrium with standard atmosphere (20°C - 65 % relative humidity). It is expressed as a percentage of the dehydrated fabric.

Fabric	Moisture regain (%)
Glass	0.1
Nomex®	4
Kermel®	3-5
Kevlar®	3.5-7
Kynol®	6-7
Rayon	8-13
Cotton	8.5-12
Wool	17-18

Figure 18 : Moisture regain for main fabrics. (According to [2-5]).

As can be noticed, natural (wool-cotton) and man-made (rayon) fibers are superior to synthetic fibers.

As far as the permeability of the fabric is concerned, there are no specific data for a given fiber. It is actually a function of the weaving mode, of the cutting, of cloth amplitude, of a possible lining ... The data that are specific to each fabric, although measurable, are not intrinsic and are not therefore of a high interest. Consequently, in this field, perception of the personnel is still of paramount importance, thus requiring in situ validation tests.

⑤ **Conservation of properties according to wear, and maintenance** : Only some punctual studies were carried out in this field [29, 30] mainly on the inflammability, thermal insulation and mechanical resistance properties.

No general conclusions can be drawn from such studies as the results are a function of the use which is made of the clothing, of the type of washing carried out etc ... We are therefore, here again, in a field where the information acquisition requires in situ testing.

⑥ **Global comfort** : There are no intrinsic parameters describing the comfort of a fabric. The latter is a function of numerous parameters such as the dimensional aspects (amplitude, stability), the contact between fabric and skin, the flexibility or the stiffness, etc ... The only way to converge toward the best compromise is by listening to the personnel, and undertaking successive tests.

Finally, two families of properties are determined :

I) Intrinsic measurable properties of the **fabrics** :

- resistance to the molten metal
- inflammability
- thermal insulation
- mechanical resistance
- moisture regain.

II) Global properties of the **clothing**, accessible by successive validations with the personnel :

- evolution of the properties over time
- global comfort.

Our strategy for the selection of casthouse clothing is built according to these two families (subsequently called family I and family II).

A STRATEGY AIMING AT CASTHOUSE WORKERS' PROTECTION

The fundamental principle of our strategy is that there is no universal solution. As a matter of fact, the selection of a fabric stems from the confrontation between the functions sought out for the protective equipment and the intrinsic properties of the fabrics (family I of the properties described hereabove) - Figure 19. This phase is guided by the analysis logic. The selected fabric must correspond to the best compromise in terms of properties, once the analysis of risk undertaken is considered. The choice is explained to the personnel whose attention is therefore drawn to this analysis process. To this effect, we have produced an educational video cassette about the main properties of fabrics (notably resistance to molten metal and inflammability).

We then proceed to a second phase, in collaboration with the personnel and using a step by step method. Here, the objective is to ensure that, for the clothing, the comfort and stability properties (family II) are indeed validated. This phase of dialogue is permanent and enables to progressively converge toward the highest performance individual protection clothes. Only one major element in this second phase is likely to question the selection of the fabric (first phase) : the fabric is actually selected to ensure the optimal protection against hazards ; it is, therefore very difficult to change.

For a given fabric, it is possible to modify the shape of the cloth, the conditions of wearing under working conditions or even to undertake technical modifications.

This strategy for the selection of the clothing fully complies with our global safety approach based on the analysis of elementary risks, personnel training and communication as described in a previous paper [1].

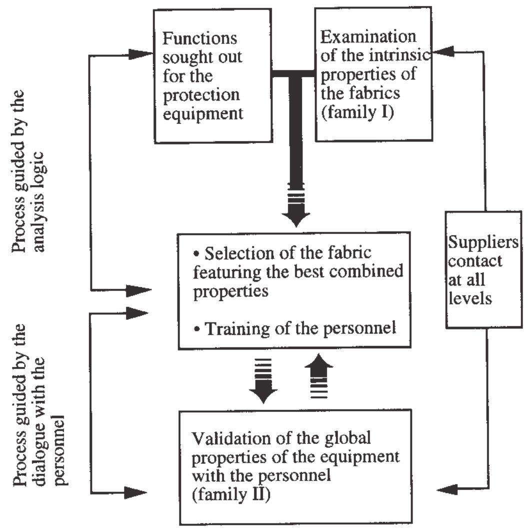

Figure 19 : Strategy for the selection of each worker's clothes.

To end with, a permanent dialogue with the supplier during each of these phases is necessary to converge faster toward the best equipment. Moreover, each of the parties has a precise role to assume in conformity with regulations in force. In Europe for example, the new E.C. provisions being worked out [34] require :

➥ **From the supplier :**
- to submit his protection equipment models to a notified laboratory which checks its compliance to the standards in force and delivers a certificate authorizing this equipment to bear the "CE" label,
- to guarantee the homogeneity of its manufacturing and its conformity over time.

➥ **From the employer :**
- to provide his personnel with suitable protection equipment subsequent to a prior risk analysis,
- to only use equipment bearing the "CE" label.

Our approach leans completely toward these guidelines and the dialogue with the supplier enables to ensure that there is indeed a match between the potential risks, the proposed equipment and the standardized tests that must be undertaken.

As a conclusion, this strategy will be illustrated with three examples :
- secondary clothing,
- primary clothing,
- casthouse gloves.

❶ Secondary clothing

In our experimental casthouse, this clothing is worn on a permanent basis, for all common operations. The two functions that must be ensured in priority for this clothing are :
- non sticking of the molten metal, in case of splash,
- uninflammability.

For commonly proposed fabrics, the following selection is obtained by successively narrowing down the choices (names in capitals correspond to the best performance data observed).

Non sticking of the liquid metal	WOOL	Pyrovicel®	untreated cotton
Uninflammability	WOOL	Pyrovicel®	
Fabrics meeting both criteria	WOOL	Pyrovicel®	
Fabric selected	WOOL		

Given the experimental aspect of our casthouse, the maximum protection, i.e. wool for secondary clothing, has been retained.
The second phase (validation of the clothing with the personnel under working conditions) has above all emphasized problems of comfort during the hot summer periods. Our current strategy is, nevertheless, to keep wool clothing during these periods and to try to reduce heat peaks at the source (ventilation of the workshop, shifting of working hours).

❷ Primary clothing

This clothing is used for any situation presenting a greater risk than the common activity described above, essentially in terms of molten metal splash or of radiative heat transfer : start of casting, ladle cleaning, setup of a filtration slab, alloying of a furnace for example. Therefore, the two functions which must be ensured for this clothing are therefore :
- resistance to high amounts of molten metal,
- protection against radiation.

This results in the following selection :

Resistance to high amounts of molten metal	ALUMINIZED FABRICS	LEATHER	VICOR
Protection against radiation	ALUMINIZED FABRICS		
Fabric meeting both criteria	ALUMINIZED FABRICS		
Fabric selected	ALUMINIZED FABRICS		

This analysis leads to generalizing the wearing of aluminized clothes inside the casthouse. Validation with personnel (second phase of the process) obviously underlines the lack of comfort of this clothing (very low permeability) when worn for too long.
The wearing of this clothing is thus limited in time and, in case it must be extended, we try to find a compromise : for example, start of a casting with an aluminized hood and an aluminized jacket and, later on, a cap with a polycarbonate face shield, with wool protection on the nape of the neck.

❸ Casthouse gloves

These gloves are used to grab objects which may be hot and feature different aspects of shape or surface. The functions which must be ensured for these gloves are :
- thermal insulation
- uninflammability
- mechanical resistance.

This results in the following selection :

Thermal insulation	WOOL	aramid fibers	cotton
Uninflammability	wool	ARAMID FIBERS	
Mechanical resistance		ARAMID FIBERS	cotton
Fabric meeting all three criteria		ARAMID FIBERS	
Fabric selected		ARAMID FIBERS	

This analysis has led to progressively adopt aramid fiber gloves (Kevlar®, Kermel®) with an inner wool lining to further reinforce their performance.
The validation with the personnel (phase 2 of the process) was organized easily, evolution being essentially located at the level of the fabric thickness, its inner lining etc...

PERSPECTIVES FOR PROGRESS AND SHARING OF EXPERIENCE

These examples and this study aim at showing that the choice of a protection clothing stems above all from a serious functional analysis and from a permanent good judgment. One should particularly be wary of fashion trends, reasoning shortcuts or universal solutions.

What must remain immutable is :

- the functional analysis of the protection equipment being sought for,
- the knowledge of the elementary properties of the fabrics,
- the matching between both of them.

What requires flexibility is :

- to take into account the human dimension of protective clothing.

This flexibility may thus result in different types of clothing from one plant to another, for reasons of comfort, of different acceptance from the personnel ... but the different choices must remain at a constant level of protection against risks.
As a matter of fact, this corresponds to the recommendations from the Aluminum Association on this topic [16, 33] : different adaptations for the primary and secondary clothing are possible, on the basis of the selected fabrics in terms of protection against molten metal splashes.

This study was meant to be an attempt towards structuring of the knowledge in the field of protective clothing.
We think that it would be useful to continue and improve this search through a sharing of experience in the field of what constitutes the foundations of our methodology :

- the **classification** of usual textiles fibers is done. New fibers could be studied,
- as for usual fabrics, the behaviour of new fabrics should be tested, according to their **reaction to molten metal splashes**,
- the determination of **fabrics intrinsic properties** is underway. The collection of data or new properties has to be achieved,
- the characterization of comfort through **clothing global properties** has to be developed,
- our attempt to build a **global strategy** for the protection of casthouse workers has to be compared to other strategies.

Finally, let us not forget that individual protection equipment by itself is not enough to improve safety performance.
Only a coherent and global approach based on the role and involvement of human beings in their workshop enables to reach this goal. This implies the involvement of each one, inside each plant of course, but also of the casthouse community considered as a whole.

"The thickness of a rampart is worth less than the will to defend it" - Thucydide

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