The Shielding of the ATLAS Forward Region from the point of view of Materials Technology and some Construction Aspects

J. Sodomka

Faculty of Transportation Sciences,
Czech Technical University, Prague, Czech Republic

C. Leroy

Department of Physics, University of Montreal, Montreal, Canada

J. Palla

Faculty of Transportation Sciences,
Czech Technical University, Prague, Czech Republic

S. Pospíšil, I. Štekl

Faculty of Nuclear Sciences and Physical Engineering,
Czech Technical University, Prague, Czech Republic

1. Introduction

The aim of this note is to discuss a concept and a construction of the ATLAS forward region shielding as a contribution to the chapter on shielding for the ATLAS infrastructure TDR. It follows our previous remarks on this question [1].

2. Some aspects of the shielding construction

From 1995, we have proposed a construction with different kinds of layers for the shielding. This was published later in [2], [3]. An example is shown in Fig. 1a : steel - cast iron - boron steel (optional) - borated polyethylene (BPE) - steel (optionaly boron steel) - lithium polyethylene (LiPE, optional).

- The inner part of the shield is made of high density steel. The hadronic cascade should be confined inside the shielding volume as much as possible.

- The second layer is made of cast iron which due to a higher content of carbon has higher moderating capabilities for neutrons compared to steel. That way, neutrons can be partly moderated and captured in the depth of the iron shield body itself via Fe(n,γ) reaction and smaller amount of energetic gamma rays will leak out of the shield [3].

- There is a boron steel layer as an option. It is the material used in nuclear reactor technology. Its aim is to increase the number of slow neutrons absorbed inside the iron layer via the reaction $^{10}B(n,\alpha)^7Li$ with subsequent emission of 478 keV gamma rays easily absorbed [2],[3].

- A borated polyethylene (BPE) layer will be the most important part of the shielding against fast neutrons ($E_n \leq 50$ MeV). This material moderates fast neutrons due to their elastic scattering on hydrogen nuclei and efficiently absorbs the slow neutrons due to $^{10}B(n,\alpha)^7Li$ [2],[3],[4].

- The outer layer of iron (optionaly boron steel). This layer should shield against 478 keV gamma rays produced in BPE in the $^{10}B(n,\alpha\gamma))$ reaction. Because this energy is significantly lower than 2.2 MeV gamma from radiative capture of neutrons by hydrogen, then the combination of BPE+iron layer should be sufficiently efficient compared to a PE+Pb combination as originally proposed and analyzed in previous reports [5],[6],[7].

- The last shielding layer would be optionaly made of lithium filled polyethylene (LiPE). The aim of this layer is also to protect the forward region shielding itself against neutrons coming from outside (neighbouring detectors, experimental hall) and in such a way to avoid production of energetic gamma rays in iron [2],[3],[4].

The thickness of these shielding layers would be determined using Monte Carlo simulations. The proposed segmented shielding with different layers does not require any outer layer of Pb contrary to earlier proposals [5],[6],[7]. The combination of layers of soft materials such as BPE and LiPE with hard materials such as iron will require spacers in between soft and hard materials to achieve rigidity of soft layers compressed by the support of the shielding and to achieve hermiticity against leaking neutrons. Similar expected shielding capabilities could be achieved with a single LiPE layer without Pb (Fig. 1b) but with overlap and mechanical support still to be solved. The polyethylene material would be directly injected in the armatures defined by the spacers and the iron layers [8].

It is desirable to change the conical shape of the layers shown in Fig. 1 into a cylindrical shape arrangement for higher stability of the shielding and its support, cost saving, and better assembly and disassembly [8]. Fig. 2 shows the cylindrical shape arrangement of layers (schematically).

The cylindrical arrangement of the shielding segments with lock system (example shown in Fig. 3) helps to ease the constraints imposed by the large weight of the segments. The shielding segments are expected to be extremely heavy (30-40 tons) and very large (4-5m^3). A suitable technology of production must be chosen as the result of a compromise between homogeneity and price of the shielding elements. Such a segmentation is necessary for assembly and rapid disassembly of the whole shielding. A lock system, longitudinal and radial, has to be designed to keep mechanical rigidity of the whole construction (mechanical aspect), and to suppress neutron leakage through overlapping of segments (physical aspect).

Fig. 3 shows an example of a possible cylindrical segmentation of inner layer (steel) with longitudinal and radial lock system for the shielding (schematically).

3. Materials technology

3.1 Steel

Steel is one of the most suitable materials for shielding against hadrons. It can be classified according

- the composition and structure,

- the manufacturing methods (melting by different procedures),

- the finishing methods, such as casting and heavy forming (rolling or forging).

A material with high density is needed for absorption of hadronic cascades. Plain carbon mild steel with the lowest amount of carbon is a suitable candidate. Higher the amount of carbon, lower the density of steel (an amount of carbon of 0.08-0.13 wt% corresponds to a steel density of 7.87-7.84 g/cm^3).

Beside carbon, other elements are present in steel. There are additive elements (Si, Mn) and harmful elements (P, S). The mild or low carbon steel is practically an alloy with 99.2 - 99.5 wt% of iron. The percentage amount of harmful elements is very small (0.03 wt%). Such elements are present in any mild low carbon steel. Steels, commonly used for casting, have the composition: C < 0.13, Mn 0.4, Si 0.2 (all in wt%). For forming, steels with $C_{max} = 0.13$ and Mn 0.5 wt% are used (e.g. AISI 1000) [9].

The structure of steel is ferritic with a small amount of pearlite where ferrite is mainly interstitial solid solution of carbon and pearlite is a mixture of two phase, ferrite and cementite. Cementite is a chemical compound Fe$_3$C [10]. The composition of this steel, ferrite (phase α) and cementite is clear from the Fe - C equilibrium diagrams (Figs. 4,5) [10].

Two finishing methods can be chosen for production of the steel shielding elements:

- Casting (foundry process). The foundry processes consist of making molds, preparing and melting the steel, pouring the metal into the molds and cleaning the casting.

- Heavy forming (forging and rolling) of ingots.

The choice among finishing methods depends on the demands on homogeneity and structure. The results of manufacturing (metallurgy) depends on the capabilities and technology available at the steelworks. Machining must be applied in both finishing methods to fit the exact dimensions of segments.

The structure of castings is not homogeneous with respect to grain size and due to macro and micro-segregation during the complicated solidification of steel [11]. A lot of material is lost during production of castings because of the risers (1/3 of weight of casting) provided in molds to feed molten metal into the main casting cavity to compensate for shrinkage. The lost (waste) material can be remelted again and re-used for another castings.

In heavy forming process an ingot of steel is formed into the desired shape by rolling or forging. Then, the casted ingot structure is destroyed by deformation and the structure is much more homogeneous than the structure after casting. The mechanical properties are better.

Low carbon mild steel belongs to the category of the cheapest steels. The mechanical properties are suitable for the elements of shielding. The tensile strength is in the range 280 - 330 MPa. Such a steel has a good value of percentage of elongation (A) and percentage reduction of area (Z). The exact composition must be discussed in details with producer of steels and with material technology experts.

3.2 Cast iron

A standard composition of cast iron is: C 2.5 - 4, Si 1 - 4, Mn 1, P 0.3 (in wt%). Optimal range of C is usually 3.4-3.8 wt% as it can be observed from Figs. 4,5. A cast iron with the highest content of C is desirable in the second layer. The exact composition has to be controlled by foundry metallurgist. This cast iron belongs to the group called grey cast iron (GCI) which is in essence made of three major elements (Fe-C-Si alloy). The production of GCI castings is the largest among all the iron castings and then is the cheapest. Shape of products, must be machined too, after solidification and cleaning.

The mechanical and physical properties of GCI are governed in part by the shape, size, amount and distribution of graphite and by the structure of the matrix which depends mainly on the amount of Si. The structure of GCI can be modified within a wide range with respect to the structure of the matrix which can be ferritic, ferritic-pearlitic and pearlitic and with respect to the shape and distribution of graphite in the matrix. A pearlitic matrix with very fine distribution of graphite flakes gives homogeneous distribution of carbon and suitable mechanical properties. The final structure of casting depends on the rate of cooling during solidification [11], too.

The Brinell hardness (HB) and tensile strength (Rm) associated with pearlite depend primarily on the spacing of the pearlitic lamella. Higher values are found in pearlite with fine interlamellar spacing which is associated with a more rapid cooling rate during solidification of GCI or alloying [11]. It is necessary to note that perlite structure is difficult to obtain in whole volume of very large casting.

A most suitable kind of cast iron with respect to mechanical properties can be the so-called ductile iron (DI) which is pratically modified GCI. Unlike common GCI, which contains flakes of graphite, DI has in-as cast structure containing graphite particles in the form of small rounded spheroidal nodules in a ductile metallic matrix. Therefore, DI has much higher strength and toughness than common GCI [11].

The design of the segments and requested tolerances in dimensions will have strong influence on the cost of the whole shielding as they will determine the price of the casting. The casting designer should indicate which mechanical properties are required in each section of a casting and which sections are critical, as well. The foundryman can then select the GCI or DI composition that will develop the desired mechanical properties after solidification.

3.3 Boron steel

Boron steel is a new steel specially developed for nuclear industry. The amount of boron in such steel can be from 1 to 2 wt%. The processing of this steel is relatively complicated due to the presence of brittle borides. Still, such a steel is in development [12] and price is not yet fixed on the market. The equilibrium of phases in Fe-B system can be found in Fig. 6 [11].

3.4 Polyethylene materials

Polyethylene (PE) is produced in four principle grades:

- high density (HDPE)

- low density (LDPE)

- linear low density (LLDPE)

- ultrahigh molecular weight (UHMWPE)

Structuraly, these grades differ in the degree and type of branching on the main chain and in overall molecular weight (MW). A particular MW branching leads to a decrease of the PE melting temperature (T_m). Therefore, UHMWPE with almost perfect chains displays the highest T_m which decreases progressively from HDPE to LLDPE to LDPE. The different types of PE melting temperatures are ranging from 160° to 100° [13].

3.4.1 High density polyethylene

HDPE represents the largest volume plastic currently used. It can be recommended as a grade for the last layer of the shielding. The polymer shape is linear in nature and creates the high density (from 0.941 to 0.965 g/cm^3) inherent to polymer. The homopolymer grades have no side branches if their density is in the range from 0.960 to 0.965 g/cm^3. The physical properties of HDPE are affected by the weight-average molecular weight ($\bar{MW}$) of the polymer. As the MW increases, the mechanical properties also improve significantly, but the polymer becomes more difficult to process. Conventional HDPE has a MW in the range 3 to $5{\times}10^5$. PE with densities in the range of 0.930 to 0.945 g/cm^3 are not normally made directly but can be produced by blending high and low density components. Typical properties of PE are reported in Table 1 [14]. Chemical resistance and environmental properties of low and high density PE are reported in Table 2 [14].

3.4.2 Additives

PE has a fairly high tolerance level for additives. It can accept a variety of performance-modifying products up to a level from 6 to 8 wt% without affecting significantly its physical properties. Materials commonly used as neutron shielding [2],[3],[4] are summarized in Table 3. Table 4 introduces some suitable additives for the shielding based on boron and lithium chemical compounds [15], [16].

3.5 Another possible material for neutron shielding

Aluminium-lithium (Al-Li) alloys were developed primarily for aircraft and aerospace industry in the mid-1950 and focused work on this technology began in 1980. Due to its lithium content, Al-Li should be eventually considered as shielding material for the last layer. Table 5 lists the composition ranges of nominal I/M and P/M Al-Li alloys in development. Al-Li alloys are considerably more expensive than the current commercially used Al-alloys. Lithium additions to aluminium (up to 4%) decrease the alloy density and increase the elastic modulus. The tensile properties are dependent on the grade and heat treatment. Yield strength varies from 280 to 585 MPa and ultimate strength from 460 to 612 MPa. Al-Li alloys have been successfully used in large welded tubular structures and other compression loaded structures [17].

4. Concluding remark

The choice of the materials of the shielding layers and their thicknesses should be optimized by Monte-Carlo simulations. Efficiency of the shielding, technological aspects and price of the shielding materials should be taken into account for the final design. The presence of elements, even in minor amount, in the shielding materials, especially iron materials, has to be checked with respect possible long term induced activation.

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Property	ASTM Test	Units	Low-density polyethylene (LDPE)	High-density polyethylene (HDPE)	HDPE 30% glass fibre
Mechanical					
Tensile yield strength	D638	MN/m^2	0.4-16	21-38	70
Flexular strength	D790	MN/m2	-	35-50	80
Elongation at break	-	%	90-650	600-1500	2-3
Modulus of Elasticity in Tension	D638	MN/m^2	120-240	420-1400	-
Flexular elastic modulus	D790	MN/m^2	55-410	690-1800	6300
Impact strength	D638(IZOD)	J/cm of notch	No break	0.6-No break	0.55
Hardness	D785	Shore	D41-50	D60-70	R85[a]
Physical					
Specific gravity	D792	-	0.918-0.940	0.950-0.965	1.17
Thermal conductivity	-	W/m per K	0.33	0.46-0.52	0.37
Thermal expansion	D696	10^{-6}K^{-1}	100-200	110-130	50
Electrical					
Volume resistivity	D257	ohm-m	$1.2\times10^{13}\rightarrow10^{14}$	$>10^{14}$	-
Dielectric strength	D149	10^2kV/m	180-400	180-200	-
Dielectric constant 60 Hz	D150	-	2.25-2.35	2.30-2.35	-
10^6Hz	D150	-	2.25-2.35	2.30-2.35	-
Power factor 60 Hz	D150	-	<0.0005	<0.0005	-
10^6 Hz	D150	-	<0.0005-0.0009	<0.0005	-
Arc resistance	D495	s	135-160	-	-
Thermal/ Environmental					
Max. continuous service temperature (no load)	-	^{o}C	85-100	120-130	-
Deflection temperature 0.45 MN/m^2	D648	^{o}C	38-50	60-95	132
1.81 MN/m^2	D648	^{o}C	32-40	43-55	127
Water absorption	D570	%	<0.01-0.03	<0.01	0.2
Processing					
Mould shrinkage	-	%	1.5-5	2-5	0.3-0.4

[a] Rockwell.

Table 1: Typical properties of PE [14].

Environment	Effect
General	The lower the melt index the better the resistance to chemical and solvent attack and to environmental stress-cracking. HDPE is generally superior to LDPE. Polyethylene copolymers are in general more susceptible to solvent and chemical attack but considerably more resistant to environmental stress-cracking than homopolymers of the same melt index.
Acids and alkalis	Resistant to most acids and alkalis. Attacked by highly oxidising acids such as concentrated nitric, glacial acetic, fuming sulphuric and hydrogen peroxide (above 20^oC).
Solvents	Insoluble in most organic solvents below 60^oC but some absorption, softening or embrittlement may occur in alcohol, esters, amines and phenols. Above 70^oC dissolves in benzene, xylene, toluene, amyl acetate, trichlorethylene, paraffin and turpentine, but not in glycerine, ether, carbon disulphide, acetone or linseed oil. LDPE is relatively poor in aromatic and chlorinated hydrocarbons.
Oils and greases	Mineral oils and petrol cause marked swelling but effect of animal and vegetable oils is much less.
Other media	Attacked by liquid and gaseous halogens, although satisfactory life may be achieved at room temperature in presence of gaseous chlorine and fluorine.
Foodstuffs	Inert-can be used in contact with foodstuffs.
Weathering and UV light exposure	Degradation occurs through photo-oxidation-can be prevented by adding 2% of carbon black.
Heat	Oxidises when heated in air to above 60^oC, hence processing time should be as short as possible. Anti-oxidants are normally added ($\sim 0.1\%$) to reduce oxidation during processing.
Water	Low absorption-equilibrum at 20^oC HDPE 0.01% LDPE 0.15%
Environment stress-cracking	Very susceptible especially when in contact with polar compounds, surface active agents (e.g. detergents) and silicone compounds. Increased by increasing molecular weight (decreasing melt index) and increasing density. Decreased by decreasing stress (eliminated below threshold level) by decreasing moulding stresses (frozen-in-stains).
Flammability	2.5 cm/min

Table 2: Chemical resistance and environmental properties of low and high density PE [14].

Material	Density [g/cm³]	Elemental composition [wt%]					
		H	Li	B	C	O	F
pure polyethylene (PE)	0.93	0.144	-	-	0.856	-	-
borated polyethylene (BPE=PE+H₃BO₃)	0.99	0.127	-	0.03	0.710	0.133	-
polyethylene with Li (LiPE-1=PE+Li₂CO₃)	1.3	0.067	0.10	-	0.487	0.346	-
polyethylene with Li (LiPE-2=PE+LiF)	1.15	0.090	0.10	-	0.536	-	0.274

Table 3: Materials commonly used for neutron shielding.

Chemical compounds	H_3BO_3	LiF	LiH	Li_2CO_3	LiCl
Characteristics					
Melting point	185	845	680	618	605
State	crystal powder	powder	crystal	powder	powder
Grade of toxicity for pure compound [15]	2-3	3	3	3	3
Flammability for pure compounds [15] [16]	no	no	flammable gas when heated	no	no
Used in industry (bricks for shielding of neutron radiation)	yes	not yet	not yet	yes	not yet

Table 4: Properties of some additives for the neutron shielding based on boron and lithium chemical compounds [15,16].

Alloy	Type	Composition [%]								Alloy density [g/cm^3]
		Si	Cu	Mn	Mg	Cr	Li	Zr	Other	
2090	I/M	0.10	2.4-3.0	0.05	0.25 max.	0.05	1.9-2.6	0.08-0.15	0.12Fe 0.10Zn 0.15Ti	2.57
2091	I/M	0.20	1.8-2.5	0.10	1.1-1.9	0.10	1.7-2.3	0.04-0.16	0.30Fe 0.25Zn 0.10Ti	2.57
8090	I/M	0.20	1.0-1.6	0.10	0.6-1.3	0.10	2.2-2.7	0.04-0.16	0.30Fe 0.25Zn 0.10Ti	2.53
643	P/M	-	0.8-1.1	-	0.4-0.6	-	3.4-3.6	0.4-0.6	-	2.47
644	P/M	-	0.8-1.1	-	0.4-0.6	-	3.0-3.2	0.4-0.6	-	2.49
IN905XL	P/M	-	-	-	4.0	-	1.5	-	0.8O 1.1C	2.57
2020	I/M	-	4.5	0.5	0.5	-	1.1	-	0.2Cd	2.71

Table 5: Composition ranges of nominal (I/M) and in development (P/M) Al-Li alloys [17].
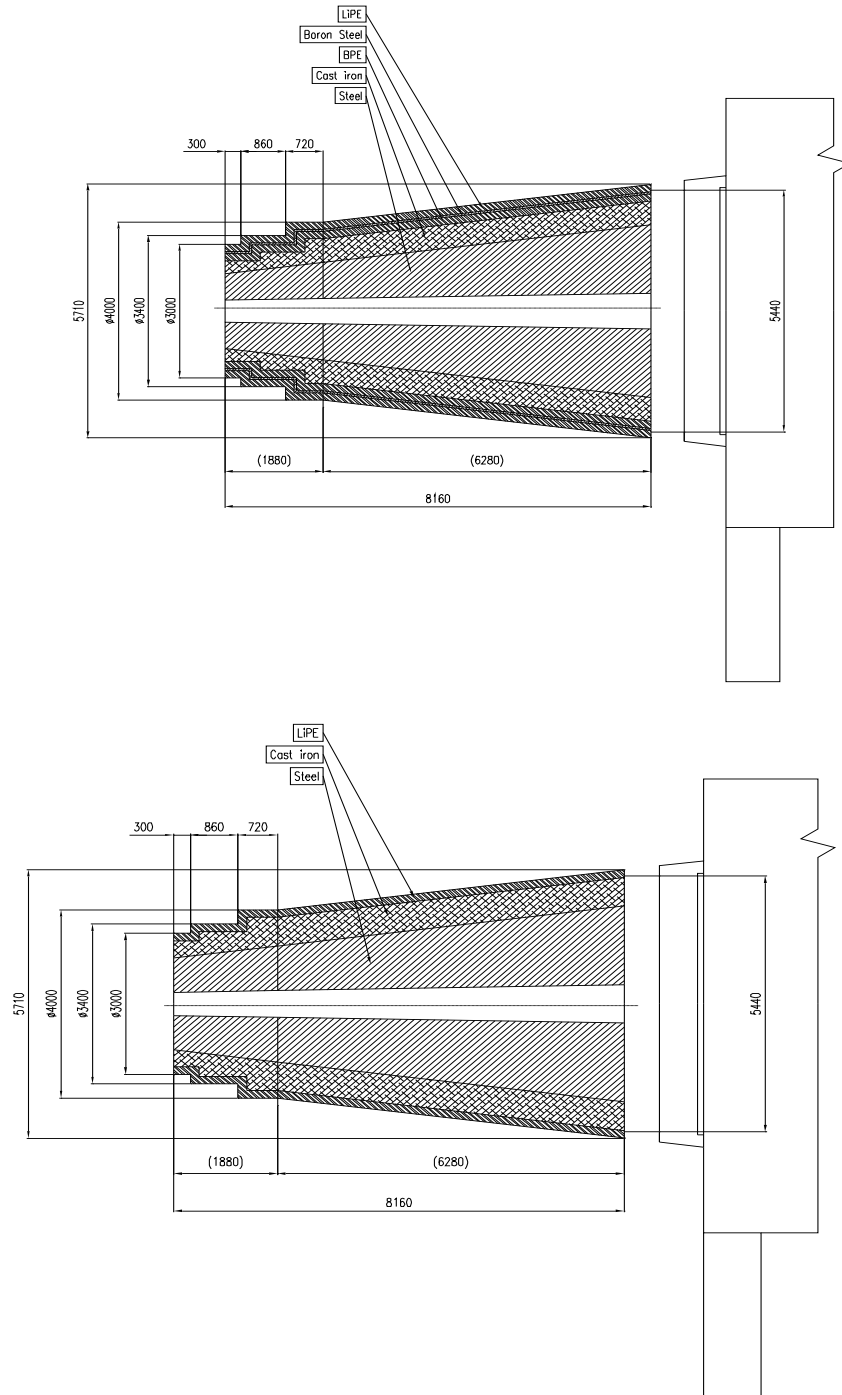
Figure 1: Examples of segmented shielding with a conical shape arrangement : a) steel - cast iron - boron steel (optional) - borated polyethylene (BPE) - steel (optionaly boron steel) - lithium polyethylene (LiPE, optional); b) steel - cast iron - LiPE (without Pb).
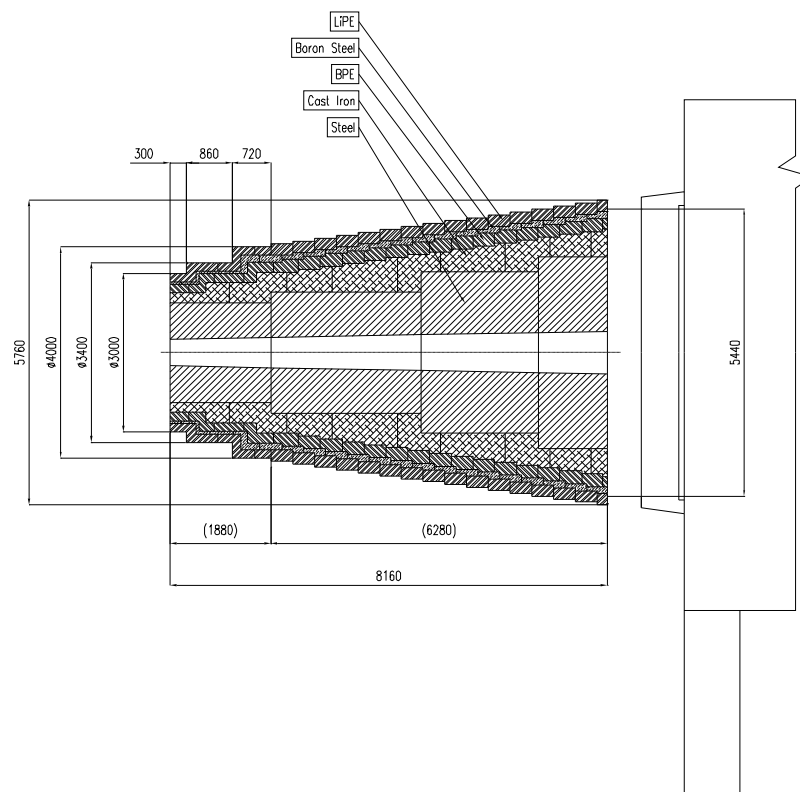
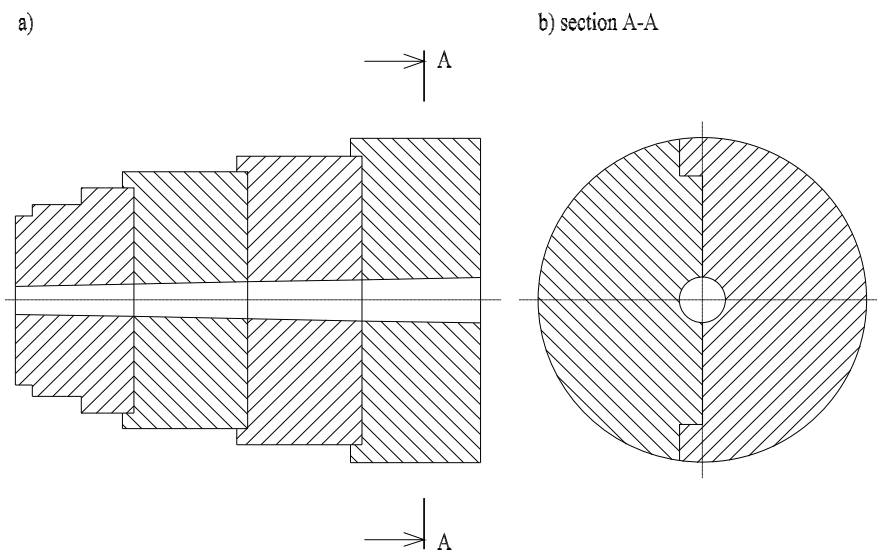Figure 2: Segmented shielding with a cylindrical shape arrangement.

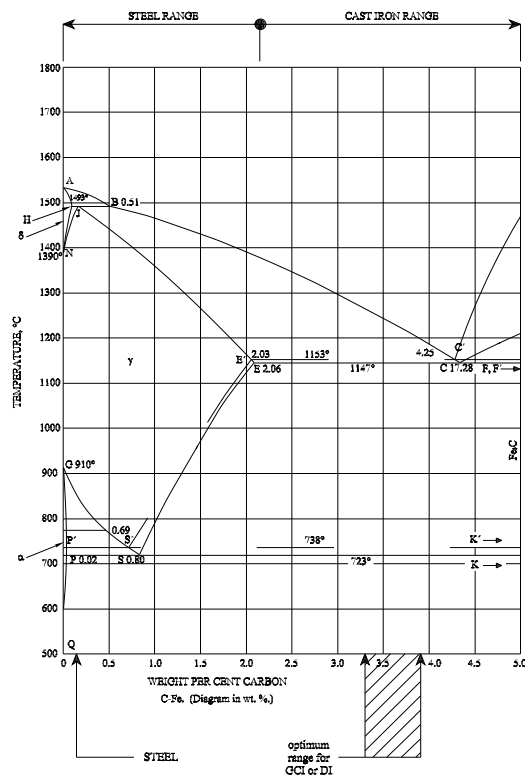Figure 3: Example of a possible cylindrical segmentation of inner layer (steel) with longitudinal (a) and radial (b) lock system for the shielding (schematically).

Figure 4: Fe-C phase equilibrium diagram (in wt%). Full line describes metastable Fe-iron carbide system. Dashed line describes stable Fe-C system.
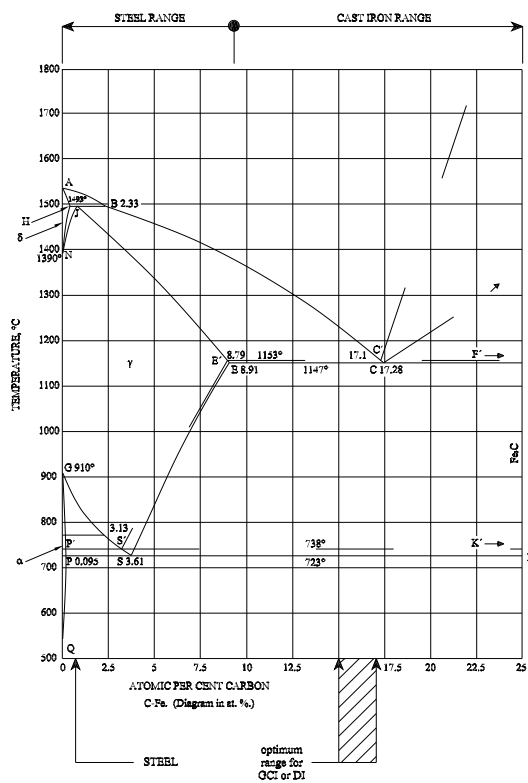
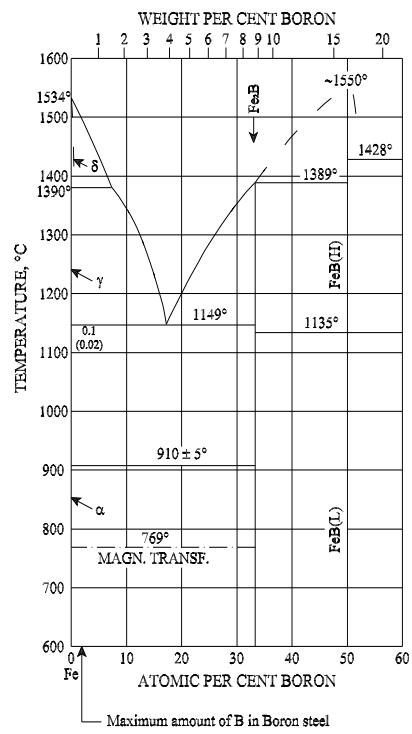Figure 5: Fe-C phase equilibrium diagram (in at%). Full line describes metastable Fe-iron carbide system. Dashed line describes stable Fe-C system.

Figure 6: Fe-B phase equilibrium diagram.