EPRI

DEVELOPMENT OF A SUPERCONDUCTING TRANSMISSION CABLE SYSTEM

....

Research Project RP7911-24

Final Report, December 1992

Prepared by

PIRELLI CABLE CORPORATION
RD&E Center
710 Industrial Drive
Lexington, South Carolina 29082

Principal Investigators
P. Metra

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
D. Von Dollen

Superconductivity Electrical
Systems Divisions

ABSTRACT

The objectives of this project were to select a feasible design for a High Temperature Superconducting cable for retrofitting existing pipes, to develop the selected design for constructional data and estimated performances and to determine guidelines for cooling system and for accessories.

A cable design based on a liquid nitrogen operated conductor, flexible cryostat and conventional room temperature PPP fluid filled insulation has been selected and detailed for a 115 kV-400 MVA three phase circuit, while a cryogenic dielectric solution has been anticipated to have the potential for 800 MVA or more.

This design of the room temperature cable resulted in a feasible solution, with respect to the issues related to materials, technologies, manufacturability, installation and operation, with a rating double than for conventional cables, and quite comparable losses.

The outline of the cooling system, the operating principles and the requirements for the components have been defined for typical 1 km sections of the 115 kV-400 MVA circuit.

Guidelines for the design of termination and joint have been defined for the same system.

CONTENTS

FIGURES

TABLES

Section 1

INTRODUCTION

The ability of superconducting cables to carry higher current than conventional cables and their potential for lower transmission losses has been taken into active consideration since many years, and superconducting cables based on liquid Helium technology have been successfully experimented and developed to some extent [1].

These cables have never been commercially exploited, essentially as a consequence of their economics and of a lower than expected need for very high ratings, while high field magnet application of the same materials has successfully grown.

The discovery of High Temperature Superconductors and the progress in the associated technologies to manufacture usable wires has made again attractive the use of superconducting cables, based on liquid nitrogen technology.

As a consequence of many studies, carried out in the U.S. and all over the world [2],[3],[4], the attention has been focused on a particular type of application, which seems to be practicable for its development towards a practical target, with a relatively limited effort.

This envisaged application is the retrofitting of existing pipes of pipe-type cable transmission systems, with the aim of increasing the transmission capability, of limiting the transmission losses and of developing a technology for a new class of more efficient, high-performance transmission cables [2].

The design study which is the content of this report is intended to be the first step of a complete program for the development of a HTS superconducting cable, to end with the complete qualification of a prototype system.

Section 2

BACKGROUND AND OBJECTIVES

The background of this design study is given by two parallel lines.

A preliminary study for design and application of superconducting cables based on HTS materials has been carried out by EPRI in the recent years, which has produced several proposals for cable concepts and for application opportunities [2],[3].

A development program for HTS elementary conductors has been jointly carried out by Pirelli Cable and by American Superconductor Corporation during the past three years, which has produced the availability of HTS tapes having lengths and performances in the range requested for cable application [5],[6].

The objective of this design study of a superconducting transmission cable for retrofitting existing pipes in pipe-type cable systems is to develop a practical design specification for such cable and in particular for its main components (HTS conductor, flexible cryostat, electrical insulation).

In addition also the other fundamental components of the system (cooling and accessories) are considered at a preliminary level.

The design study is intended to take into consideration the aspects related to materials, technologies, manufacturability, installation and performances.

Economic aspects, although not explicitly considered, being outside of the scope of this design study, are indirectly involved to some extent in both preliminary studies [2],[3] and in design and performance considerations.

Section 3

ANALYSIS OF PREVIOUS EPRI PRELIMINARY DESIGN STUDIES

3.1 Generalities

3.1.1 EPRI preliminary Design Studies

A preliminary approach to the design of HTSC cable systems for power transmission has been developed under the STI EPRI Project RP7911-10, to end in a "Technology Base Document".

The activity described in the present report has been largely based on the outcome of this previous study, and in particular on the following sections, which have been made available in substantial details before or during the present contract:

Chapter 1	Introduction to HTSC Materials
" 3	Cable Design
" 5	Cryogenic System

Additional inputs from the previous EPRI activity on this subject have been:

- documentation produced by USI for several presentations to technical audiences (EPRI,DOE,DARPA meetings);
- information collected by USI from several utilities (Baltimore,PEPCO,PG&E, Commonwelth Edison) on projected needs and opportunities for application;
- information organized in the USI/EPRI paper presented at the 1991 Annual Conference on Superconductivity.

The above activities had already identified a range of possible design concepts for HTSC power transmission cables as well as the corresponding peculiar characteristics, some envisageable applications in the electric system, both in the near and in the long term and the critical issues to be investigated and developed to proceed towards a practical solution.

Whenever necessary, the available information has been implemented with existing background from literature, with common practice in cable technology and with additional analysis and calculations, in order to assess different cable concepts in the light of their effectiveness in terms of materials, manufacturability, handling, operation and performances.

3.1.2 Main inputs to the design

From the preliminary design studies, the following conclusions had been obtained, as outlined in Sections 1,2 and 3 of [3]:

- the design and the development of a completely new cable concept, optimized for the best use of HTSC would require a very extensive amount of work and of time, although promising a more attractive level of both performances and costs. In this perspective the development of a simpler retrofit solution, having actual advantages for use would be the most effective approach as the first step for practical applications;

- a fully flexible cable structure would be required to comply with the retrofit application and, more widely, with installation in pipes;

- d.c. cables, easier to be designed and to be operated at a lower level of losses and at a higher rating, would be difficult to be integrated in the present power systems, particularly in the light of retrofitting;

- the alternative between a room temperature dielectric and a cryogenic dielectric should be carefully analyzed, due to an apparent balance of the amount of required development and the possible benefits for the two alternatives.

More detailed indications on preferable design concepts have been outlined in Section 2 of [3] and in several presentations from 1989 to 1991 [7],[8],[9],[10],[11] and synthetically described in [2].

The following structures have been suggested in particular:

- three phase warm insulation (WI), with single conductor enclosed in a cryostat and room temperature dielectric for each phase (# 1 of [8]);

- coaxial cryogenic insulation (CI), with coaxial high voltage and return conductors and low temperature dielectric for each phase with overall cryostat (# 5 of [8]);

- three phase cryogenic insulation, with single conductor and low temperature dielectric for each phase with overall cryostat (# 3 of [8]).

In addition preliminary calculation of losses had been performed to assess typical levels of:

- a.c. losses (resistive,hysteretic,eddy);

- dielectric losses;

- thermal losses;

- pumping losses;

- cooling losses;

and to estimate rating and costs [9],[11],[2].

Different types of HTSC elementary conductors, such as wires, tapes, flat and corrugated layers had also been discussed for use in assembled conductors [7], as well as different structures for the conductor assembly, in terms of cooling channel, support, sealing, cryostat, thermal insulation [10].

3.1.3 Guidelines for the present design study

Since it has been evident from the beginning that an application intended for retrofitting saturated pipes in the existing pipe-type cable system would have a good chance of being used, while being relatively easy to be developed, the focus of the present program has been be concentrated on this type of application.

This decision had been taken in spite of the evidence of a significantly better performance to be expected from an optimized new installation, which on the other side would demand a quite substantial development work.

Therefore the guidelines for this design study have been defined as follows:

- to focus on the retrofit application;
- to look for a high power rating, at a convenient level of losses;
- to make the widest possible use of available technologies and to reduce to a minimum the need for new developments;
- to ensure an industrial feasibility and manufacturability for the application;

The most critical developments required have been anticipated to be:

- the development of the HTSC conductor (completely new development);
- the development of the flexible cryostat (extension of technologies in use for cable sheathing and for flexible transfer lines of cryogens);
- the development of the accessories (extension of technologies in use with substantial new development);
- the development of the electrical insulation (new technology for CI and extension of a consolidated cable technology for WI);
- the development of the cooling system (extension of technologies in use);
- the development of installation, operation, maintenance and repair techniques (extension of technologies in use with more or less substantial new developments as required by the new components).

The specific issues which have been analyzed for the preliminary cable and system design are:

- definition of the system operating requirements;
- identification and definition of the basic design parameters;
- comparative evaluation of different retrofit solutions;
- selection of the most attractive design;

3.2 System Requirements

The basic system requirements for the cable and the system to be designed have been analyzed and discussed in order to identify the range of feasibility of the different solutions for the cable and to focus the final design on the most practicable and attractive type of application.

The main factors which have been considered are voltage class, current rating, installation length and topology.

3.2.1 System Voltage

Three widely used voltage classes have been studied for possible retrofit solutions, namely 69, 115 and 230 kV.

Lower voltages have been neglected due to the very unlikely advantages and economies to be expected, while higher voltages have been considered not to be relevant to the case for retrofitting with a new type of cable. For the reason of compatibility with the existing system also voltages different from the normalized classes in use have not been considered.

3.2.2 Current rating

Starting from the present level of current rating, typically in the range of 1000 A for HPFF cables with natural cooling, and in consideration of the possible increase up to 1500 to 2000 A by means of force cooling and of larger conductors for the same type of cables [3], the minimum target for HTSC cables has been set at 2000 A, with additional exploration of the upper limit achievable with the most efficient design concepts.

3.2.3 Installation

After a first consideration of different sizes of pipe [3], the design has been concentrated on the most common 8" size and on magnetic pipes, as representative of the most commonly existing installations; the section lengths have been set at a minimum target of 1000 m.

3.3 Operating Parameters

The operating parameters for the design of the cable represent the degree of utilisation of the materials used for carrying the current, for withstanding the voltage and temperature differences and the mechanical loads.

3.3.1 Electrical Stress

The selection of the appropriate level of electrical stress is decided by the adopted design concept and by the type of insulation to be used.

In the case of <u>warm electrical insulation</u> a quite conventional type of dielectric can be applied.
As it will be made clear in the following paragraph 3.4.5, one of the most demanding issues in the cable design for retrofit is to save any possible space in the radial direction, in order to accommodate at the best the thermal insulation, which is the additional element with respect to conventional cables.
The consequence is that highly stressed fully developed dielectrics are the dictated solution: either gas filled or fluid filled Kraft paper and PPP have been considered for use, while extruded dielectrics have been left aside due to their considerably higher standard specified thickness, as shown by **Table 3-1** ,[12],[13],[14].

In particular the thicknesses specified by AEIC standards [12] for conventional paper and for PPP have been assumed for the design; in addition also an enhanced stress level has been used for PPP, based on the limit stress levels recommended for the considered voltage classes from [3] and proved to be feasible by extensive testing to optimize the use of the PPP dielectric for higher voltage classes [15].
In the latter case the insulation thickness has been calculated for a fixed allowed level of stress at both inner and outer screen of the insulation, in order to optimize the space used for the dielectric.
An appreciation of the minimum level of a.c. and B.I.L. stresses necessary to accommodate the dielectric inside a given diameter for the voltage classes in the range from 69 to 345 kV is given in **Fig. 3-1,3-2.**
The adopted design parameters for electrical stress of the warm dielectric are listed in Table 3-1 for the case of fluid filled cables.
Extension to gas filled insulation would be feasible as a minor modification as a more recent development [3].

In the case of the <u>cryogenic dielectric</u>, a new situation would occur for the use of existing dielectrics in quite different conditions.
On the basis of the available data [3],[4],[16], the candidate materials have been identified to be:

- LN impregnated lapped insulation, made either of Kraft paper, PPP, or entirely plastic tapes (polyethylene or polypropylene);

- extruded insulation (PE or XLPE).

In the first group PPP appears to be the most reliable solution, while an excessive level of losses might be expected for cellulose paper and possible difficulties to obtain a fully reliable impregnation might occur for purely plastic tapes.

Table 3-1

Minimum specified insulation thickness (mils/mm) for different dielectrics of H.V. cables

	69 kV	115 kV	138 kV	230 kV
HPFF paper stand.	-	375/9.53	440/11.18	605/15.37
[12] PPP stand.	-	250/6.35	270/ 6.86	450/11.43
XLPE [13]	650/16.51	800/20.32	850/21.59	-
PE [14]	512/13	670/17 (90 kV)	-	866/22

HPFF PPP/S (PPP designed for allowed stresses) [3]

conductor shield : ≤ 84 kV/mm B.I.L.
≤ 15 " a.c.
insulation shield ≤ 70 " B.I.L.

Table 3-2

Insulation thicknesses adopted for the preliminary design of cryogenic dielectrics and design data for Liquid Nitrogen-impregnated PPP as cryogenic dielectric

DESIGN PARAMETERS FOR THE CRYOGENIC DIELECTRIC (LN IMPREGNATED PPP) AT 65 TO 90 K	
- BIL conductor stress	110 kV/mm
- BIL insulation shield stress	75 kV/mm
- a.c. operating stress	15 kV/mm (rms)
- ϵ x tgδ	2.2 x 8 10^{-4}

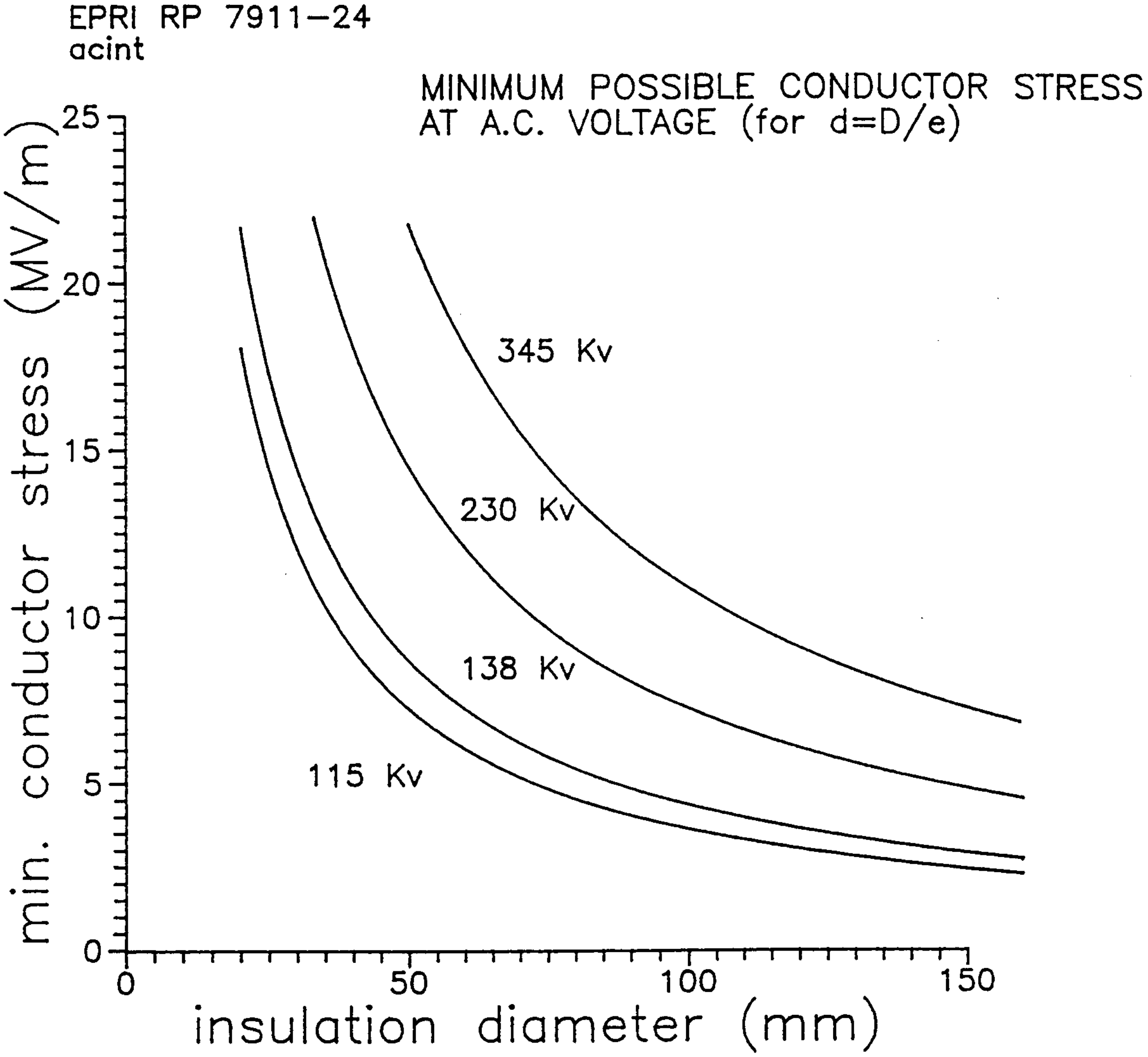


Fig. 3-1

Calculation of the minimum a.c. conductor stress which is geometrically allowed by the external diameter of the dielectric, for voltage classes in the range 69 to 345 kV.

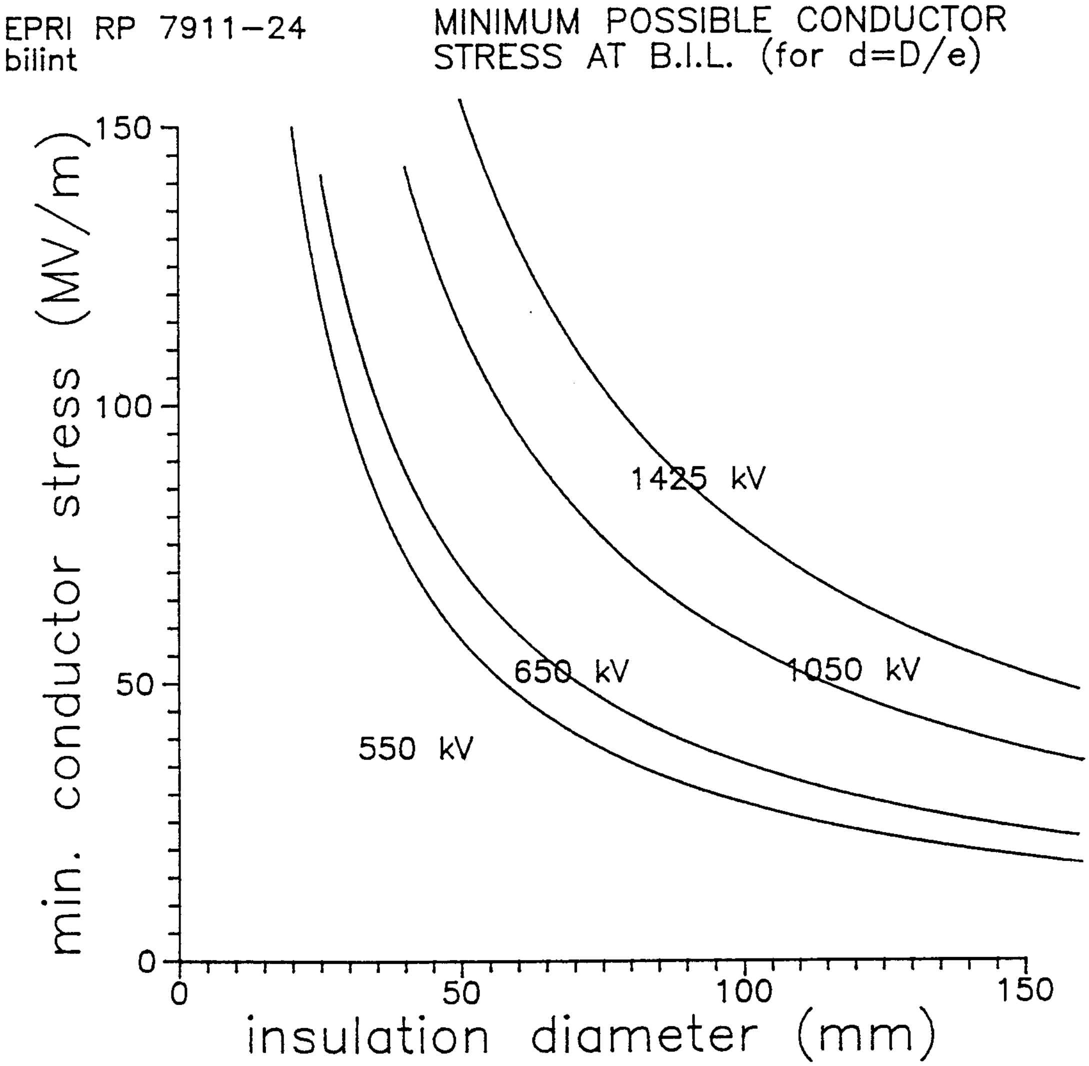


Fig. 3-2

Calculation of the minimum conductor stress at B.I.L. voltage, which is geometrically allowed by the external diameter of the dielectric, for voltage classes in the range 69 to 345 kV.

In the case of extruded insulation, although it has been proved that the material may provide quite satisfactory electrical and mechanical characteristics at low temperature [17], a quite extensive development is deemed to be necessary in order to obtain a cable structure free of limitations arising from the thermomechanical stresses induced by the extrusion and cooling history of thick and long volumes of extruded insulation [18].

As the first approach to design a cryogenic dielectric cable and to evaluate its performances, mainly the PPP solution has been considered, based on design stresses and loss parameters reported in **Table 3-2.**

In addition also the same standard thickness used for Kraft paper and for PPP at room temperature have been used for preliminary exploration of CI solution design.
It is understood that some preliminary study of the cryogenic dielectric should be necessary to be performed to assess the feasibility of the above solutions, to define their design parameters and to develop suitable manufacturing technologies for the selected solution(s).
This activity should involve both the evaluation of the electrical and mechanical properties of the materials at LN temperature and the investigation of the manufacturing related performances and of the characteristics of the full size cable structure.

3.3.2 Current Density

The current density, which may be expressed in terms of either average current density in the cross section of the superconductor (A/m^2) or surface current density (A/m or mT) represents the degree of utilization of the superconducting material with respect to its current carrying capability [19].

In principle this fundamental design parameter should be selected according to the performances of the superconductor, in order to optimize the compromise between the size of the conductor and the level of losses.
This conceptual approach would require a sufficiently deep knowledge (both theoretical and experimental) of the superconductor behaviour with respect to a.c. losses and current capability of complex structures, which is not yet understood to the extent necessary to design an optimized conductor.

In fact for the simplest case of bulk monofilament structures of superconductor it has been verified that the conventional interpretation of a.c. losses as hysteretic and depending on the surface magnetic field level is in good agreement with the experimental data [20],[21]; the amount of eddy losses in silver sheaths of such wires can also be calculated with well reliable methods for such simple geometries [22],[23].
However several important factors cannot be at present estimated by reasonable calculations, due either to the lack of knowledge on the characteristics of HTSC materials and to the geometrical situation, which prevents the use of fully reliable models even in the case of LTSC conductors [24].

These factors have been identified as:

- the low level of the lower critical field, below the operating field for a.c. cables;
- the presence of a substantial transversal field, at least in the case of the three phase, non coaxial configuration;
- the use, practically dictated by the need for sufficient mechanical performances, of multifilamentary structures for the elementary wires of the conductor;
- the use, for reason of flexibility, of multilayer stranded structures for the assembling of wires into conductors.

All the above factors should be clarified from the theoretical and experimental side in order to design a fully optimized and highly efficient cable.

For the present study of the retrofit solution the approach has been simplified on the basis of the highly dominant importance of the conductor size in the overall design of the cable and of the system.
In fact, as it will be clarified in Section 3.4, the main constraint for this design is to accommodate inside a given cable diameter the required thermal and electrical insulations, so that a maximum available diameter is left in practice for the conductor (leading to a subsequent surface current density); the amount of superconducting elementary wires must then be a compromise between the acceptable bulk current density (with the associated losses) and the size of the internal channel to be left to ensure the circulation of the coolant.

This procedure has been in fact used to define the operating surface current density H and the active cross section of superconductor, based on the extrapolation of the available data on current capability and a.c. losses level of HTSC tapes.

3.3.3 Short Circuit

An acceptable level of short circuit current is a basic requirement for the use of a HTSC cable in an existing system.

For the preliminary design this performance has not been calculated, but it has been assumed as being verified a priori.

In the following stage of detailed design the thermal short circuit capability has been verified in terms of both full stabilization and adiabatic stabilisation [19], and the corresponding levels in per unit of the nominal current have been estimated.
This performance was found to be adjustable to a substantial extent, if required, by means of suitable selection of the characteristics of the elementary wires and of the conductor structure.

Valuable information to this purpose would be obtained from the knowledge of a.c. losses dependence from current and temperature on one side and from the full characterization of conductor prototypes under overcurrent and short circuit conditions.

As for the dynamic performance under short circuit, calculation of the mechanical stresses on the conductor and on the elementary wires has been performed during the finalization stage.

3.3.4 Thermal Losses

The need for a limited level of losses, in the range of 1 W/m dictates the use of highly efficient thermal insulations; at present only superinsulation in vacuum can comply with these requirements.

From the wide range of data available [3],[25] a reference performance of this type of thermal insulation has been defined (**Fig. 3-3 and 3-4**) and used for the thermal design of the cable.

The assumption has been made that these performances, currently being obtained on rigid, concentrated structures and on short flexible elements can be reliably reproduced on very long flexible structures, as required for cables.

The confirmation of the actual thermal performance and of the overall reliability of the cryostat based on this technology will require the experimental evaluation of the manufacturing procedures and of the behaviour of suitable cryostat samples.

The thermal insulation being so critical for the effectiveness of the cable, it would be also highly advisable to explore any further possible improvement, with respect to both thermal efficiency and reliability for manufacturing and for operation.

3.3.5 Mechanical Requirements

The cable for retrofit application must be transportable, flexible and suitable for pulling into the pipe at the same (or very similar level) as conventional cables.

In particular for the preliminary design a flexible construction suitable for bending over around 20 times the core diameter for transportation has been devised, on the basis of the current cable practice [3].

The cable weight and the length for transportation and for installation, with their implications on pulling forces and on lateral pressure, have been taken into consideration for verification only at the stage of the design finalization.

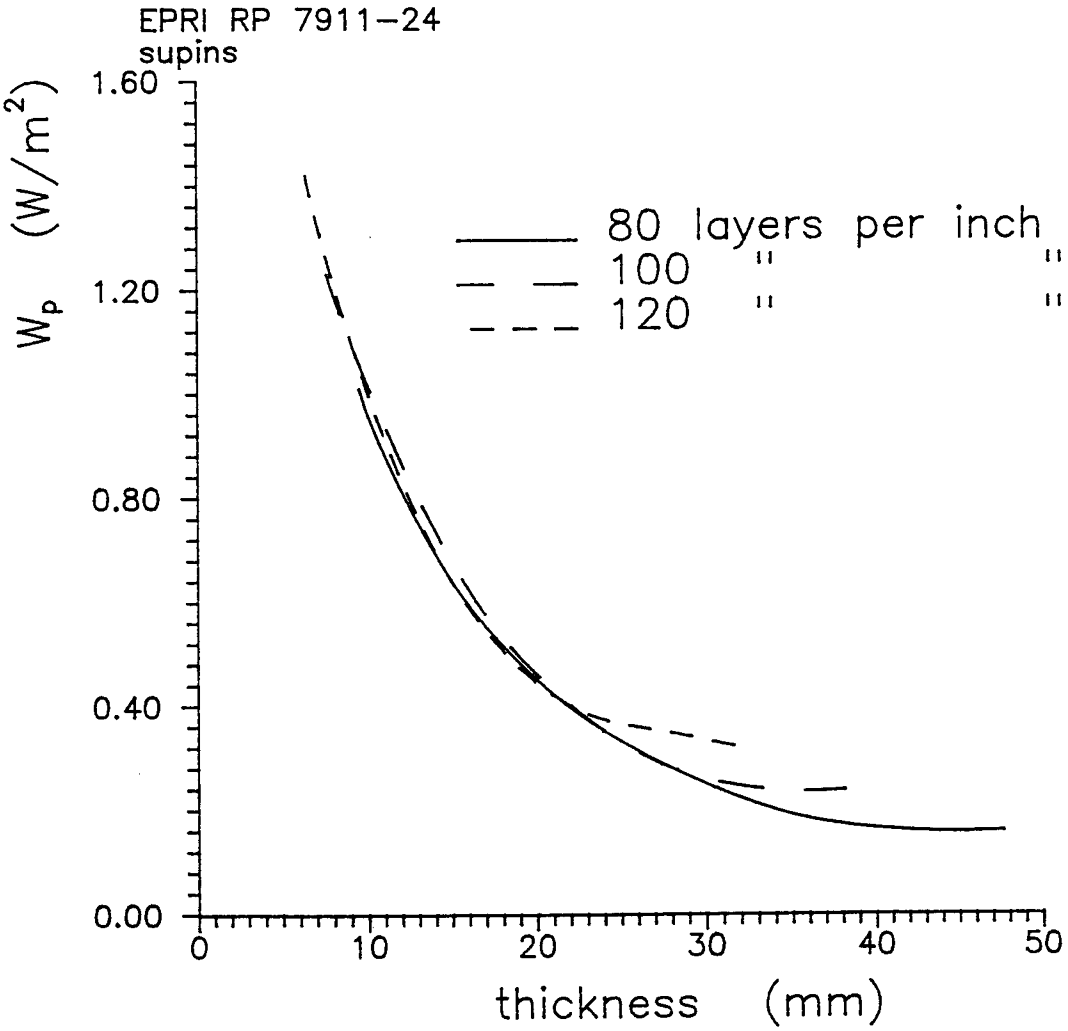


Fig. 3-3

Experimental characteristics of the performance of the superinsulation between room temperature and 77 K, for different levels of compaction of the metallized mylar tapes [25],[41]

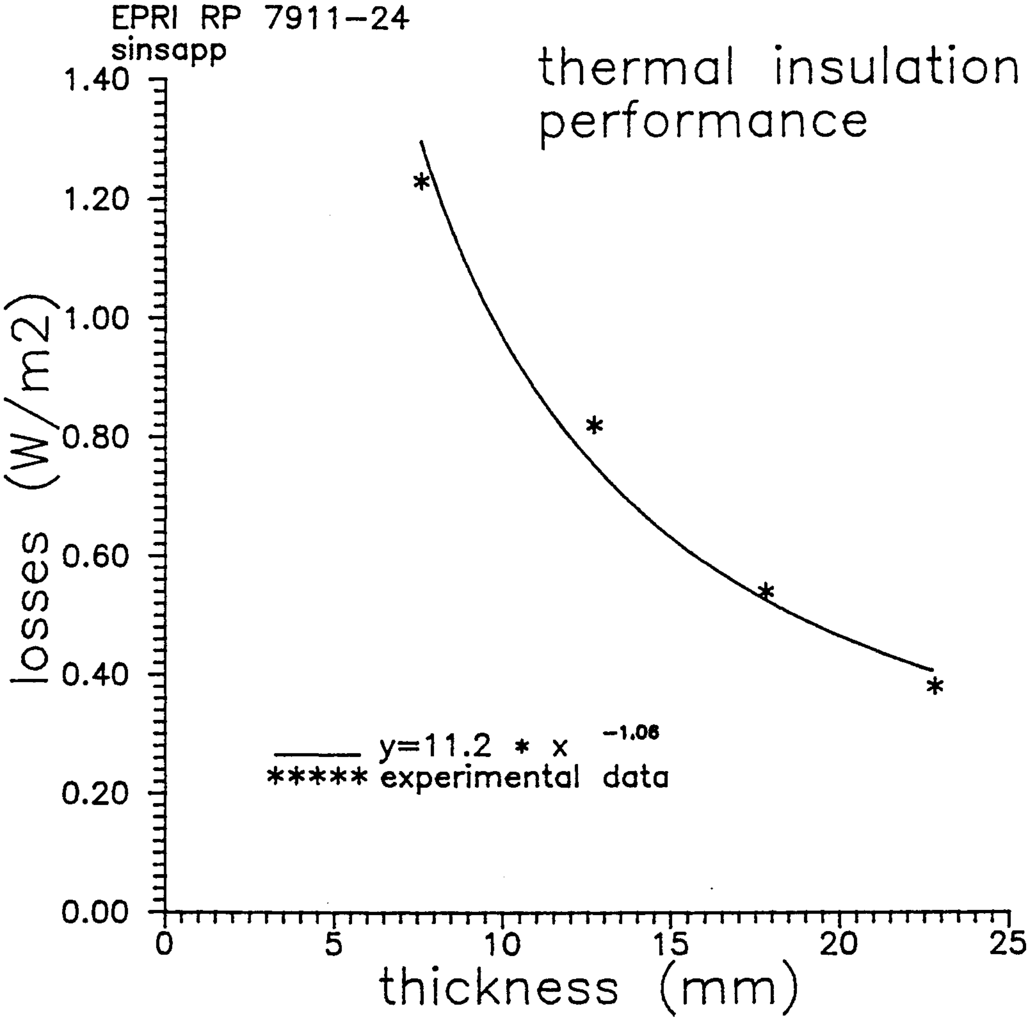


Fig. 3-4

Interpolated equation for the performance of the thermal insulation (surface heat leak between room temperature and 77 K) versus its total thickness, used for the cable design.

3.3.6 Cooling Requirements

The need for cooling the cable conductor(s) with a suitable flow of liquid nitrogen has been analyzed as a primary requirement since the preliminary steps of the design.
The operating range for the coolant has been assumed in a combination of temperatures and pressures, selected to guarantee the presence of a liquid phase whit sufficient safety margin to avoid the risk of vapour bubbles, which would seriously affect both thermal and hydraulic performances [3].
The typical diagram for the closed cycle operation of the fluid is represented in **Fig. 3-5**, based on a temperature drop of 15 K, on a pressure drop of 10 bar, and on a minimum pressure of 10 bar.
These operating parameters have been used to calculate the cooling capability for the extraction of the estimated amount of losses with the available channel and to verify that the length of each cooling section can reach the range required for the installation of the cooling and pumping equipment at an acceptable spacing.

3.4 Preliminary Design of Alternative Solutions

For the main components of the cable the following assumptions have been made, as derived from the collected input data:

3.4.1 Conductor

The performance of the HTSC elementary conductors and their structure have been assumed according to the estimated evolution in a time span of 1 to 2 years from the presently available prototypes.
Due to the need for achieving a sufficient tolerance to the manufacturing induced strains in the superconducting material, which is intrinsically brittle, elementary conductors in the shape of thin tapes have been selected as the most appropriate geometry to reduce to a minimum the strain from both stranding to assemble the conductor and bending to wind the whole conductor during the following manufacturing steps and to transport and install the cable.
On the other hand it has been widely proved that the best electrical performances of long HTSC elementary conductors at LN temperature can be obtained with 2223 BSCCO materials, suitably processed as tapes.[26],[27], [5],[6],[28],[29],[30].

The selected conductor structure has been configured as an even number of tape layers, alternatively stranded in an opposite direction to compensate for the axial component of the magnetic field.
The tape size has been selected among the thinnest proved to be feasible with good electrical performances, in order to achieve the best flexibility.
The lay angle has been selected in order to limit the actual strain at the surface of the tapes to the assumed acceptable level of 0.35 %, as the result of stranding the tapes and of pulling, bending and cooling the conductor.

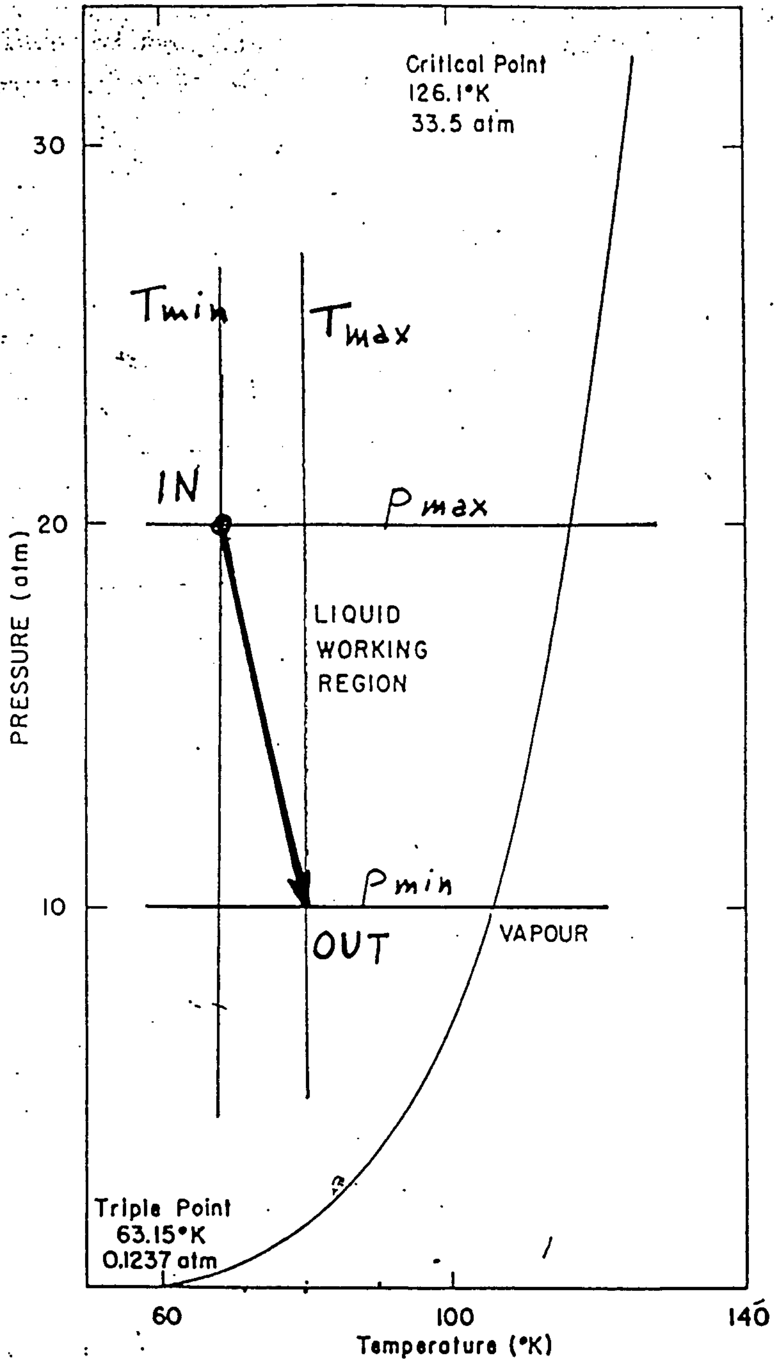


Fig. 3-5

Schematic representation of the coolant conditions in the pressure-temperature diagram for liquid nitrogen. The line with arrow represents the variation along the cable assumed for the design.

The preliminary calculations for conductor diameters in the range 25 to 35 mm, whit tapes 4 mm wide and 0.2 mm thick have indicated that lay angles from 40 to 50 ° would be appropriate to keep the strain within said limits and would permit to accommodate 10 to 15 tapes per layer.
For the same conductor diameter the surface magnetic field, in the coaxial configuration, would be up to 25 A/mm (or 30 mT) at a rated current of 2000 A.

The d.c. critical current density in currently available tapes has presently reached the level of 10 kA/cm^2 for lengths in the range of 100 m , the a.c. critical current level being around 70 to 80% of said value [5],[6].
The design value for the operational current density in the superconductor has been estimated to be not less than 5 kA/cm^2 (r.m.s.), under the assumption that a critical current level up to 10 to 15 kA/cm^2 will be achieved in the time frame available before the manufacture of the cable.
This current density, for a filling factor of 20 % would give an operational current of 11 A(r.m.s.)/tape for the considered size 4.5 x .25 mm.

The conductor losses have been estimated from theoretical considerations (Bean and London-Carry equations) [31],[32] and compared to the experimental data available [21], **Fig.3-6.**
From this evaluation provisional estimations of conductor losses, assumed to include also eddy losses in metal, have been made at the level of 2 to 3 W/m/phase at 2000 A, for both WI (1 conductor/phase) and CI (2 conductors per phase).

The spiral support for the stranded HTSC tapes has been assumed to have a standard thickness of 1.2 mm and no stabilizing tape has been considered as the first approach.

3.4.2 Cryostat

The cryostat concept has been based on the use of continuously manufacturable corrugated stainless steel tubes, including the superinsulation layers and a suitable spacer under permanent vacuum.
The thickness of the superinsulation structure, as well as the number of layers, have been calculated from the reference curve representing its performance, to explore a predetermined level of distributed thermal losses ranging from 0.1 to 0.5 W/m/phase.

The thicknesses of the SS tubes have been fixed at 0.7 mm for the WI construction and at 1.5 mm for the CIa construction, as the first approach to withstand the maximum operating pressure of 20 bar of the coolant (inner tube) and the operating pressure of 15 bar of the impregnating fluid (outer tube) and their corrugation depths have been set at the usually adopted value of 2 times the tube thickness, to allow for the typical degree of flexibility for cable structures.
Eddy losses in the cold structure have been neglected in the preliminary design.

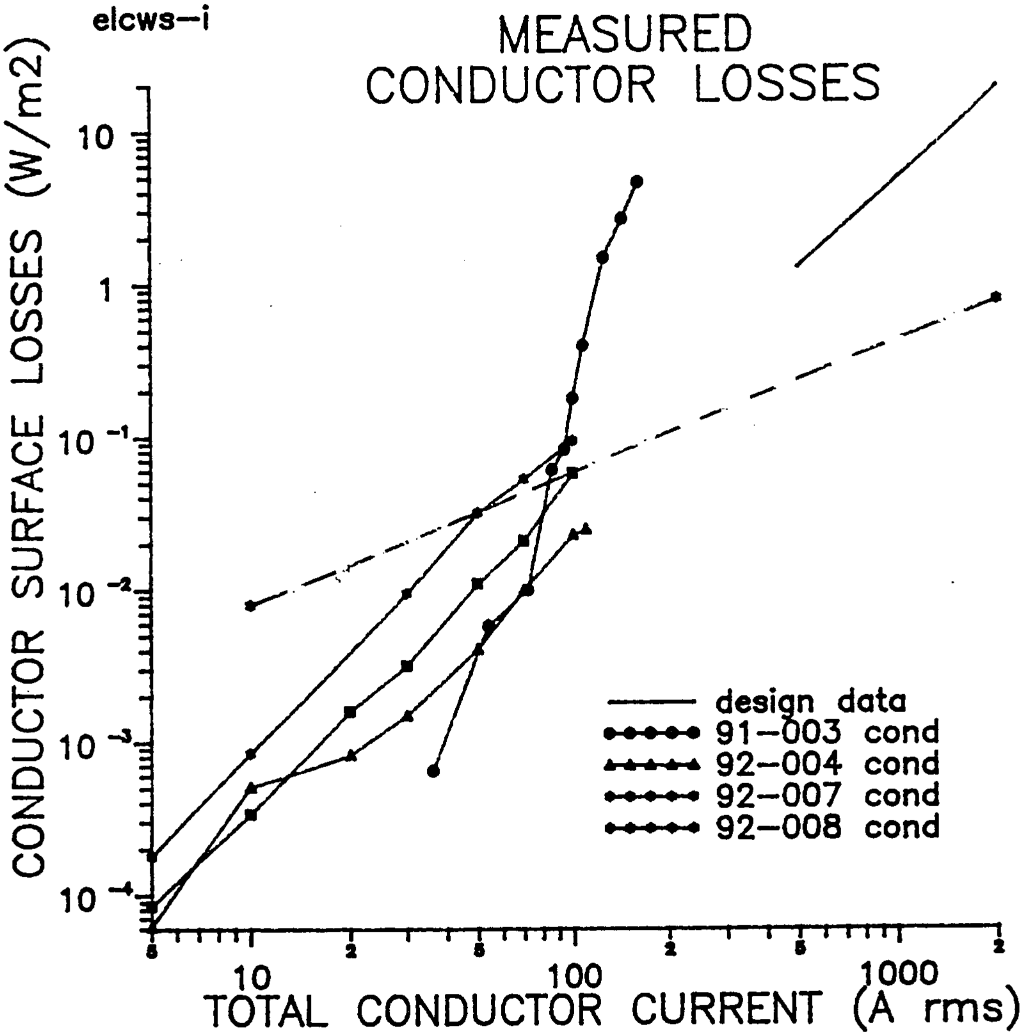


Fig. 3-6

Experimental values of conductor losses versus total current, measured in self field at 50 Hz on short conductor prototypes from the ASC-Pirelli development program (see Table 4-1).
The interrupted line represents the critical level, assumed at 10^{-4} V/m.

The diameters of the tubes have been selected following the predetermined type of solution and the range of voltages to be explored, according to the design flow under 3.4.5.
This resulted in two distinct families of diameters, for the warm insulation and for the cryogenic insulation respectively, involving a quite different degree of technical problems and of machinery size for their manufacturing (**Fig. 3-7** and **Table 3-3**), which appears to be reasonably feasible for the smaller size and quite more difficult for the larger one.

3.4.3 Electrical insulation

As already anticipated in Section 3.3.1, several options have been examined for the standard insulation to be used at room temperature, in the attempt to maximize the space available to the other cable components.
For the case of cryogenic insulation (PPP) the design stress has been selected at 110 kV/mm at BIL level and up to 15 kV/mm (r.m.s.) for a.c. operation.
The thickness and structure of both conductor and insulation shields have been set at the usual values for large size conductors in high voltage cables, with some additional elements where specifically needed (e.g. over the corrugated tubes).

The dielectric losses have been calculated for the actual dimensions and from the standard properties of the insulation at room temperature; for the cryogenic dielectric values of Table 3-2 have been used.
The losses resulted in the range from 1 to 3 W/m/phase for WI and from 0.3 to 1 W/m/phase for CI, depending on the selected case and materials.
In particular paper at cryogenic temperature has not been considered, due to the unacceptable level of losses estimated on the basis of the parameters $\epsilon \times \mathrm{tg}\,\delta = 2.21 \times 0.14 \times 10^{-2}$, found in the literature [16].

3.4.4 Cooling

The flow configuration for the cooling of the cable has been adopted with a parallel GO flow in the internal channels and RETURN between the cores for the CI solution (**Fig. 3-8**).
For the WI solution the flow has been assumed to be inside the conductor channels, with the GO path in one phase and the RETURN in parallel through the remaining two (**Fig. 3-9**).
A preliminary calculation has been made for the maximum distance allowed by a given channel diameter to remove with the LN flow different amounts of losses (in the range from 0.5 to 5 W/m/phase) with practicable temperature drop (15 K) and pressure drop (10 bar); these indicative results, used for the first assessment of the cooling capability as a function of the channel diameter, are reported in **Fig. 3-10**.

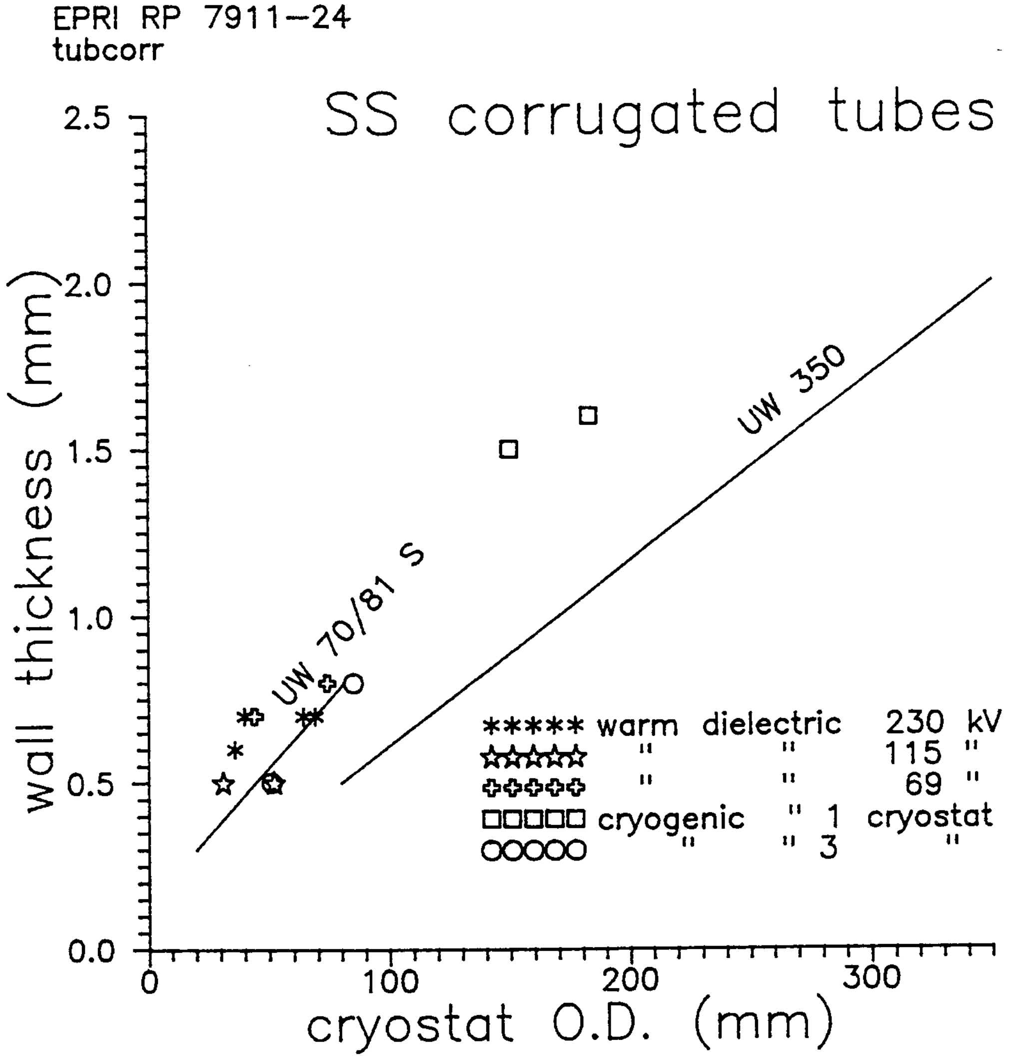


Fig. 3-7

Dimensions of the corrugated SS tubes as obtained from the preliminary design for different cable concepts and voltage classes.
The lines represent the typical central range of operation of the corrugating machines considered to this purpose, (see Table 3-3).

Table 3-3

Specifications for the equipment considered for the corrugation of the SS tubes for the cryostat.

Table 1

UNIW

Application of the Uniwema-method for cable sheaths, armor, coaxial conductors, wave-guides, shields and tubes.		1		2		3		4		5		6		7	
		Telephone Exchange Cables		Multi-Tube Coaxial Telephone Cables		Signal Cables		High-Frequency Cables and Waveguides		Low-Voltage Power Cables		High-Voltage Power Cables		Tubes	
		corr.	sm.	corr.	sm.	corr.	sm.	corr.	sm.	corr.	sm.	corr.	sm.	corr.	sm.
1	Steel (Carbon Steel 0.06%C)	1 2	–	1 2	2	1 2	1 2	(4)	–	1	–	(1)	–	1	1
2	Stainless Steel	–	–	–	–	–	–	–	–	–	–	①	–	1	1
3	Copper	1 2	2	1 2 3	1 2 3	1 2	1 2	1	–	(1)	–	1	–	1	1
4	Aluminium	1 2	1 2	1 2	1 2	1 2	1 2	1	1	1	1	①	–	1	1
5	Non-Ferrous Alloys	–	–	–	–	–	–	–	–	–	–	–	–	1	1

1) Sheath, 2) Shield, 3) Coaxial pairs, 4) copperclad () = in the past, ○ = future, corr. = corrugated, sm. = smooth

Table 2

UNIWEMA machines and their range of application

			UNIWEMA 5	UNIWEMA 20/25	UNIWEMA 70/81[3]	UNIWEMA 70/81 S[4]	UNIWEMA 178/200	UNIWEMA 350
1	Core Inside Diameter	mm	1.2 to 5	3 to 20	15 to 70	15 to 70	45 to 178	70 to 315
2	Wellmantel Outside Diameter	mm	smooth tube only	6 to 25	20 to 81	20 to 81	50 to 200	80 to 350
3	Metals		Steel, Copper, Aluminium & Alloys					
	Normal Wall Thickness							
4	Steel[1]	mm	0.1 to 0.2	0.15 to 0.3	0.3 to 0.6	0.3 to 0.8	0.5 to 1.2	0.5 to 2
5	Copper[1]	mm	0.05 to 0.3	0.15 to 0.5	0.3 to 1.0	0.3 to 1.2	0.5 to 1.8	0.5 to 2.5
6	Aluminium[1]	mm	0.2 to 0.4	0.15 to 0.8	0.3 to 2.0	0.3 to 2.3	0.5 to 2.0	0.8 to 4
7	production speed[2]	m/mm	5 to 40	4 to 25	3 to 15	3 to 30	2 to 8	2 to 8
8	Manufacturing Lengths		unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
9	Floor space for Machine	mm	2400 x 1650	9400 x 1500	13500 x 1800	14200 x 1800	21000 x 2300	38800 x 3950
10	Power requirements	kVA	20	27	68	140	120	250

[1] Thinner walls associated with smaller diameters

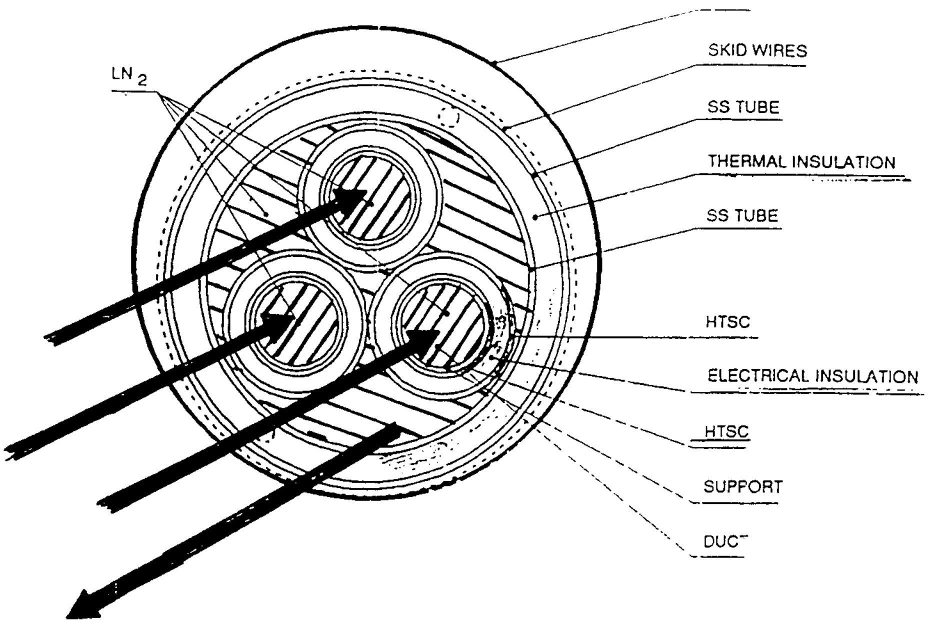
[2] Dependent upon material, wall thickness and O.D.

[3] Equipped with Single Arc (1-electrode) welding torch

[4] Equipped with Polyarc (3-electrode) welding torch

COLD INSULATION a)

FLOWCI



WARM INSULATION

FLOWWI

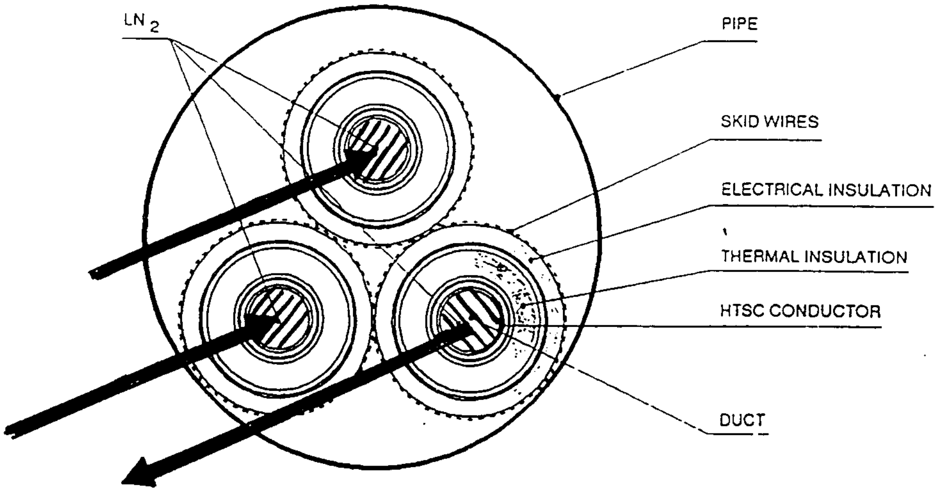


Fig. 3-8, 3-9

Schematic diagram for the arrangement of the coolant flow in the cryogenic dielectric cable (Fig. 3-8) and in the room temperature dielectric cable (Fig. 3-9).

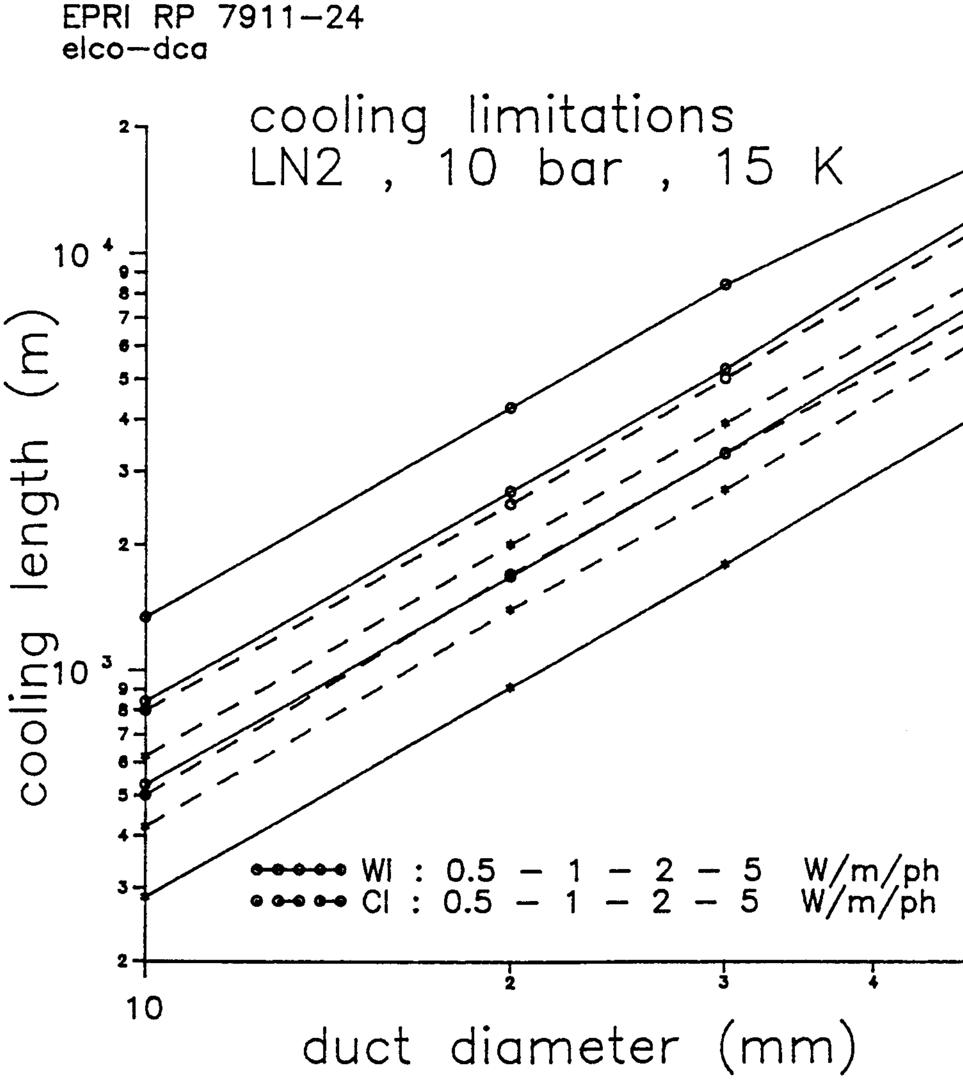


Fig. 3-10

Calculated cooling capability as a function of the conductor channel diameter.
The maximum length for a cooling section, based on 10 bar for pressure losses and on 15 K for temperature drop of LN is shown for different levels of losses to be removed.

3.4.5 Design Principles and flow diagram

Three design concepts have been selected for further analysis among those proposed by the preliminary study for an extensive investigation of their feasibility in terms of geometrical constraints, operating parameters and manufacturability.

These solutions are :

- warm dielectric, three phase conductor configuration (WI) (**Fig. 3-11** and **3-12**);
- cryogenic dielectric, coaxial configuration, with an overall cryostat applied over the three phase assembly (CI-a) (**Fig. 3-13**);
- cryogenic dielectric, coaxial conductor configuration, with individual cryostat applied over each phase (CI-b), as a possible alternative to solution CI-a, using a smaller size of cryostat and single phase elements, easier to transport and to install (**Fig.3-14**).

The remaining proposed solution,based on cryogenic dielectric and three phase conductor configuration has not been considered worthy of further investigation, because it would have substantial limitations in current capability due to the magnetic field configuration inside the pipe (see par.4.1.4), while requiring the full development of the cryogenic dielectric.

For each selected design concept the following parametric analysis has been carried out:

- fixed pipe diameter (8-5/8" pipe, ID 206 mm);
- range of installation clearance from 15 to 19 mm;
- range of operating voltage from 69 to 230 kV;
- electrical insulation of standard thickness, using either Kraft paper or PPP for both WI and CI;
- thermal insulation thickness for a range of thermal losses from 0.1 to 0.5 W/m/phase;
- active conductor thickness fixed at 2.5 mm (2.0 mm for the return conductor in CI).

The above parameters have been worked out in the design flow diagram shown in **Table 3-4**, according to the following classification of the variables:

F fixed value, well known parameters and/or assumed not to be varied

(pipe diameter)

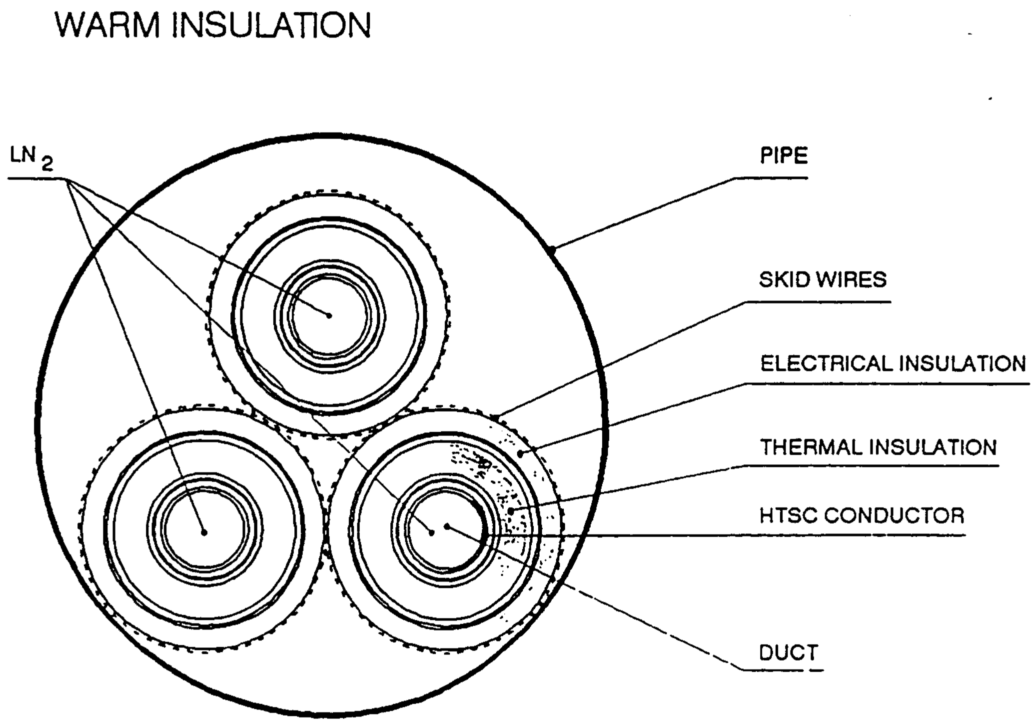


Fig. 3-11

Schematic cross section of the room temperature dielectric cable (WI) considered for the design.

WICOND

WARM INSULATION - CONDUCTOR ASSEMBLY

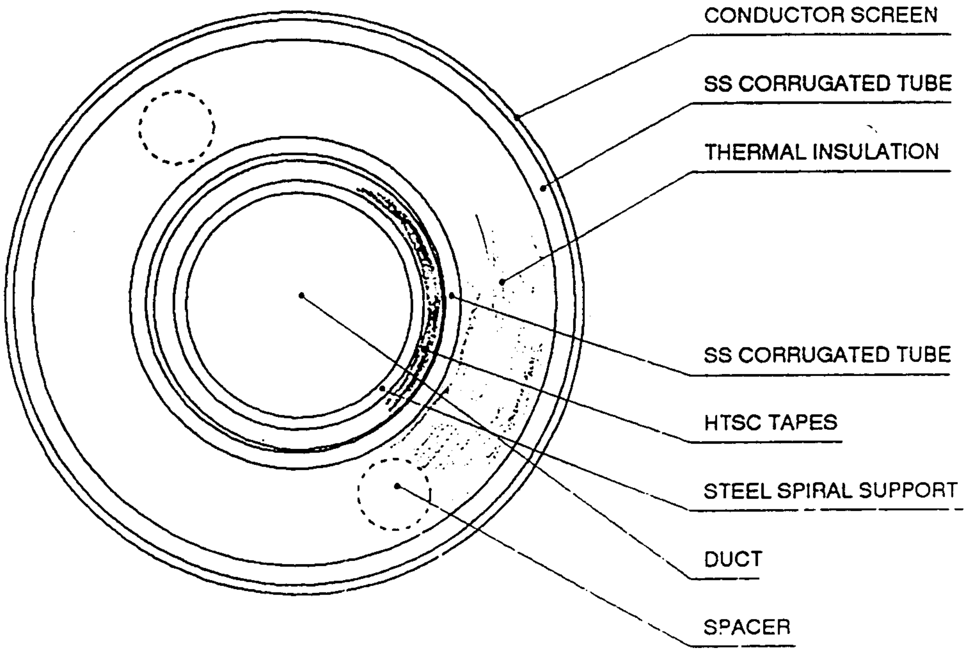


Fig. 3-12

Schematic cross section of the conductor assembly of the room temperature dielectric cable (WI) considered for the design.

CIATOT

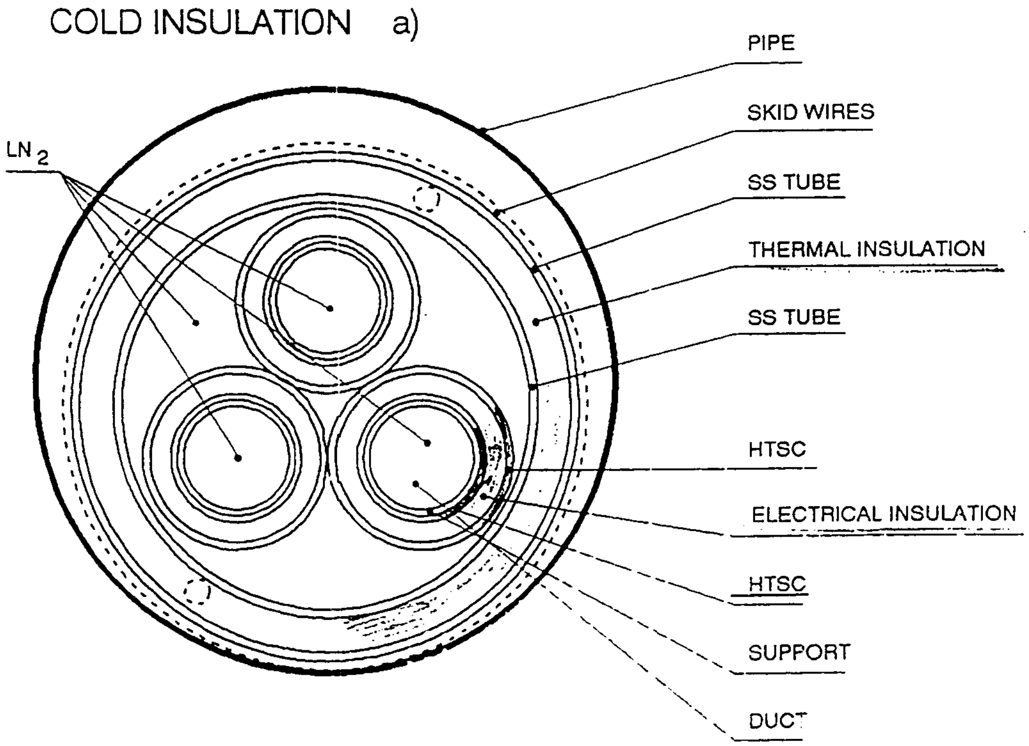


Fig. 3-13

Schematic cross section of the cryogenic dielectric cable with single overall cryostat (CI-a) considered for the design.

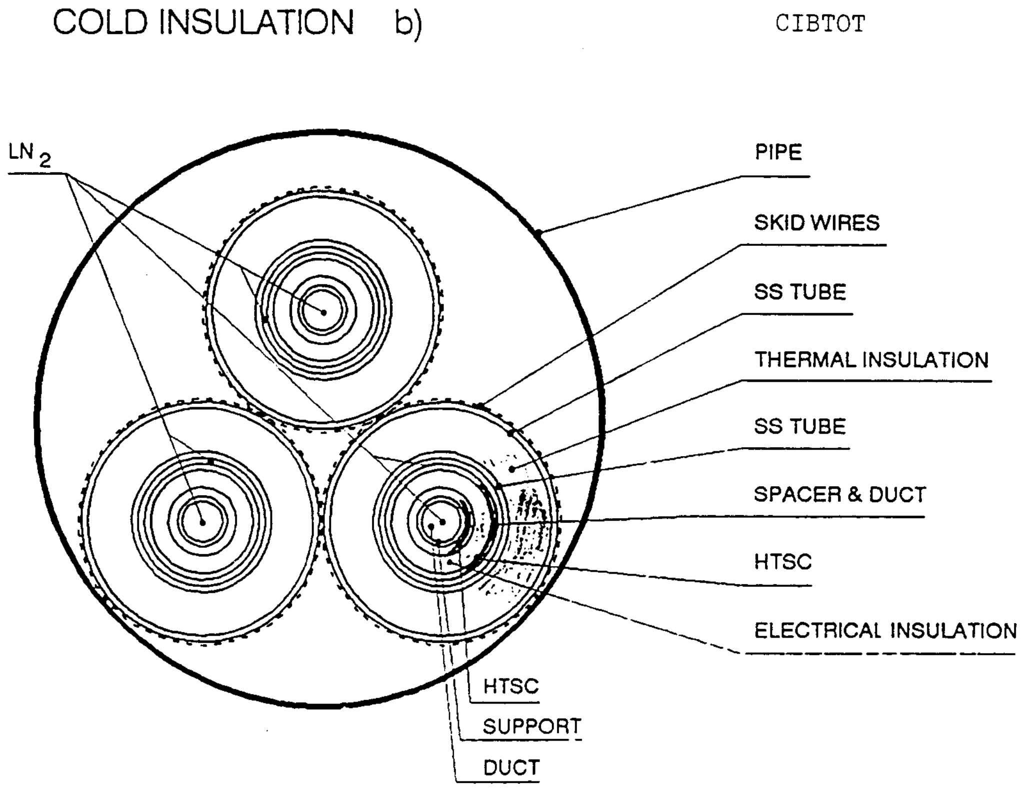


Fig. 3-14

Schematic cross section of the cryogenic dielectric cable with three separated cryostats (CI-b) considered for the design.

H assumed value, requiring further analysis or experimental confirmation

(conductor losses, current density, cryogenic dielectric performances, thermal insulation performances);

C standard choice of materials for the required performance

(room temperature electrical insulation);

V primary design variable

(thermal losses, clearance in pipe, rated voltage).

Additional minor variables have not been explicitly considered in the preliminary design and include:

- conductor and insulation shield details (a fixed thickness has been assumed, equal to .9 and .4 mm for inner and outer screen respectively);
- conductor support (fixed thickness, equal to 1.2 mm);
- pumping losses (fixed at 5 % of extracted heat);
- active conductor thickness (2.5 and 2.0 mm for inner and outer conductor respectively);
- a.c. conductor losses level (2.5 W/m for WI and 1.5+1.3 W/m for CI, both at 2000 A);
- cryostat tubes thickness (0.7 mm and 1.5 mm for WI and CI respectively);
- tube corrugation depth (twice its thickness).

From the combination of the above variables, several sets of results have been obtained, representing the design specifications and the performances of the corresponding solutions.

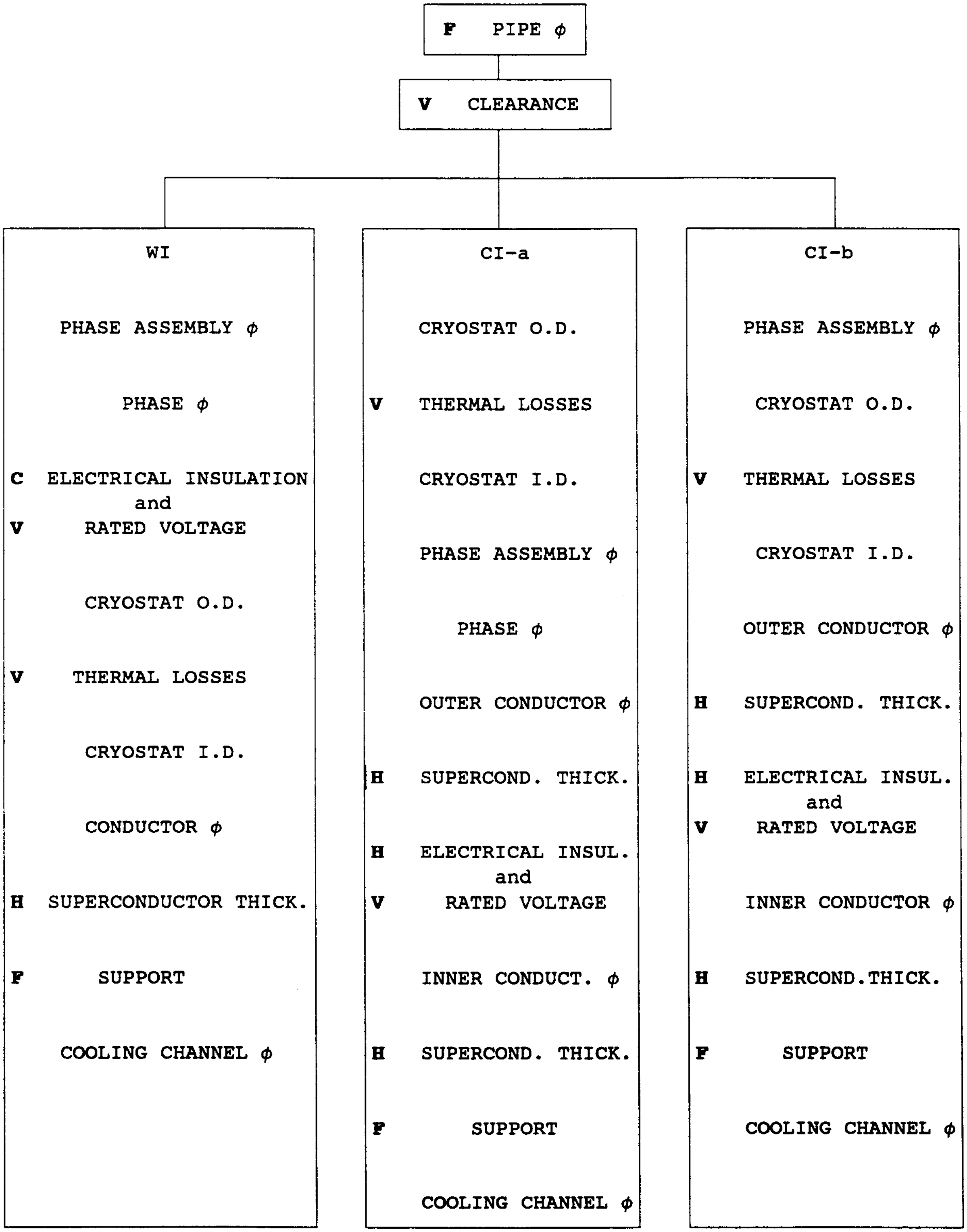
The fundamental results, which have been analyzed as a function of the variables are expressed as:

- geometrical data;
- current (or power) rating;
- transmission losses;
- cooling section maximum length.

The outcome of the preliminary design has been collected in a group of diagrams showing the dependence of the above results from the main variables.

Table 3-4

Flow diagram used for the preliminary dimensioning of the room temperature dielectric cable and of the two cryogenic dielectric alternatives.



3.4.6 Geometrical Analysis

A first conclusion has been that the solution CI-b cannot be adopted in practice due to the too large size of the three phase assembly, when each phase is enclosed in an individual cryostat.
A general comparison between solutions CI-a and CI-b is shown in **Fig. 3-15** where the ratio of the overall cable diameter to the diameter over the insulation of each core has been calculated as a function of the amount of thermal losses, and subsequently of the cryostat thickness.
It is evident that for a given overall diameter D allowed for the cable, the diameter of each phase insulation can be up to D/2.8 to D/2.5 in the case of an overall cryostat, but it must be reduced down to D/4 to D/3 in the case of individual cryostats, the worst case being at the lowest level of thermal losses.

The practical conclusion is that the space available in 8" pipes is insufficient for the accommodation of the cryogenic solution of type CI-b, and that only solution CI-a has to be considered, provided the feasibility of the large size cryostat is verified.

The second step in the preliminary design has been to evaluate the space available for the conductor and for the cooling channel, for the geometrically feasible solutions.

For the WI case, starting from the core O.D. allowed by the selected clearance and depending on the combinations of rated voltage and of type of electrical insulation, the inner diameter of the dielectric resulted from the minimum thickness required to keep the electric stress at the design value. The cryostat, to be inserted inside this diameter, has been calculated for different levels of thermal losses and its inner diameter ended in the space basically available for the conductor.

For the CI case (a) the cryostat O.D. has been the starting point derived from the clearance; the cryostat I.D. resulted from the level of thermal losses and determined the diameter of the core assembly and subsequently of each core. From the same combination as for WI of voltages and dielectrics the diameter available for the conductor and for the channel have been then calculated.

The tree of the channel diameter calculation according to the design flow diagram is shown in **Tables 3-5** and **3-6** for the WI and CI-a case respectively.

An example of geometrical data sheet for WI and CI cases is shown in **Tables 3-7** and **3-8** respectively.

The results of these calculation are reported in terms of channel diameter versus thermal losses for different dielectrics at given voltages in **Fig. 3-16** and **3-17**, indicating that

- WI solutions are in general more limited in available size for conductor and channel than CI;

- PPP, in particular when optimized at the limit acceptable stress is the most favourable dielectric to save space for the conductor;

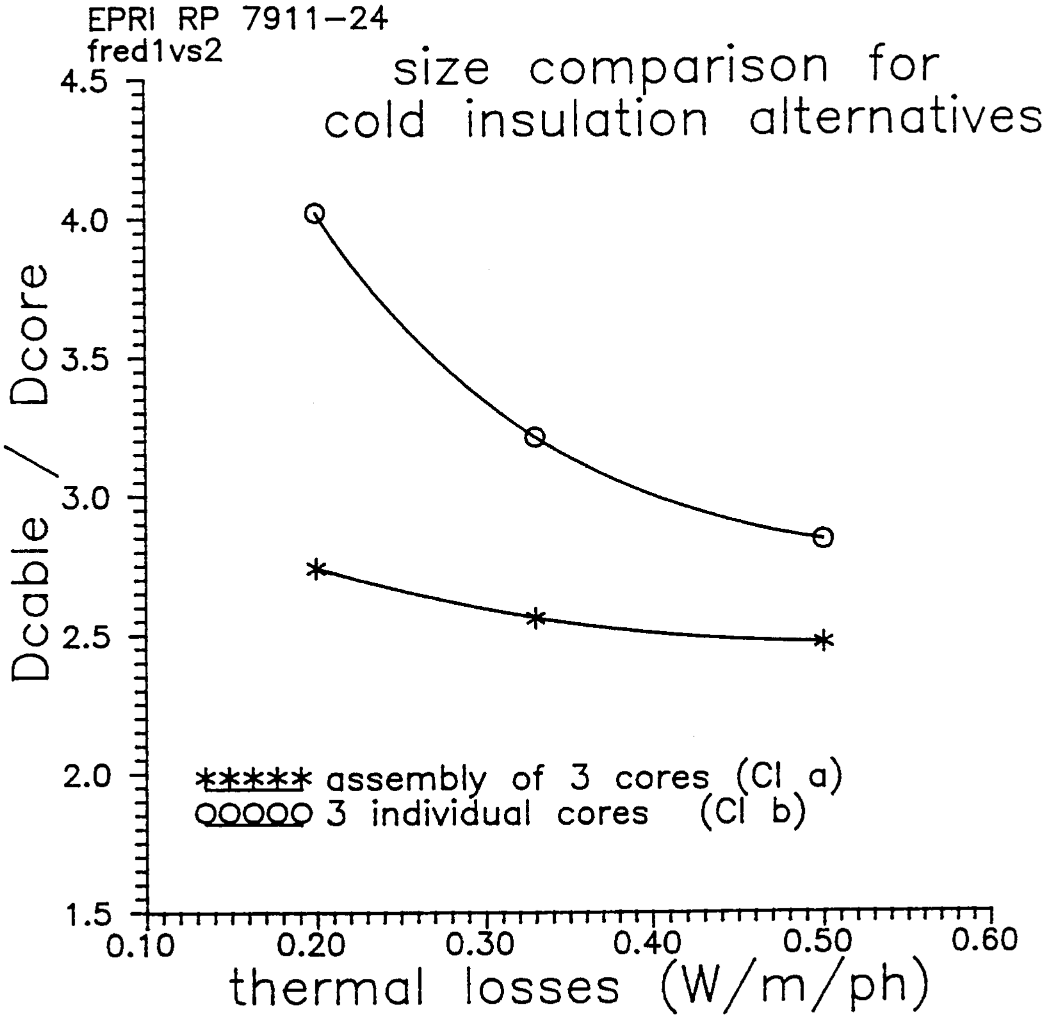


Fig. 3-15

Size comparison for the two considered cryogenic dielectric design. Ratio of the cable to core (dielectric O.D.) diameter versus design thermal losses for the single cryostat (CI-a) and the three cryostat (CI-b) alternatives.

Table 3-5

Calculated values of the conductor channel of the room temperature dielectric cable, for different combinations of the considered design variables.

8" pipe (ID 206 mm)												
clearance 15 mm core OD 87 mm							clearance 19 mm core OD 85 mm					
115 kV			230 kV			heat inleak. (W/m/ph)	115 kV			230 kV		
PPP/S	PPP	PAP	PPP/S	PPP	PAP		PPP/S	PPP	PAP	PPP/S	PPP	PAP
1.3	1.4	-	0.1	0.6	-	0.1	1.2	1.3	0.8	< 0	0.5	< 0
-	-	25.8	20.9	23.9	-	0.2	27.5	28.3	25.1	20.1	23.2	19.2
42.3	43.7	-	29.6	34.8	-	0.5	41.0	42.4	36.9	28.9	33.5	26.6

PPP/S : PPP insulation at fixed max stress (see Table 3-1)
PPP : " " " standard stress " " "
PAP : paper " " " " " " "

Table 3-6

Calculated values of the conductor channel of the three cryostat (CI-a) cryogenic dielectric cable, for different combinations of the considered design variables.

	8" pipe (ID 206 mm)											
	clearance 15 mm cable OD 191 mm						clearance 19 mm cable OD 187 mm					
	0.1 W/m/ph		0.2 W/m/ph		0.5 W/m/ph		0.1 W/m/ph		0.2 W/m/ph		0.5 W/m/ph	
cryogenic dielectric	115 kV	230 kV	115 kV	230 kV	115 kV	230 kV	115 kV	230 kV	115 kV	230 kV	115 kV	230 kV
PPP/S	28.6	-	38.1	26.8	43.6	-	27.7	9.1	37.0	24.5	42.4	31.2
PPP	-	-	-	29.0	-	-	27.7	17.6	38.0	27.1	42.8	32.7
PAP	-	10.6		21.1	37.8	-	20.7	9.7	32.0	20.0	36.5	24.1

PPP/S : PPP insulation at fixed max stress (see Table 3-2)
PPP : " " " standard stress (" " 3-1)
PAP : paper " " " " (" " 3-1)

Tab 3-7

Example of preliminary dimensional data for a room temperature dielectric cable for 115 kV, PPP/S insulation, 0.2 W/m/ph, 19 mm clearance in 8" pipe.

		Thickness (mm)	Diameter (mm)
Voltage (kV)	115/√3		
Clearance		19.0	206.0
Skid wires		3.6	187.0
Core assembly O.D.		-	183.4
Insulation shield		0.4	85.3
BIL stress min (kV/mm)	70.0		
BIL stress max (kV/mm)	84.3		
A.C. stress (kV/mm)	10.2		
PPP dielectric		7.2	84.5
Conductor shield		0.9	70.1
Bedding		-	68.3
Warm tube O.D.		0.7	67.7
Corrugation depth		1.4	
Thermal insulation		11.8	63.4
Thermal losses (W/m)	0.2		
Thermal losses (W/m2)	1.0		
Cold tube O.D.		0.7	39.9
Corrugation depth		1.3	
Bedding and reinforcement		-	35.9
HTS layer		2.5	34.9
Support		1.2	29.9
Channel		-	27.5

Tab 3-8

Example of preliminary dimensional data for a cryogenic dielectric cable for 115 kV, PPP insulation, 0.2 W/m/ph, 19 mm clearance in 8" pipe.

			Thickness (mm)	Diameter (mm)
Voltage	(kV)	115/√3		
Clearance			19.0	206.0
Skid wires			2.8	187.0
Warm pipe O.D.			1.6	181.5
Corrugation depth			3.3	
Thermal losses	(W/m)	0.600		
Thermal losses	(W/m2)	1.112		
Thermal insulation			10.5	171.7
Cold pipe O.D.			1.5	150.7
Corrugation depth			3.0	
Core assembly O.D.			0.8	141.7
Reinforcement			0.2	65.2
Outer HTS layer			2.0	64.8
Insulation shield			0.4	60.8
PPP dielectric			6.5	60.0
BIL stress max	(kV/mm)	95.8		
BIL stress min	(kV/mm)	75.0		
A.C. stress max	(kV/mm)	11.6		
Conductor shield			0.5	47.0
Inner HTS layer			2.5	46.0
Support			2.0	41.0
Channel			-	37.0

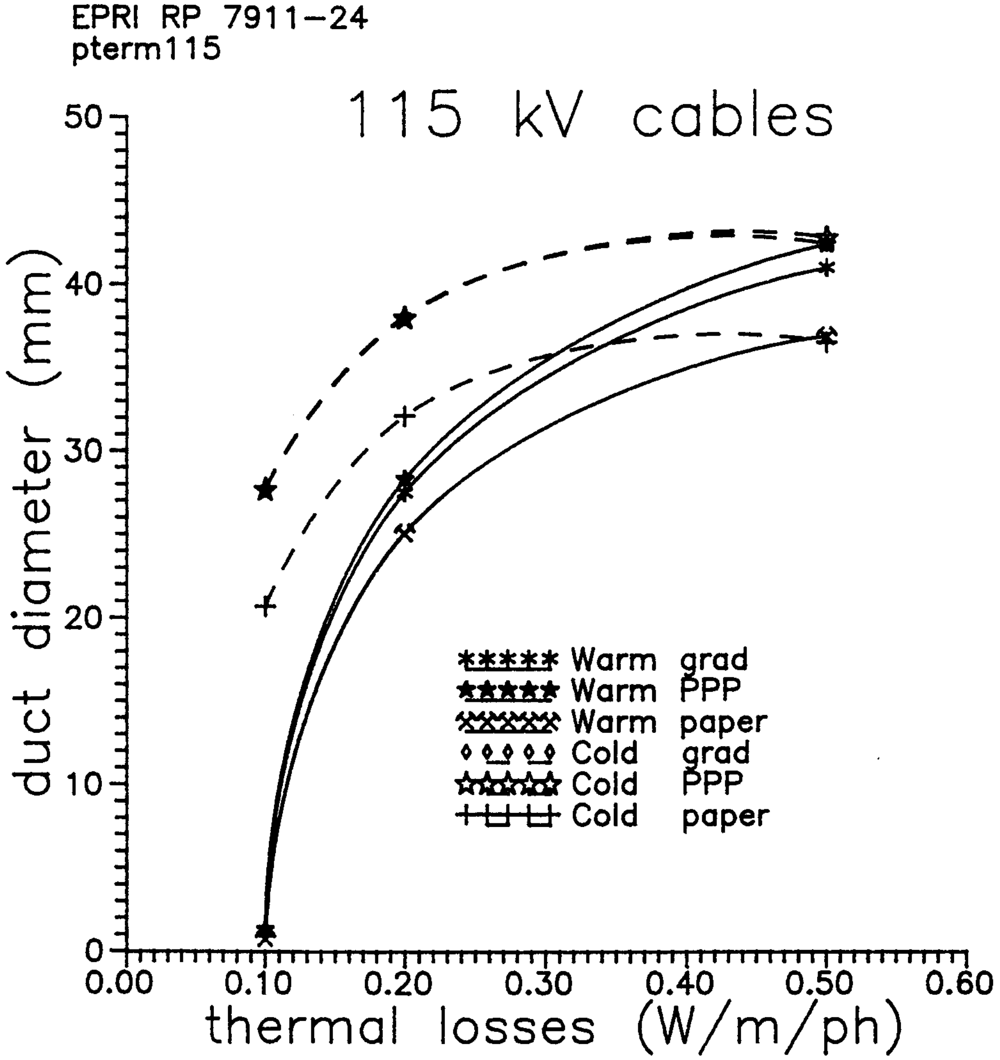


Fig. 3-16

Calculation of the conductor channel diameter versus design thermal losses for 115 kV cables with different electrical insulation (room temperature and cryogenic alternatives).

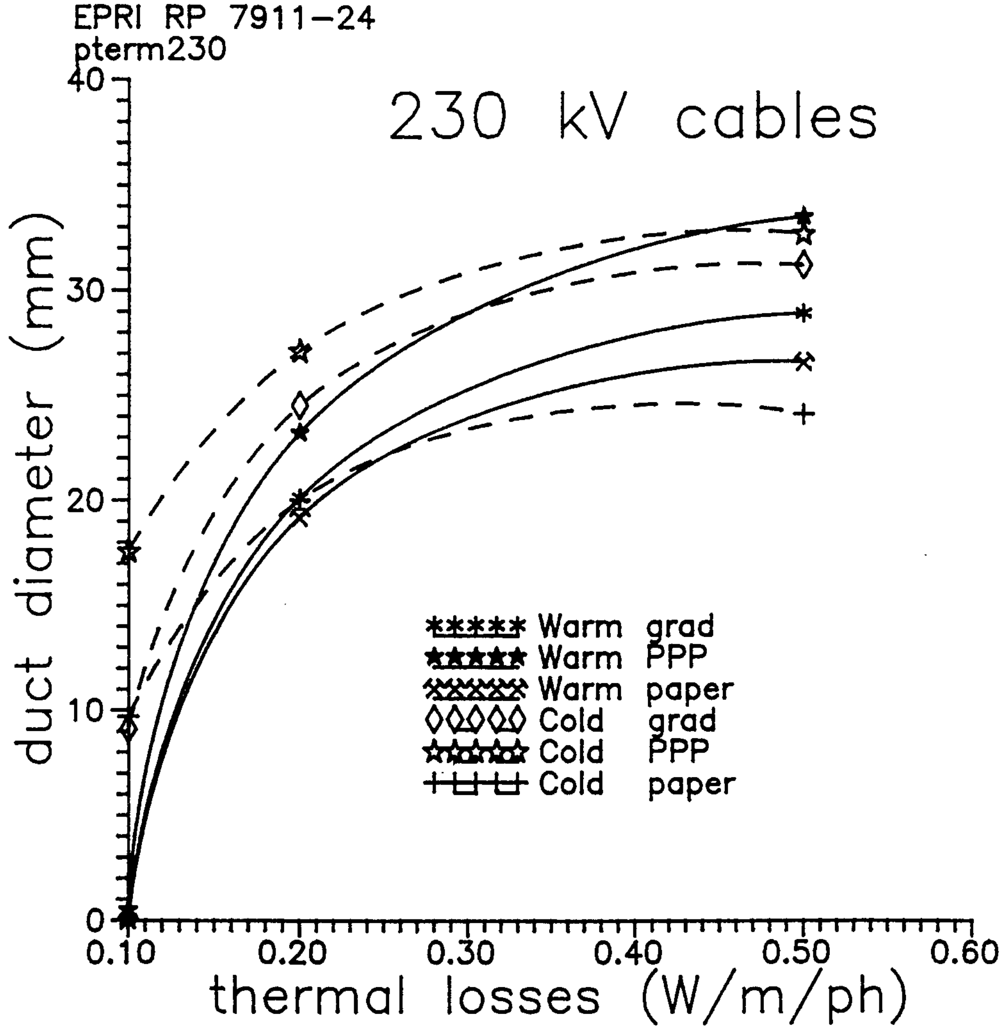


Fig. 3-17

Calculation of the conductor channel diameter versus design thermal losses for 230 kV cables with different electrical insulation (room temperature and cryogenic alternatives).

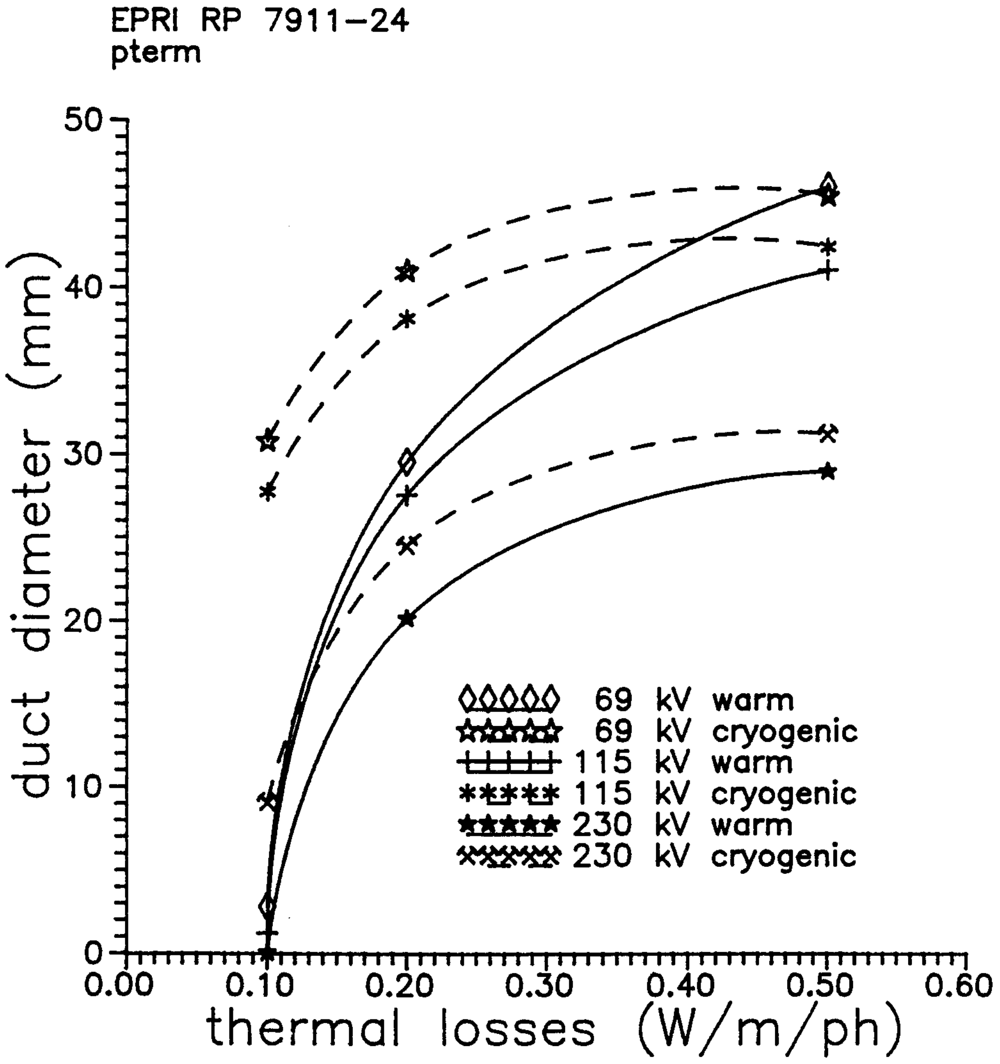


Fig. 3-18

Calculation of the conductor channel diameter versus design thermal losses for 69 to 230 kV cables with PPP electrical insulation (room temperature and cryogenic alternatives).

- a cryostat design based on thermal losses below 0.2 W/m/phase would give rise to serious problems for accommodation of the conductor also for CI at higher voltages and would leave an absolutely insufficient space for WI

A similar representation, limited to the best case of PPP and comprehensive of the full range of voltages from 69 to 230 kV is given in **Fig. 3-18,** which has been the basis to focus on the more practicable solutions in terms of channel diameter and consequent cooling capability.

3.4.7 Performances

The cooling capability of the available conductor channel has been calculated in a parametric form for both CI and WI flow configurations.
The maximum allowed length for the cooling sections is represented in Fig. 3-10 for each situation, as a function of the channel diameter and for levels of cold heat load to be removed from the cable ranging from 0.5 to 5 W/m/phase.
The calculation has been performed for the adopted cooling design parameters (10 bar and 15 K), for the configuration of Fig. 3-9 in the case of WI and of Fig. 3-8 for CI; in the latter case the pressure drop along the return path between the phases has been neglected and the transversal heat exchange between the go and the return flows has been accounted for [33].

From this diagram it appears that channels above 25 mm (20 mm for CI) would allow for cooling sections up to 1 km, even at a 5 W/m/ph heat load.

The calculation of losses has been limited to the case of 115 and 230 kV cables, both WI and CI, dimensioned for thermal insulation to give 0.2 W/m/ph losses and for different dielectrics.
The conductor losses have been estimated (**Fig. 3-19**) from theoretical calculations of hysteretic losses [31],[32] and extrapolated from data measured on small scale conductors (see Fig. ELCIWC-I) and from levels corresponding to the critical current (**Fig. 3-20**) ; conservative design values have been identified as a function of current.

Thermal losses have been fixed for the calculation of the performance at the total level of 0.5 W/m/ph, resulting from 0.2 W/m/ph distributed losses (corresponding to the selected thickness of thermal insulation), with the addition of 0.3 W/m/ph due to conduction through the spacer between the two tubes of the cryostat.
Losses in the cold and warm tubes, in the shields and in the pipe have been calculated as a function of the current, according to the standard methods for circulation and eddy losses [3],[22],[23],[34].
Dielectric losses have been calculated for the particular sizes and for the three stresses and the two temperatures to be considered.
Hydraulic losses have been assumed to be 5% of the total cold heat flow to be evacuated by the coolant.
Cooling losses have been calculated on the basis of 14 W/W, as the typical efficiency of coolers for the actual level of rating and of temperature [35].

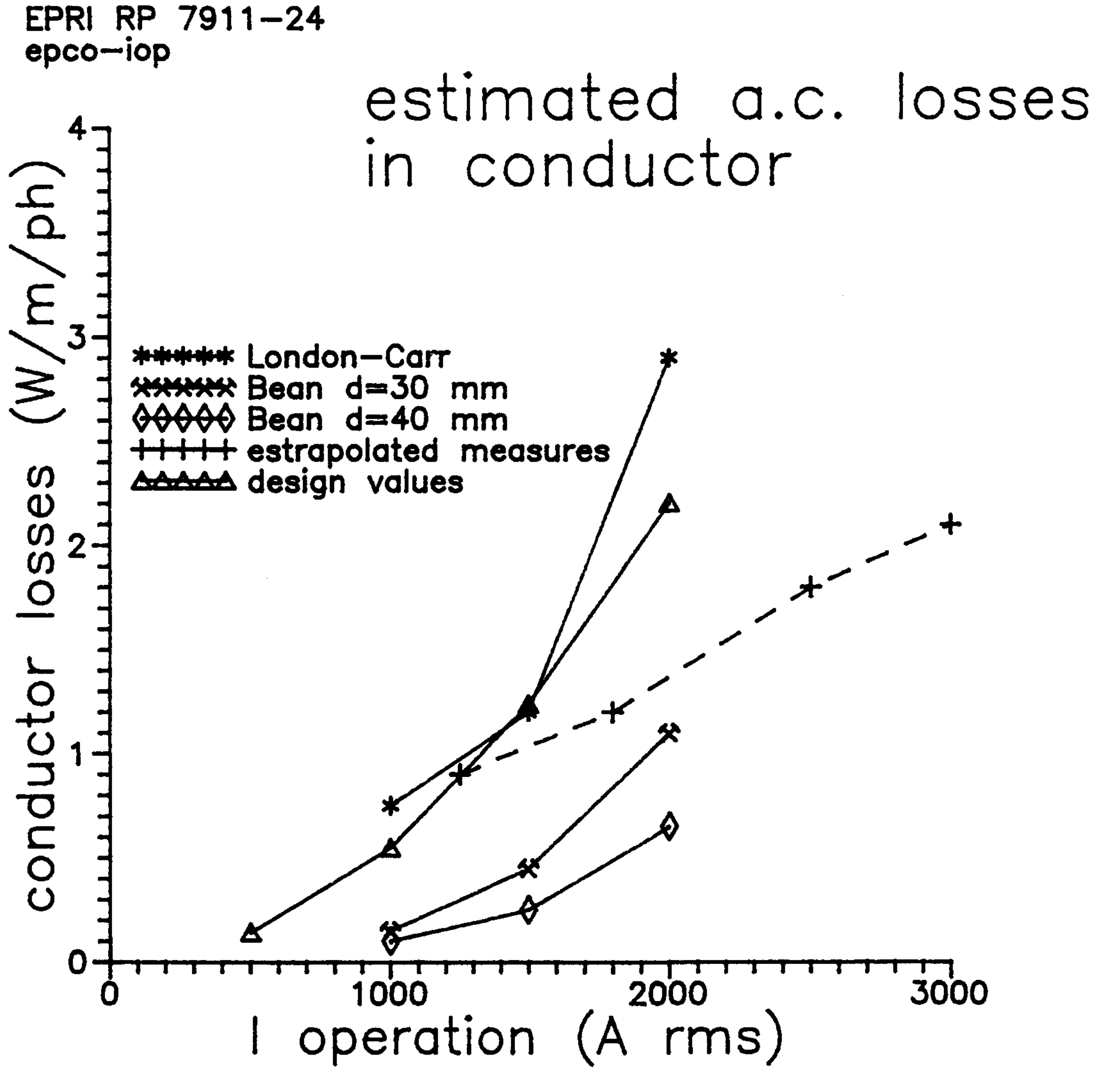


Fig. 3-19

Estimated conductor a.c. losses versus current: Theoretically calculated values, extrapolations from measurements and values adopted for the design are compared.

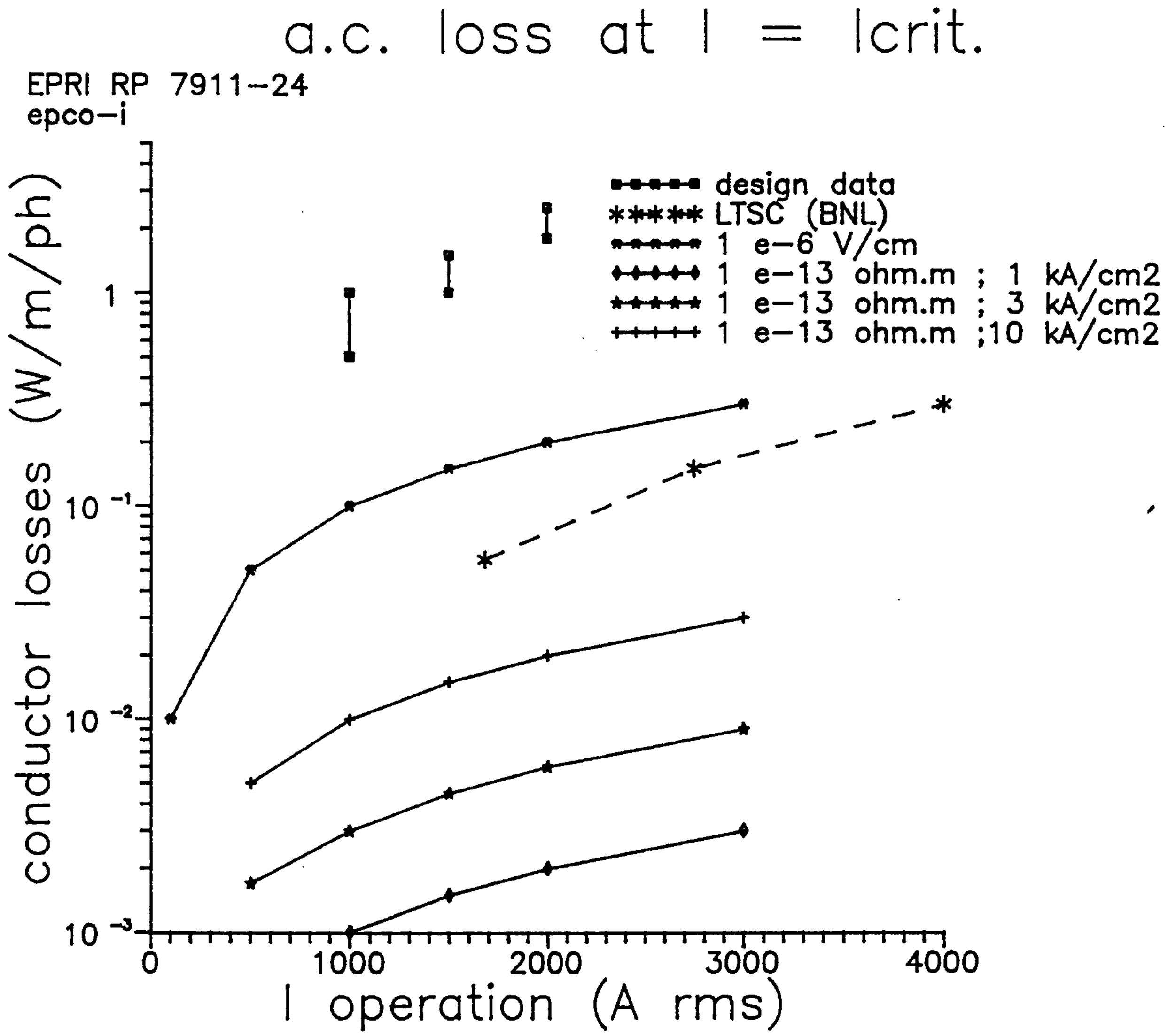


Fig. 3-20

Estimated conductor a.c. losses versus current: Values corresponding to typical critical current levels, to typical LTSC performances and design values are reported.

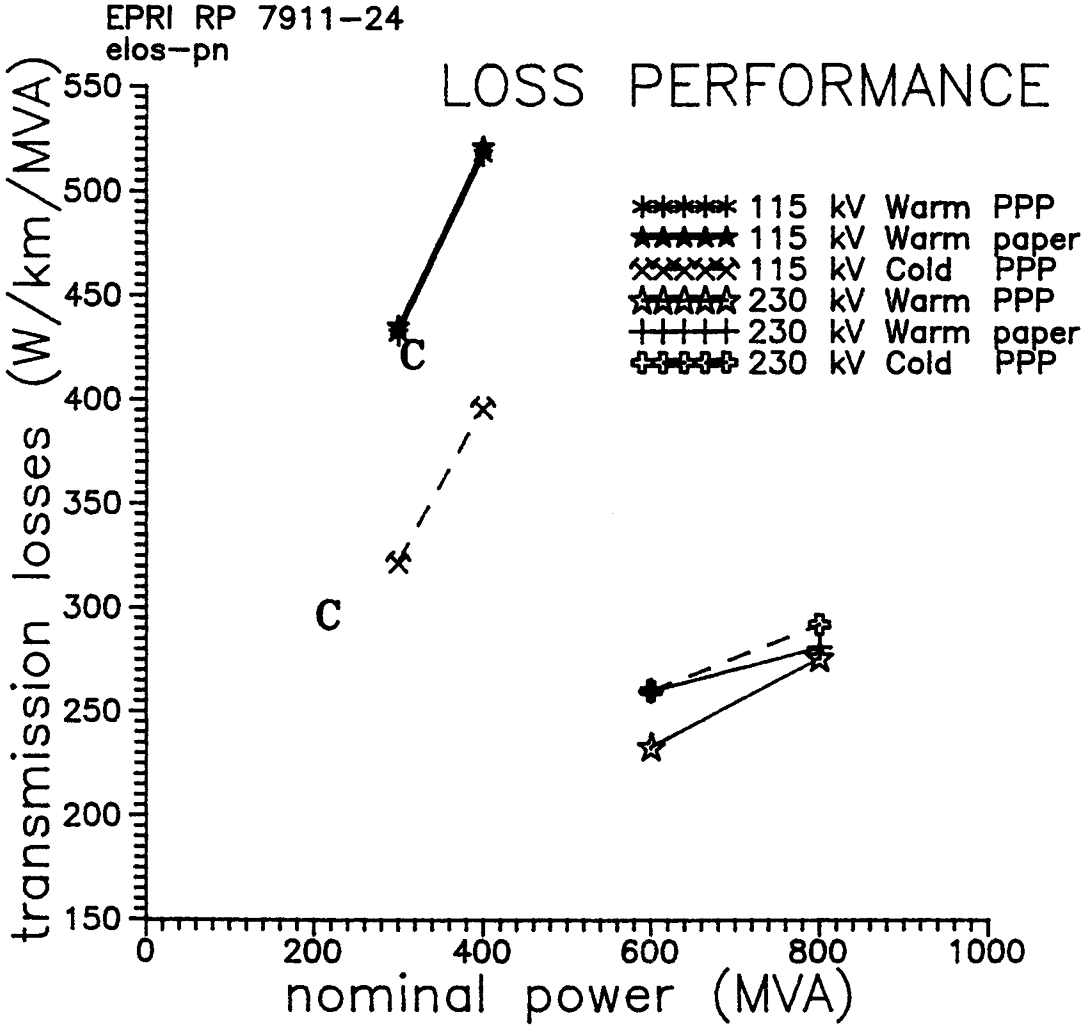


Fig. 3-21

Transmission losses versus power for some preliminary designs of 115 and 230 kV cables with different dielectrics. Low temperature losses have been added with cooling losses (14 W/W) for all cases.
The performance of 200 MVA conventional cables and of 300 MVA updated cables is also indicated by the "C" marks for reference.

Table 3-9

Preliminary specifications for 115 kV HTS cables derived from the preliminary design of both room temperature and cryogenic dielectric solutions for retrofitting of 8" pipes.

TYPICAL CABLE SPECIFICATION					
type		WI		CI	
voltage	kV	115		115	
current	A	1500	2000	1500	2000
power	MVA	300	400	300	400
ϕ duct	mm	27.5		37.0	
conductor O.D.	mm	35		47/66	
cold tube O.D.xthick.	mm	40x0.7		151x1.5	
warm tube O.D.x thick	mm	687x0.7		182x1.6	
electrical ins. thick.	mm	10.2		6.6	
thermal ins. thick.	mm	11.8		10.5	
conductor losses	W/m/ph	1.5	2.5	0.8+0.6	1.5+1.3
thermal "	"	0.5		0.5	
cold tube "	"	0.03	0.08	-	-
dielectric "	"	0.95		0.30	
warm tube "	W/m	0.01	0.02	-	-
hydraulic "	"	0.10	0.14	0.10	0.20
shield "	"	1.3	2.3	-	-
pipe "	"	37	68	-	-
cold heat load	W/m/ph	2.1	3.2	2.3	3.77
warm losses	W/m	41	73	-	-
total"hot"losses (14W/W)	"	129	207	97	158
max. cooling length	m	3200	2200	5300	4800
transmission losses	W/km/MVA	431	517	322	396

Finally all losses, have been summed up to evaluate the total transmission losses for each solution at full load and at 50% load; these data are presented in **Fig. 3-21.**

Numerical values are also presented in **Table 3-9** for the 115 kV cables.

A first analysis of the results indicates that:

- the total transmission losses in all cases increase with the load, due to the high contribution of current related losses in the conductor, in the metallic structures and (for WI) in the shield and pipe;

- the CI solution appears to have 25% less transmission losses than the WI solution at 115 kV: this is mostly to be attributed to the lack of pipe losses and to a much lower level of eddy losses in the metallic elements of the cable; at 230 kV this difference is fully recovered by the higher proportion of the dielectric losses, at low temperature;

- for different warm dielectrics (paper and PPP) the difference in losses is very low, due to the low contribution of dielectric losses to the total; it can be appreciated only for the 230 kV cable at half of the load;

- the absolute level of losses, if compared to that of equivalent conventional cables (see the reference marks in Fig. 3-21) appears to be in the same typical range.

Using the above calculated values of losses, the admissible length of the cooling sections has been calculated for the same cases.

A first approach to this analysis is given in **Fig. 3-22,** where the calculated cold heat load (at 50% and full load) and the actual channel diameter of each solution are compared to the requirements derived from the previous general calculation in Fig. 3-10 to achieve a section length of 1 and 2 km.
More definite results are presented in **Fig. 3-23,** where the calculated maximum possible length is given as a function of the load for each cable.

It can be seen that:

- the variations with the level of load from 50 to 100% are very limited;

- the CI solutions have an essentially double potential for the cooling distance with respect to the WI at 115 kV and significantly higher also at 230 kV; this is due to the larger channel size available for CI solutions;

- the use of different dielectrics at room temperature does not affect in practice the cooling length (small differences are due to a second order effect on the actual size of the channel);

- the absolute level of the cooling length is in excess of 2 km for 115 kV cables and between 1 and 2 km for 230 kV cables, therefore in an acceptable range for the feasibility of the system.

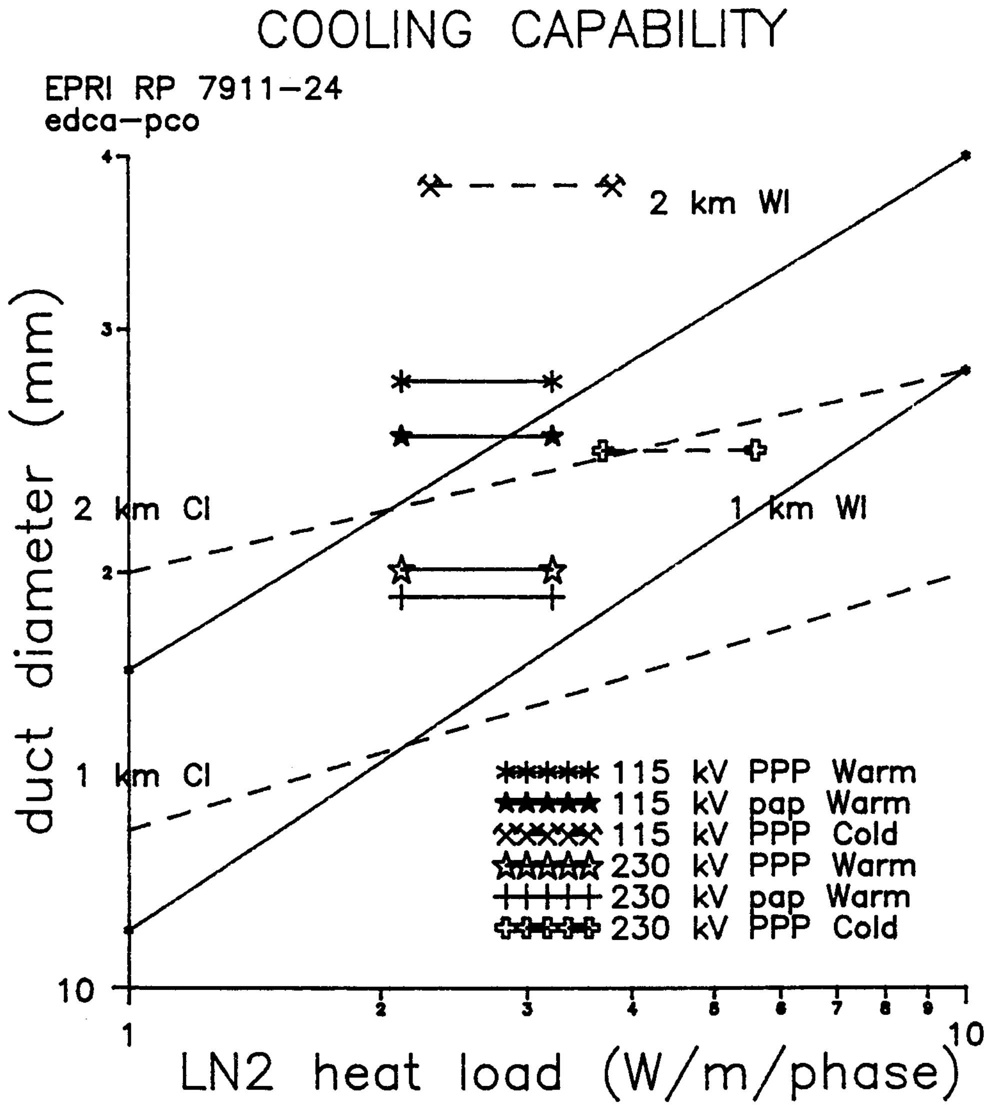


Fig. 3-22

Calculated cooling performance for the cable designs considered in the preliminary phase.
The cooling capability of the conductor channel is compared to the total calculated cold heat load, for both room temperature and cryogenic dielectric alternatives.

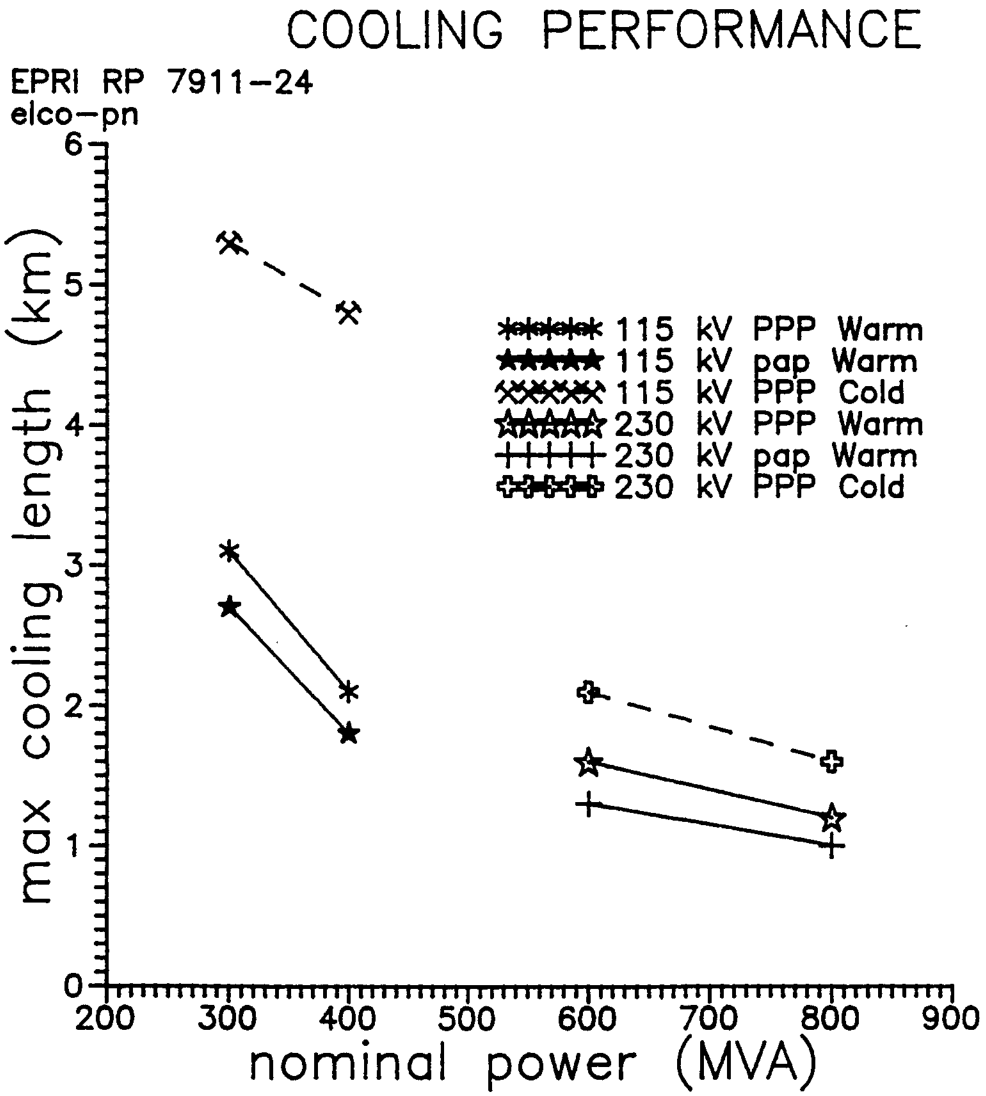


Fig. 3-23

Calculated cooling performance for the cable designs considered in the preliminary phase.
The allowable length for the cooling sections is shown as a function of the transmitted powerfor the considered alternatives.

3.5 Selection of the design for retrofit application

3.5.1 Generalities

The comparative assessment of the different solutions examined has been carried out in the light of the fundamental issues related to manufacturing, installation and operation and considering the characteristics of each component of the cable.
The estimated advantages and disadvantages considered for the selection of the retrofit solution will be presented according to these lists of items.

3.5.2 List of the critical issues

The critical issues considered to assess the different solutions and each component of the cable and of the system are listed in **Table 3-10**, with the indication of their consideration at the level of the preliminary or final design phase.

3.5.3 List of the cable and system components

The fundamental components, including sub-components and details, have been identified for the assessment of their importance for different possible solutions; they are listed in **Table 3-11.**

3.5.4 Assessment of components for different solutions

Table 3-12 shows the most evident remarks to the structure of each component as it has been envisaged from the preliminary design for the different solutions which have been examined; also solution CI-b has been included in this analysis for completeness.

3.5.5 Analysis of components for their importance

The following **Table 3-13** illustrates for each component listed under 3.5.3 the estimated judgement in relation with the critical issues listed under 3.5.2.

3.5.6 Analysis of solutions for their importance

The two practicable solutions which have been identified from the previous analysis (WI and CI-a) have been more specifically examined for their peculiar characteristics; the relevant conclusions with reference to the critical issues listed in 3.5.2 are reported in **Table 3-14.**

Table 3-10

Critical issues for the assessment of the different cable designs.

			prelim.	final
A	MATERIALS			
	1	availability	X	
	2	technology for use	X	
	3	performances	X	
B	MANUFACTURABILITY			
	1	feasibility	X	
	2	availability of technology/machinery		X
	3	practical aspects	X	
C	INSTALLATION			
	1	transportation	X	
	2	pulling		X
	3	filling and cooling	X	
D	OPERATION			
	1	procedures		X
	2	functional parameters	X	
E	PERFORMANCES			
	1	current/power rating	X	
	2	losses	X	
	3	cooling length	X	
	4	short circuit		X
	5	electrical (voltage)		X
F	MAINTENANCE			
	1	reliability		X
	2	repairs (thermal cycles)		X
	3	replacements		X

Table 3-11

List of the sub-components of the cable and of the system identified for the assessment of different designs.

CONDUCTOR	
internal (WI,CI)	cooling channel support (+stabilizer) superconducting tapes binder
external (CI)	superconducting tapes stabilizer binder
CRYOSTAT	
	internal tube metallized plastic tapes vacuum external tube
ELECTRICAL INSULATION	
	internal shield insulating tapes impregnant external shield
COOLING	
	circuit configuration coolers pumps controls fluid
TERMINATIONS	
	electrical field control thermal field control connector HTS to copper mechanical support feeding
JOINT	
	connector HTS to HTS electrical field control thermal barrier mechanical enclosure

Table 3-12

Peculiar aspects related to each component for different designs:

WI: room temperature dielectric
CI-a:cryogenic dielectric, single cryostat
CI-b:cryogenic dielectric, three cryostats

COMPONENT	solution WI	solution CI -a)	solution CI - b)
CONDUCTOR	-sufficient space left -single phase in the cryostat -may be loose in the cryostat	-larger space left -coaxial structure -highly bonded to the insulation	-not enough space left - as for CI-a) - as for CI-a)
CRYOSTAT	-three, small, at high voltage, not accessible	-one, large, ground potential, in principle accessible	-three, small grounded, in princ. access.
ELECTRICAL INSULATION	-large size conduct. -shield over corrug. tube -standard materials and performances	-normal size cond. -normal shape cond. -material to be developed	-smaller than a) - as for a) - as for a)
COOLING	-in conductor channels (1 "go", 2 "return") -no heat leak from go to return	-"go" in three cond. channels, "return" between phases -heat exchange between "go" and "return" flows	-as for WI -as for WI
ACCESSORIES	-in principle standard type over large conductor -electrical and thermal controls may be independent -3 single phase possible	-stress cone at LN temperature or copper end conduct. in standard stress cone -electrical and thermal fields to be integrated	- as for a) - as for WI

Table 3-13

Analysis of the importance of the cable and system components with respect to the fundamental issues listed in Table 3-10.

part 1

	COMPONENTS					
ISSUE	CONDUCTOR	CRYOSTAT	ELECTRICAL INSULATION	COOLING	ACCESSORIES	PIPE
A 1	becoming available	available	in use	in use	available	existing (CS)
A 2	specific development needed	available	WI:in use CI:to devel.	in use	available	-
A 3	sufficient towards good	expected good	quite good	expected good	expected sufficient	limited for WI
B 1	yes	yes	in use	yes	yes	-
B 2	adaptation needed	large size for CI	yes	to select best size	design to develop	-
B 3	to pursue better flexibility	high quality required	-	to define operation procedures	WI simpler than CI	-
C 1	yes	yes	yes	check size	yes	-
C 2	check design	check design	yes	-	-	-
C 3	yes	yes	to develop CI	check cooling time	feasible	in use
D 1	nearly usual	to be defined	usual	to be defined	complex	-
D 2	check design	-	unusual Z_0, P_c	-	-	-

<u>Table</u> 3-13

part 2

COMPONENTS						
ISSUE	CONDUCTOR	CRYOSTAT	ELECTRICAL INSULATION	COOLING	ACCESSORIES	PIPE
E 1	> 2 kA	-	-	not limiting	feasible	thermal limit 2kA for WI
E 2	high for WI	high for WI	WI low CI fair	check efficiency	design for minim.	WI high CI very low
E 3	effective	-	-	normal size	local circuit	-
E 4	10 x I_n likely	10 x I_n likely	-	check cool recovery	check mech. and thermal design	-
E 5	likely good	check for contact between tubes	CI check for reliability	-	usual for WI check for CI	-
F 1	check time stability	highly critical	expected good	expected good	lower than usual	old installation
F 2	not possible	not possible	not possible	yes	yes	as usual
F 3	complete cable	complete cable	complete cable	yes	yes, complex	-

Table 3-14

Analysis of the importance of the two main solutions with respect to the fundamental issues listed in Table 3-10.

WI : room temperature dielectric
CI-a : cryogenic dielectric, three cryostats.

part 1

ISSUE	WI SOLUTION	CI (a) SOLUTION
A 1	-to improve HTS	-to improve HTS -to select dielectric
A 2	-to develop for conductor	-to develop for conductor and for dielectric
A 3	-HTS approaching target	-HTS less near to target -to check dielectric
B 1	-yes	-very likely
B 2	-to develop for conductor, cryostat and accessories	-to develop for conductors, cryostat, electrical insulation and accessories (harder than for WI)
B 3	-cryostat quality and reliability	-cryostat quality and reliability -accessories
C 1	-standard length/size	-large size (3 phase assembly)
C 2	-standard procedure (3 cores)	-single large size flexible tube
C 3	-standard filling to define cooling procedure	-LN filling + cooling to be combined
D 1	-nearly standard, more controls needed	-nearly standard, more controls needed
D 2	-nearly standard	-low impedance, high char. power

Table 3-14

part 2

ISSUE	WI SOLUTION	CI (a) SOLUTION
E 1	-limit at 2 to 2.5 kA in CS pipe	-no conceptual limit up to several kA
E 2	-slightly higher than conventional cables	-significantly lower than conventional cables
E 3	-feasible ≥ 1 km	-feasible ≥ 2 km
E 4	-thermal around 10 x I_n, adjustable by design	-to be verified for high rating, adjustable by design
E 5	-standard performance	-likely standard performance
F 1	-cryostat very critical -accessories likely fair -cooling expected good	-cryostat very critical -accessories likely fair -cooling expected good
F 2	-not possible for cable -feasible for accessories -easy for coolers	-not possible for cable -feasible for accessories -easy for coolers
F 3	-possible for all components	-possible for all components

3.5.7 Comparative evaluation of solutions

From the considerations outlined in the above paragraphs the overall merits and demerits of the two practicable solutions WI and CI-a have been quantified for each critical issue according to the following five levels:

++
feasible, well reliable, little development, effective
+

=

-
critical, less reliable, hard development, little effective
--

The comparative evaluation of the two solutions is reported in **Table 3-15.**

Table 3-15

Comparative overall assessment of the two main solutions, with respect to the critical issues of Table 3-10.

WI :room temperature dielectric
CI-a :cryogenic dielectric, three cryostats.

ISSUE		WI SOLUTION	CI-a SOLUTION
A	MATERIALS		
1	availability	+	+
2	technology for use	+	=
3	performances	++	+
B	MANUFACTURABILITY		
1	feasibility	++	+
2	technology/machinery	-	--
3	practical aspects	=	=
C	INSTALLATION		
1	transportation	++	--
2	pulling	++	--
3	filling and cooling	-	-
D	OPERATION		
1	procedures	-	-
2	functional parameters	=	+
E	PERFORMANCES		
1	current/power rating	+	++
2	losses	-	++
3	cooling length	=	+
4	short circuit	+	=
5	electrical (voltage)	++	+
F	MAINTENANCE		
1	reliability	--	--
2	repairs	--	--
3	replacements	=	=

Table 3-16

Preliminary design specifications adopted for the room temperature dielectric cable for retrofit application.

System voltage	115 kV
Current rating	2000 A
Installation	8-5/8" CS pipe, 14 mm clearance
HTS tapes	4.5 x 0.25 mm, $J_{c\ oper.} = 5000\ A/cm^2$
Conductor	10 layers x 15 tape/layer at 45° over SS spiral O.D. 35 mm
Cryostat	SS corrugated tubes, with 12 mm superinsulation over each phase conductor
Dielectric	Fluid filled (14 bar), 7.2 mm thick PPP

From this comparison it appears that the WI solution has advantages in terms of materials, manufacturability and installation, while better performances can be expected from the CI solution and that both solutions need substantial development of the specific technology to ensure a good reliability.

These conclusions are an analytical confirmation of the preliminary evaluations made for the two alternatives (see 3.1.2) and support the final choice of the room temperature dielectric solution for the final design of the retrofit application.

3.5.8 Preliminary cable specifications

For the selected warm insulation solution the specifications listed in **Table 3-16** have been adopted to proceed with the design finalization for the retrofit application.

Based on this specifications a full size mock-up of the cable has been assembled and supplied to EPRI to facilitate the understanding of the cable structure and to support the presentation of the cable design to the technical representatives of the utilities (Fig **3-24** , **3-25**).

Section 4

CABLE DESIGN FINALIZATION FOR RETROFIT APPLICATION

4.1 Review of preliminary design

4.1.1 General

The preliminary design obtained under 3.4 for the room temperature retrofit cable (WI solution) has been reviewed in order to define those details which had not yet been finalized and in particular:

Conductor:
    SS support
    actual thickness of the HTS tapes
    binder
    hydraulic resistance of the channel

Cryostat
    actual tube thickness
    corrugation parameters

Electrical insulation
    structure of shields
    actual thickness

Pipe
    thermal calculations

Cable performances
    losses
    cooling
    short circuit

The said components have been reconsidered in a whole and in the perspective of the electrical, mechanical, thermal performances as well as of the overall performance of the cable, in terms of total losses, cooling length and rating.
Calculation have been carried out with the best available parameters, using the most appropriate equations and with some necessary extrapolations, on the basis of the final dimensional specifications listed under 4.2.

Parallel calculations have also been performed for the cryogenic dielectric retrofit solution (CI-a), although limited to a lower degree of refinements; the basic design data have been verified and the losses and main performances of the cable have been calculated and compared to those of the WI solution and of conventional cables for reference (see 4.3).

4.1.2 Electrical design

The conductor has been based on normal operation at I_n equal to 0.4 times

|

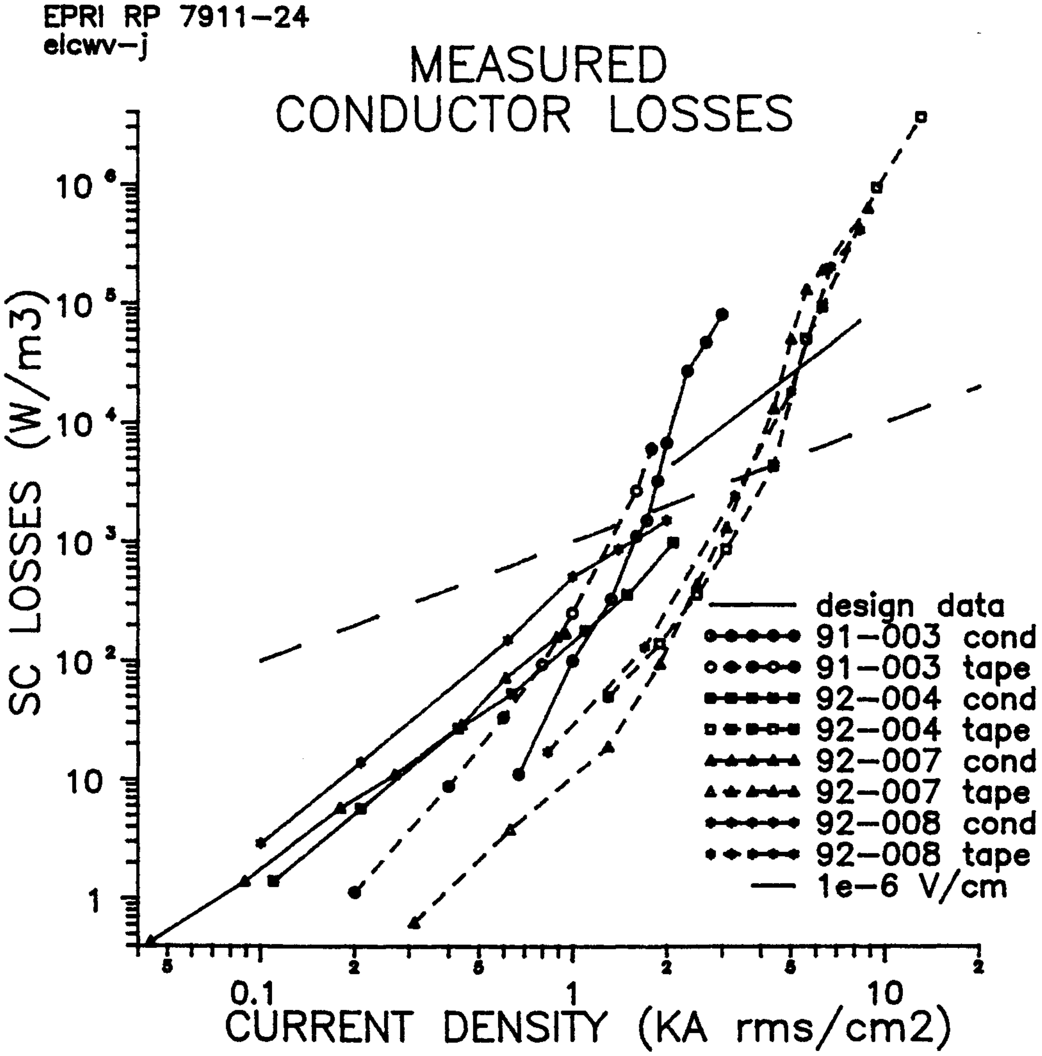


Fig. 4-1

Experimental values of conductor and tape losses versus current density, in self field at 50 Hz for short conductor prototypes from the ASC-Pirelli development program (see Table 4-1).
The interrupted line represents the critical level, assumed at 10^{-4} V/m.

Table 4-1

Characteristics and performances of tapes and prototype conductor samples (PMC) from the ASC-Pirelli development program.

PMC's PERFORMANCES					
#	date	length (m)	N x tape Ic d.c.(A) a.c.(Arms)	PMC Ic d.c. (A) a.c. (Arms)	%
91-003	May 91	0.3	2 x 18 x 3.2 1.7	102 60	90 97
92-005	June 92	0.3	2 x 18 x 14.6	288	55
92-P1	June 92	0.3	2 x 17 x 9.9 7	≥180 ≥150	≥55 ≥65
92-004	May 92	1	2 x 18 x 6-10 4-7	202 160	80 89
92-008	Aug 92 (MP	0.3	61 x 4 + 20 x 2.4 2.5 1.9	240 120	82 63
92-007	Aug 92	1	4 x 18 x 8.2 6	500 300	85 70

the critical (10^{-4} V/m) current I_c and calculations have been made at 0.5, 1 and 2.5 I_n and for the short circuit in adiabatic conditions during 0.5 s.

The performance which has been assumed for tapes is a critical current level of 12.5 kA/cm^2 (r.m.s.), which has been extrapolated from the available performance (**Fig. 4-1, Table 4-1**) of 5 kA/cm^2 (r.m.s.); this corresponds to an assumed operating current density of 5 kA/cm^2 , for a typical HTS cross section (24% of the total for the assumed size 4.3 x 0.25 mm) of 0.26 mm^2/tape.
To obtain the total rated current of 2 kA with the rated tape current of 13 A, a number of 154 tapes will be needed; their arrangement in lay angle and number per layer has then been defined on the basis of mechanical considerations (see 4.1.2) and the final actual structure has been used to calculate losses.
As a first approach it has been verified that 10 layers of such tapes (**Fig. 4-2**) would permit to reach a total current in excess of 5 kA before incurring in self field limitations of the tape current capability. (**Fig. 4-3,4-4**)

Conductor losses have been calculated as the sum of two independent components:

- HTS material losses, extrapolated from the available measurements in low self-field (Fig.3-6, 4-1) which have been expressed for the whole phase conductor by the equation

$$P\ (I) = P_{crit}\ (I/I_{crit})^2 = 10^{-4}\ I^2/I_{crit} \qquad (4.1.2.1)$$

- eddy losses in the metals (SS spiral support, silver matrix of the tapes, SS binding tape) calculated according to the standard equations for spiral elements of cables in three phase field configuration [3],[22],[23].

The relatively high degree of uncertainty in the determination of the HTS losses has been accepted because they appear to be quite smaller than the eddy losses in the metals, and in particular in the silver matrix, at least in the examined case of three phase field configuration (**Fig. 4-5**), the eddy losses component being calculated in a well reliable way as a common practice in cables.

The case of tape performances significantly lower than the levels assumed for the design of the conductor has also been considered.
Starting from the assumption that the basic parameter would be the a.c. critical current of the conductor, at the 10^{-4} V/m voltage gradient, corresponding to the dissipated power 10^{-4} x I_{crit}, and that the current dependance of the losses would be quadratic, the values reported in **Fig. 4-6** and **Fig. 4-7** have been calculated.
These figures show the conductor losses versus total current which are expected for different levels of critical current of the conductor (both in absolute and relative to I_{oper} values).
From these results it appears that levels of losses which might significantly affect the design of the cable and its overall loss and cooling performance are unlikely to be reached, even for conductor performances significantly below the present expectations.
It is important to remark in this respect that a current dependance of losses more than quadratic would give rise to lower losses than those given in Fig. 4-6 and 4-7 at the operating current, this being below

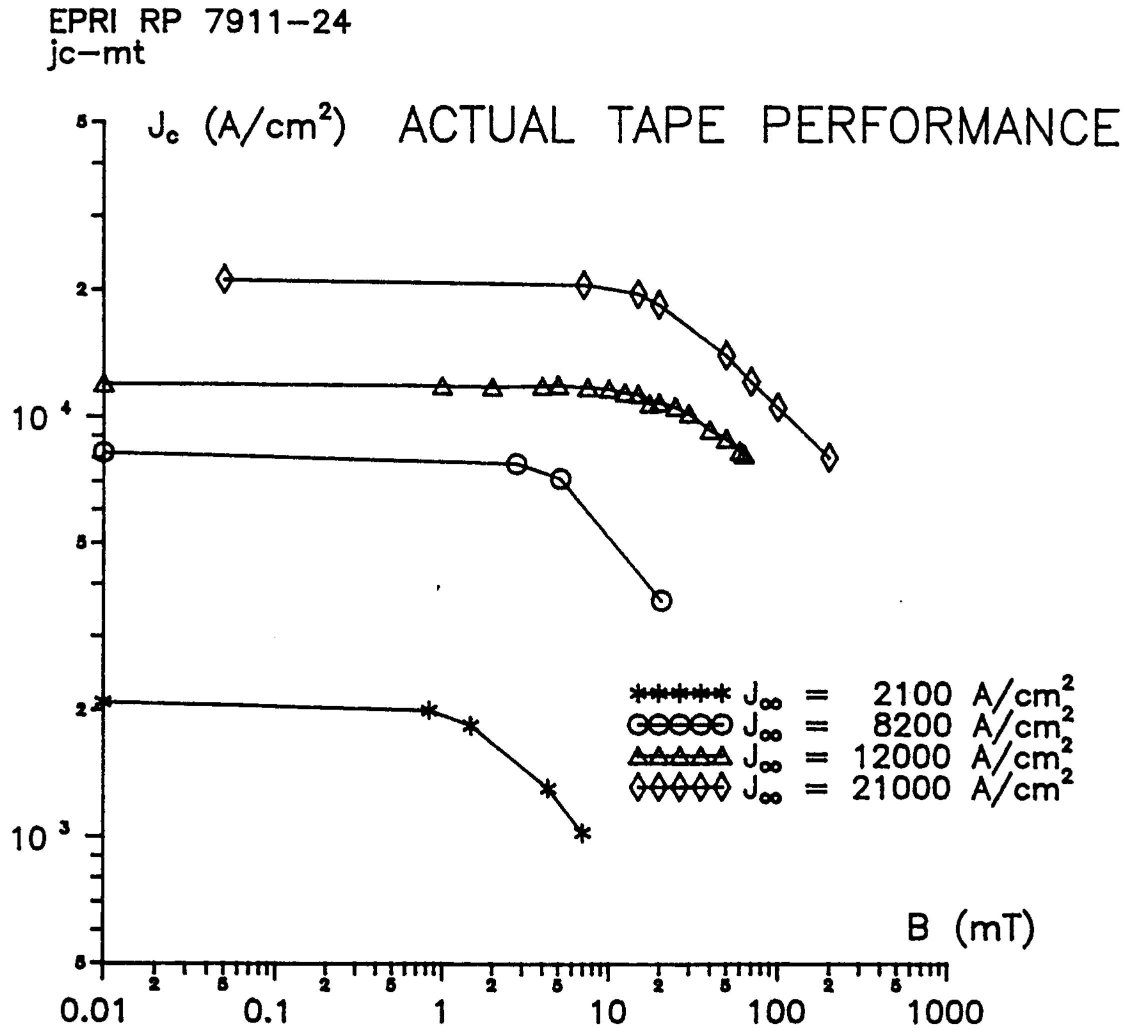


Fig. 4-2

Typical performance for critical current density versus magnetic field for 2223 BSCCO tapes.

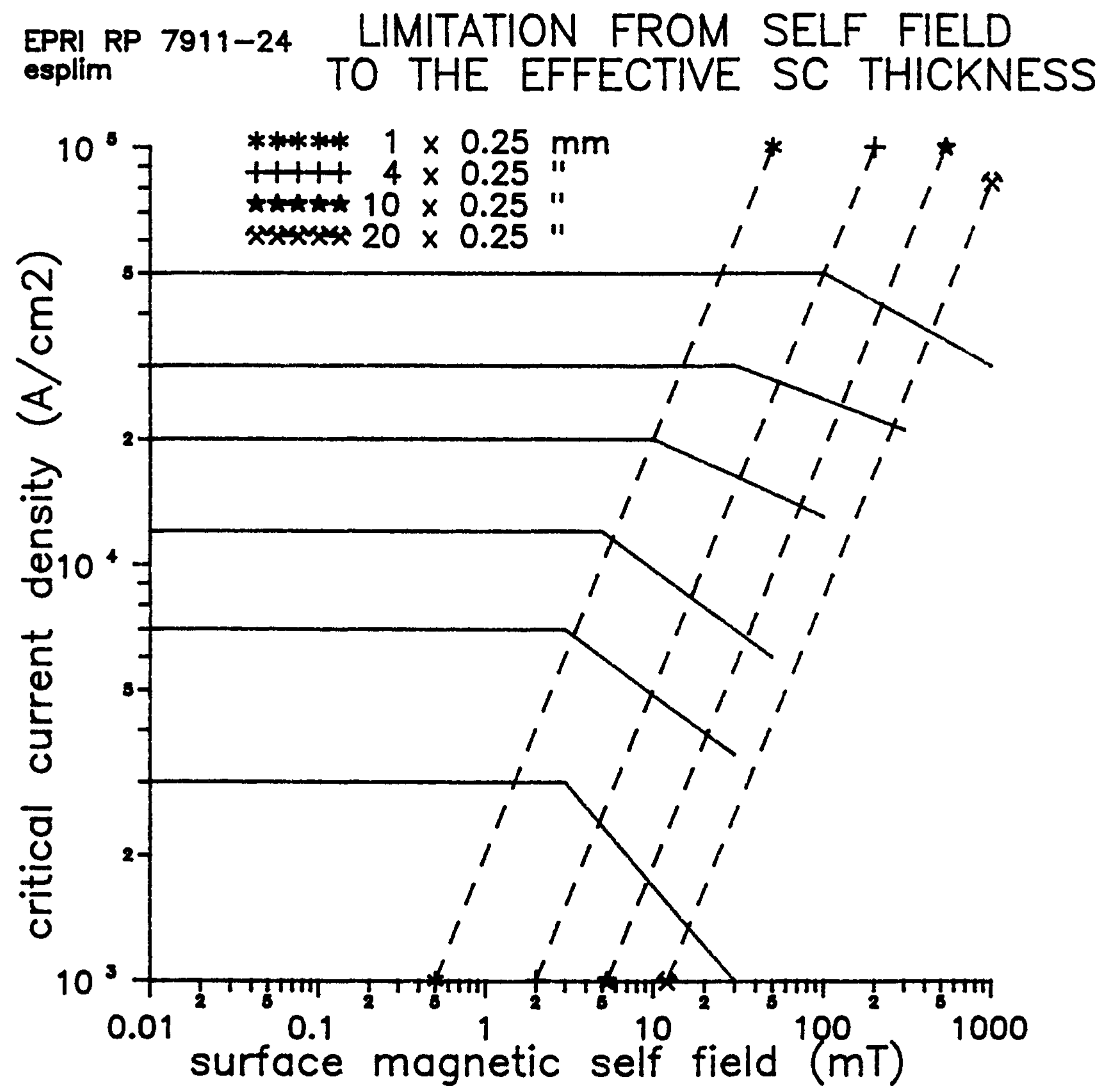


Fig. 4-3

Schematic representation of the current limitation arising from self field effect in thick conductors, for tapes having different performances and for increasing total thickness of the tapes in the conductor.

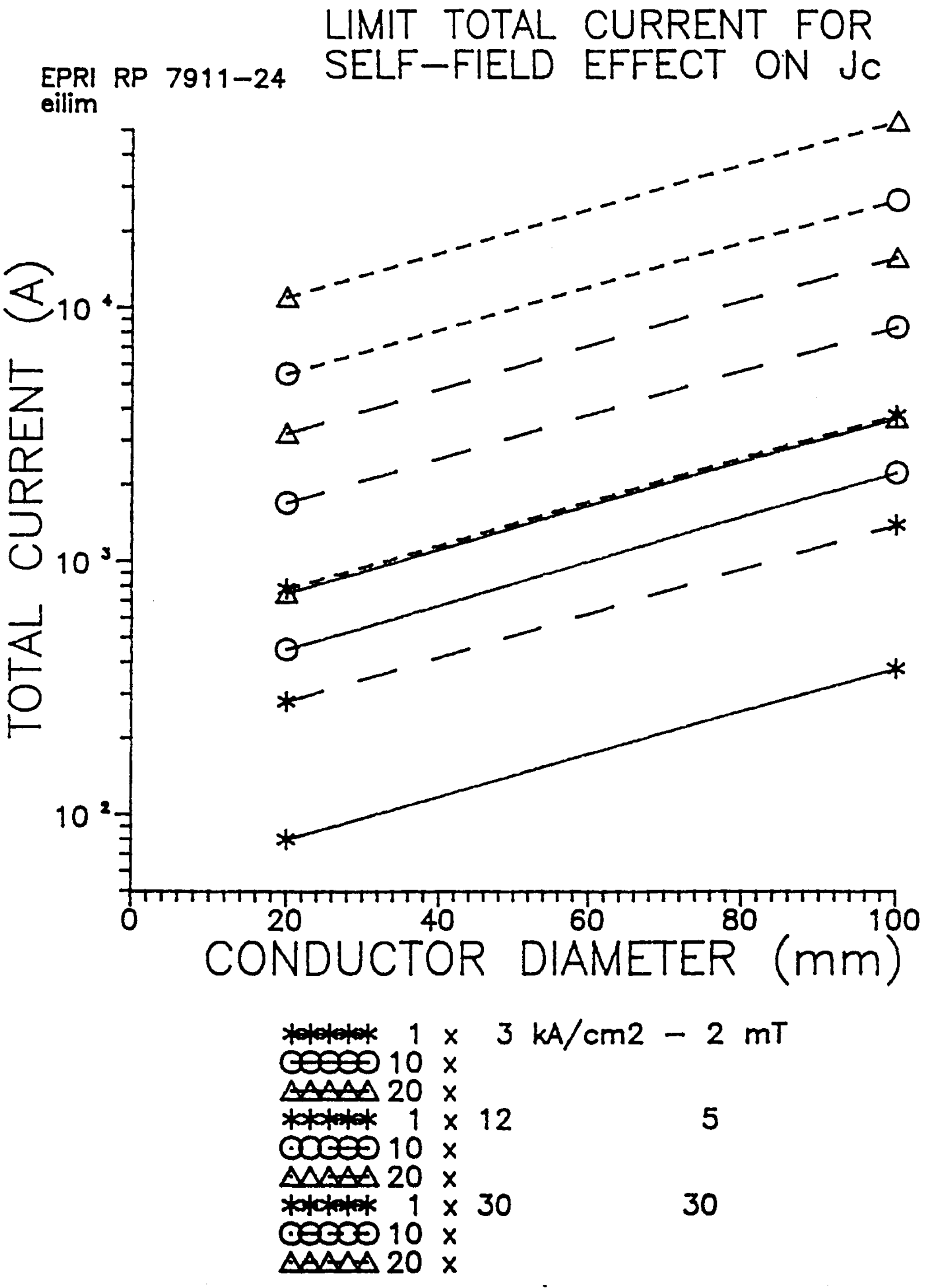


Fig. 4-4

Calculated value for the inception of self field effect in conductors made of increasing number of tapes having the performances as in Fig. 4-3 versus the conductor diameter.

the critical current, and that the actual measurement of the conductor a.c. performance has to be considered a critical step for the development of the cable.

The effect of temperature on the superconductor losses has also been examined.
Very few data are available on a.c. loss measurements on HTS samples at different temperatures, while most data are related to critical current versus temperature [21],[30].
It is possible to estimate the loss dependance on temperature by applying the loss equations to the temperature-dependent values of the critical current [3]: this calculation would estimate variations in losses by a factor from 3 to 5 for a 70% variation in J_c to be expected in a temperature range of 15 K.
Some recent experimental data (**Fig. 4-8**) are confirming that this values are in fact approached on actually available tapes.

In conclusion the values from the adopted equation, given also in Fig. 4-5 have been used, and variations along the cable due to temperature differences and/or to local inhomogeneities of the performance have been neglected versus eddy losses and thermal losses, until sufficient experimental data will be available.

The PPP electrical insulation has been structured as for a conventional cable and designed with the following stress levels:

inner shield (helical SS wire to fill the corrugation grooves
SS tape + three conducting tapes
two conducting tapes + one duplex tape)

a.c. stress: <= 15 kV/mm
B.I.L. stress: <= 84 "

outer shield (one duplex tape + two metal.tapes
one SS tape + one mylar tape
two 5 x 2.5 mm skid wires)

a.c. stress: <= 15 kV/mm
B.I.L. stress: <= 70 "

4.1.3 Mechanical design

The structure of the conductor has been reconsidered mostly with the aim to verify its flexibility with respect to the strain performance of HTS tapes.

The strain induced in tapes has been verified for the following conditions:

- winding of tapes to assemble the conductor, with the associated bending strain (depending on the diameter and lay angle) and winding tension (assumed to be 5 N/tape);

- pulling of the conductor for the manufacturing (assumed to be 10 N/tape);

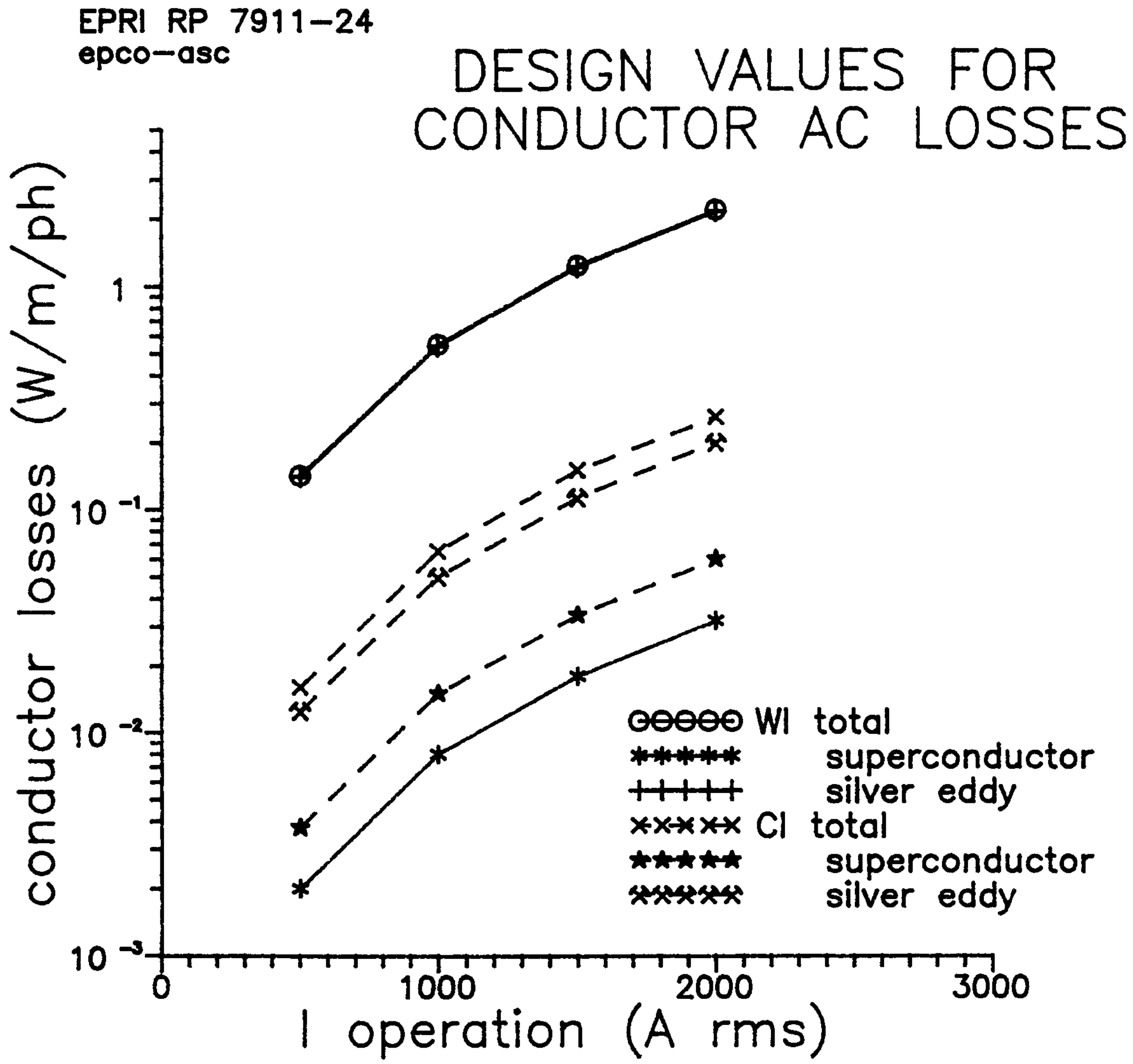


Fig. 4-5

Design values for conductor losses, calculated as the sum of superconductor losses from equation (4.1.2.1) and of eddy losses in the silver matrix.

WI: room temperature dielectric, three phase field configuration
CI: cryogenic dielectric, coaxial configuration.

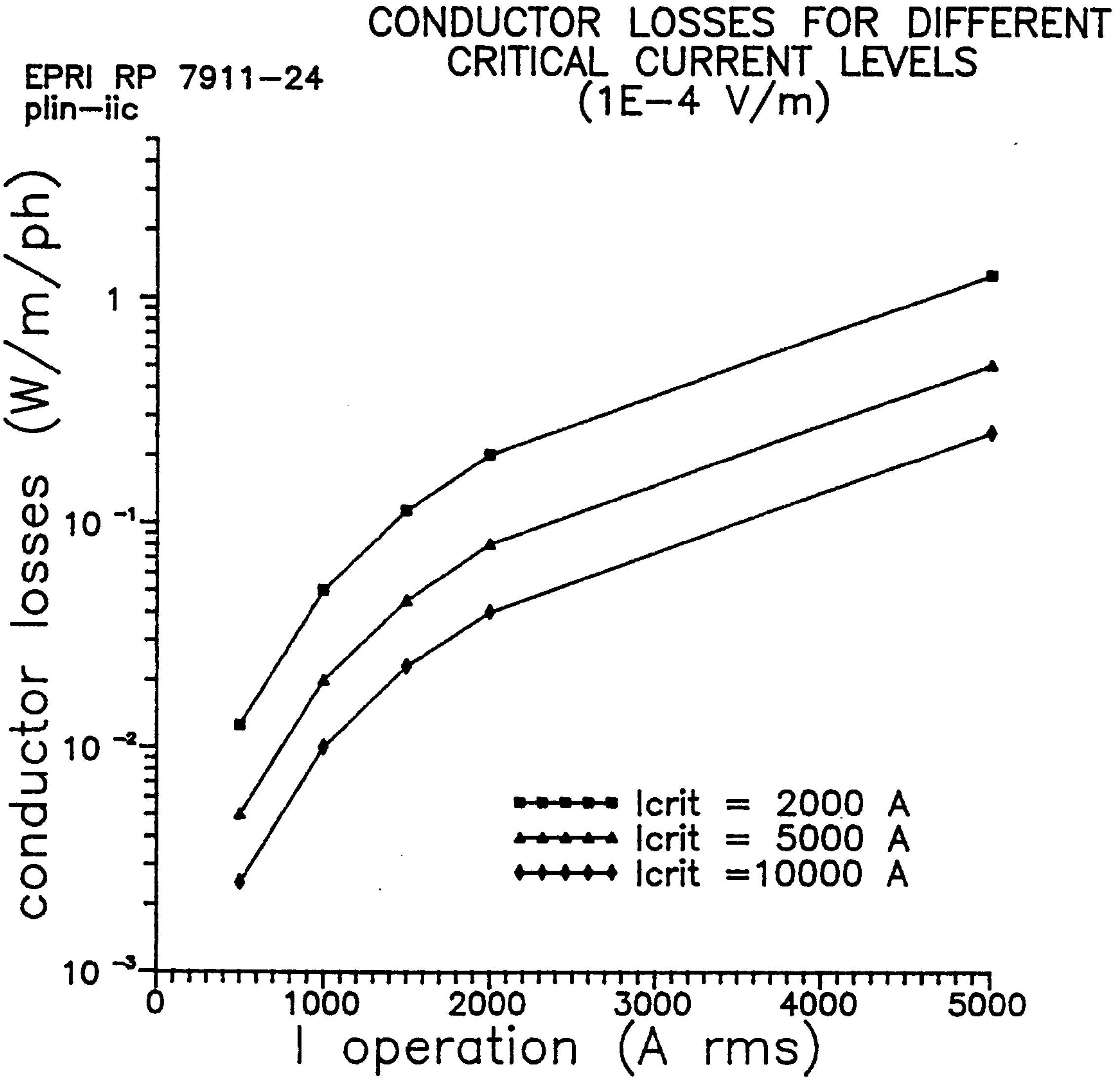


Fig. 4-6

Conductor losses calculated from eq. 4.1.2.1 for conductors having different critical current levels, versus the operating current.

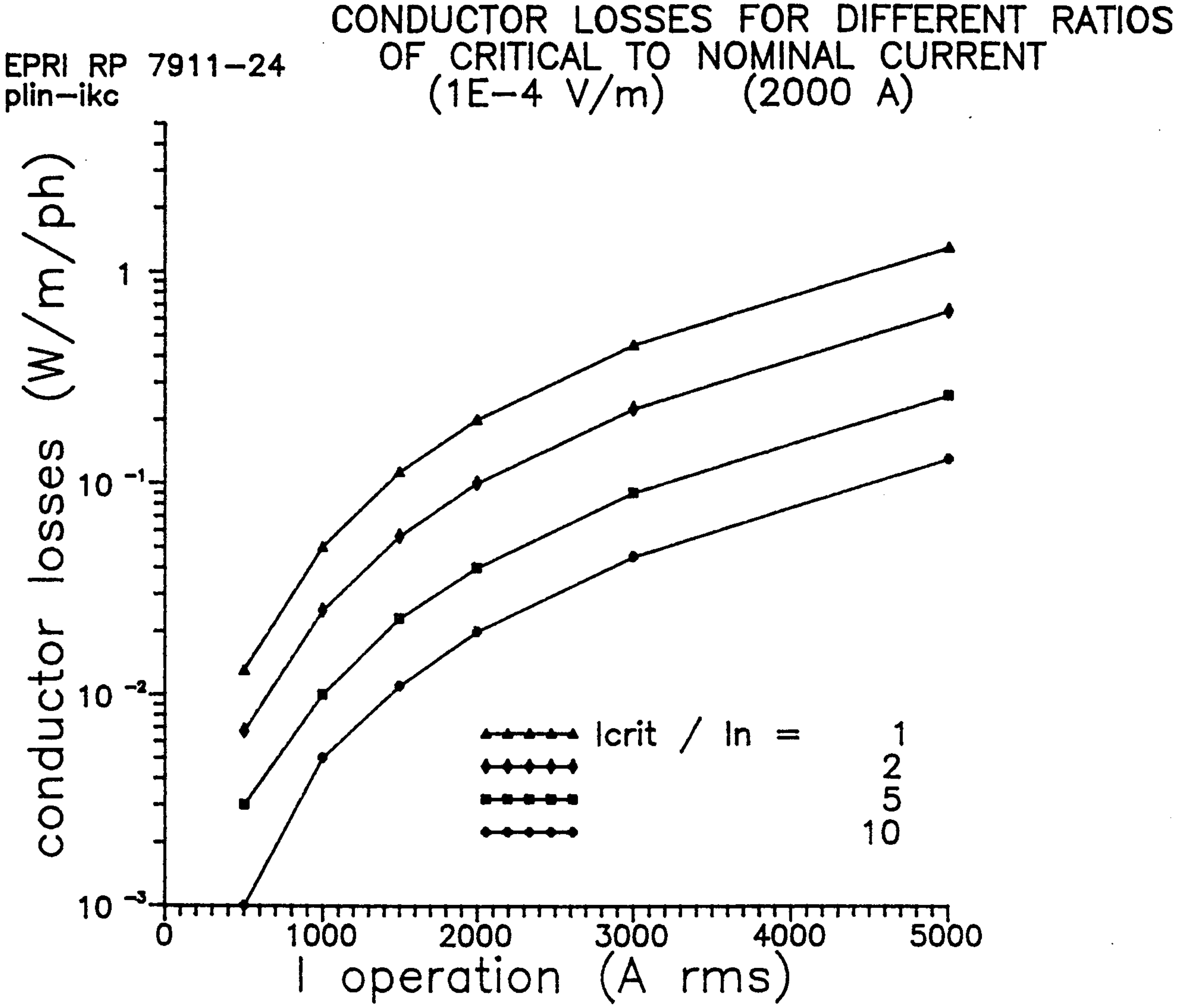


Fig. 4-7

Conductor losses calculated from eq.4.1.2.1 for conductors rated 2000 A, having different levels of critical current to rated current, versus the operating current.

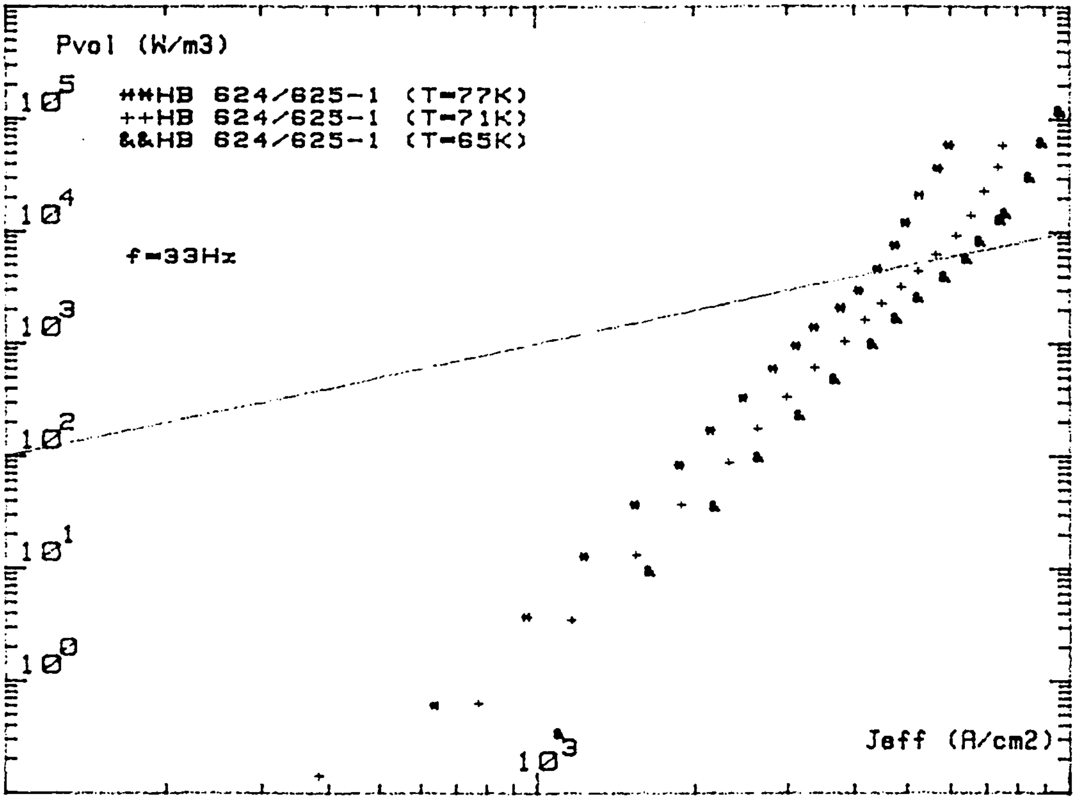


Fig. 4-8

Experimental values of tape losses versus current density, at different temperatures, in self field at 50 Hz for prototypes from the ASC-Pirelli development program (see Table 4-1).
The interrupted line represents the critical level, assumed at 10^{-4} V/m.

- bending of the conductor for the manufacturing (assumed over 2 m diameter);

- cooling of the conductor with fixed ends after installation (from room temperature to LN);

Less critical situations have not been directly calculated; they include all bendings for transportation and installation (over larger diameters and with additional mechanical reinforcements than during manufacture), pulling during installation (essentially withstood by the other cable components).

Starting from an internal diameter of 30 mm, 10 layers made of 15 tapes each have been assumed to be laid in alternatively opposite directions with a pitch of 110 mm. This geometry leads to openings between tapes ranging from 0.47 to 0.88 mm and to lay angles from 41 to 45 degrees.

The strains calculated for the said conditions are listed in **Table 4-2** and indicate that with the adopted geometry the level of 0.4 % strain, which appears to be acceptable for tapes as the expected limit for degradation of their performance [5],[6] can be accepted.
The very small safety margin (mostly needed for possible anomalous overstrains in manufacturing) adopted for the calculated strain with respect to the actual degradation limit assumes that an appreciable improvement of the strain performance of tapes is expected in the next future, as suggested by recent results [6].

This aspect will have to be verified to a wider extent than the first encouraging data obtained on simple hand-made conductor samples (Table 4-1 and Fig. 4-1), by means of experimental measurements of both tape performances and possible manufacturing induced degradation on machine assembled conductor samples.
It would be possible in any case to limit the tape strain to a lower level, by selecting a more conservative design for the conductor geometry, if necessary to achieve a safer operating condition, and within the limits allowed by the other design constraints.

The support spiral has been dimensioned as usual for conventional conductor supports, using a 7 x 1.2 mm stainless steel strip wound with a suitable pitch of 10 mm, this geometry leads to a sufficiently regular surface (2.6 mm opening) for the tape winding and to a good flexibility, with an internal channel of 27.5 mm (see 4.1.4) and an overall diameter of 30 mm.

The overall reinforcement has been designed to withstand the surface magnetic pressure at the HTS tapes for ϕ= 35 mm in short circuit conditions

$$p = 1/2 \mu H^2$$

with a stress of 100 MPa up to 70 kA (peak).

The resulting total thickness of the tape has been fixed at 0.1 mm , and structured in two overlapped 0.05 mm thick SS tapes, 19 mm wide and laid with a 22 mm pitch.

Table 4-2

Calculated strains for HTS conductor tapes based on specifications of Table 3-16.

MECHANICAL DESIGN			
CONDUCTOR			
- HTSC nominal tape strain:			
winding	(ϕ = 32 mm α = 43°)	0.36	%
pulling	(10 N/tape)	0.01	%
bending	(ϕ = 2 m)	0.01	%
cooling	(room to LN_2)	-0.15	%
- reinforcement tape stress	(50 kA_{rms})	95	MPa

For the same level of short circuit current the lateral pressure in the case of a phase to phase short circuit has been calculated to be 12 kN/m, which is expected to be acceptable without damage to the HTS tapes; an experimental verification has of course to be planned also in this case.

The structure of the cryostat (based on a 12 mm thick space for the superinsulation layers) has been designed for the following conditions:

- internal pressure of the coolant (20 bar max operating value);
- external pressure of the impregnating fluid (15 bar);
- pulling force for installation (10 kN);
- bending during manufacture (min diameter of 2 m).

For an operating stress assumed at approximately 50 MPa at the said pressures, the thickness of both tubes has been confirmed at 0.7 mm and the strains resulting from the adopted corrugation depth of 2 x 0.7 = 1.4 mm have been found quite acceptable.
The actual results from calculation are listed in **Table 4-3.**

4.1.4 Thermal design

For the conductor the thermal aspects to be verified have been the cooling efficiency, the overload and short circuit thermal capability and the behaviour in the case of cooling failures.

Table 4-3

Mechanical performances related to the cryostat based on specifications of Table 3-16.

MECHANICAL PERFORMANCES OF THE FLEXIBLE CRYOSTAT AND OF THE CABLE			
- cryostat ID/OD		36.2 / 68.2 mm	
- stress under pressure:	(cold tube 20 bar)	54	MPa
	(warm tube 15 bar)	47	MPa
- strain under pulling:	(10 kN/phase)	0.3	%
- strain under bending:	(ϕ = 2 m)	<0.01	%
- installation pulling force:		10 kN/500 m phase	
- installation lateral pressure:		2 kN/m = 76 N/skid wire	
- short circuit lateral pressure:		12 kN/m phase	
- cable weight		8 kg/m	

Table 4-4

Final cable specifications for the room temperature dielectric cable (WI) and refined preliminary specifications for the cryogenic dielectric cable (CI).

TYPICAL CABLE SPECIFICATION					
type		WI		CI	
voltage	kV	115		115	
current	A	1500	2000	1500	2000
power	MVA	300	400	300	400
φ duct	mm	27.5		37.0	
conductor O.D.	mm	35.2		47/66	
cold tube O.D.xthick.	mm	40.4 x 0.7		151 x 1.5	
warm tube O.D.x thick	mm	68.2 x 0.7		182 x 1.6	
electrical ins. thick.	mm	7.25		6.6	
thermal ins. thick.	mm	11.8		10.5	
conductor losses	W/m/ph	1.2	2.2	0.15+0.06	0.25+0.11
thermal "	"	0.5		0.5	
cold tube "	"	0.60	1.08	0.3	0.5
dielectric "	"	0.93		0.30	
warm tube "	"	0.47	0.85	0.3	0.5
hydraulic "	"	0.17	0.20	0.15	0.20
shield "	"	0.24	0.43	-	-
pipe "	W/m/cct	46.3	83.4	5.5	10
cold heat load	W/m/ph	2.49	3.9	2.46	2.86
warm losses	W/m	51.2	87.3	5.5	10
total"hot"losses (14W/W)	"	156	268	60	78
max. cooling length	m	2100	1600	4100	3600
transmission losses	W/km/MVA	520	670	200	195

The pressure drop along the conductor channel has been calculated for the scheme of Fig. 3-9 according to the standard methods [23],[36],[37] with the relevant parameters of the coolant [38] and taking account of the additional hydraulic resistance due to the presence of the spiral support, for the actual dimensions selected and for the calculated amount of losses. The results, shown in **Table 4-4**, confirm that hydraulic losses are limited to 0.20 W/m/phase (equal to less than 7% of the total cold heat load) and that cooling sections up to 1.6 km can be permanently operated at full load.

In the case of overload of the order of twice the rated current, that is up

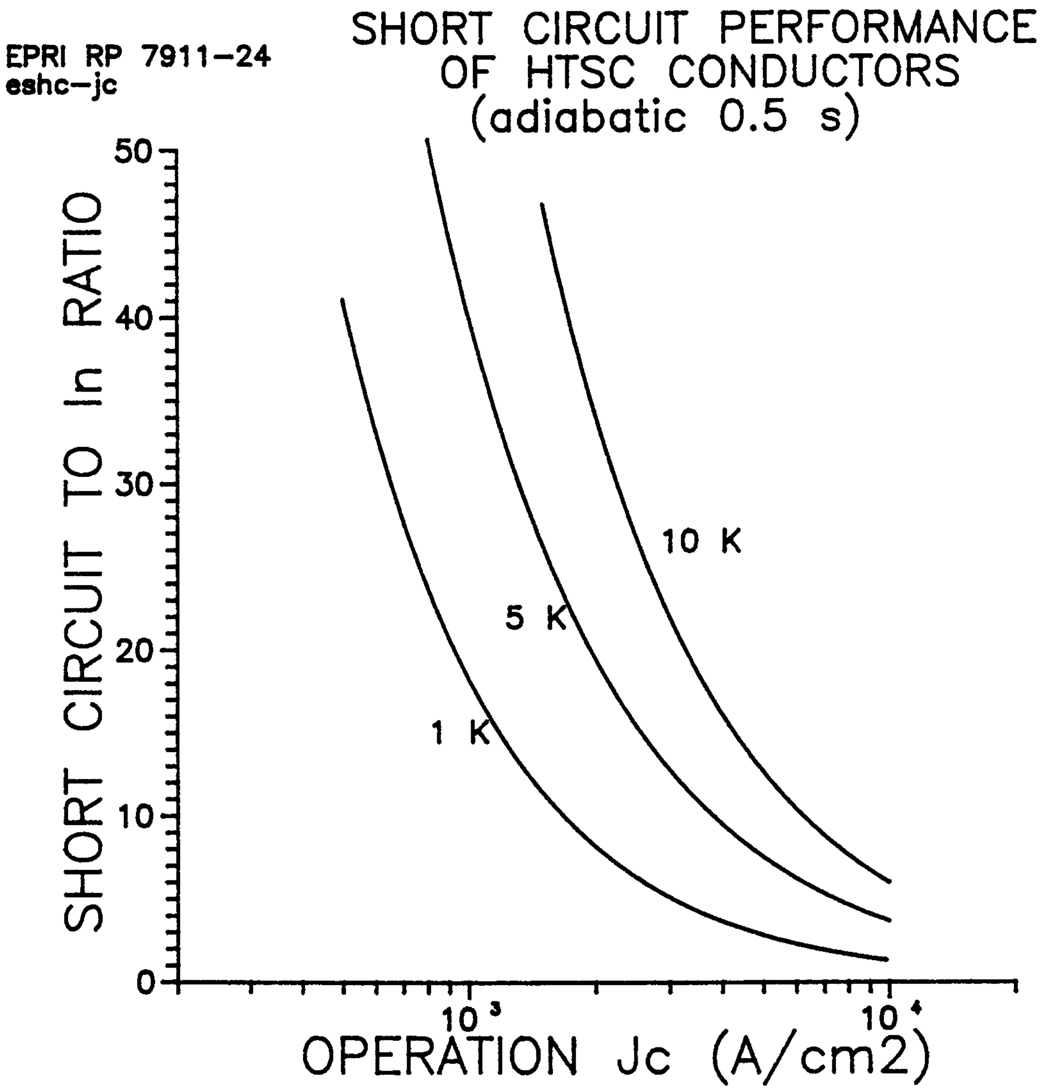


Fig. 4-9

Thermal short circuit performance of HTS conductors versus the rated current density, for different adiabatic temperature increases.

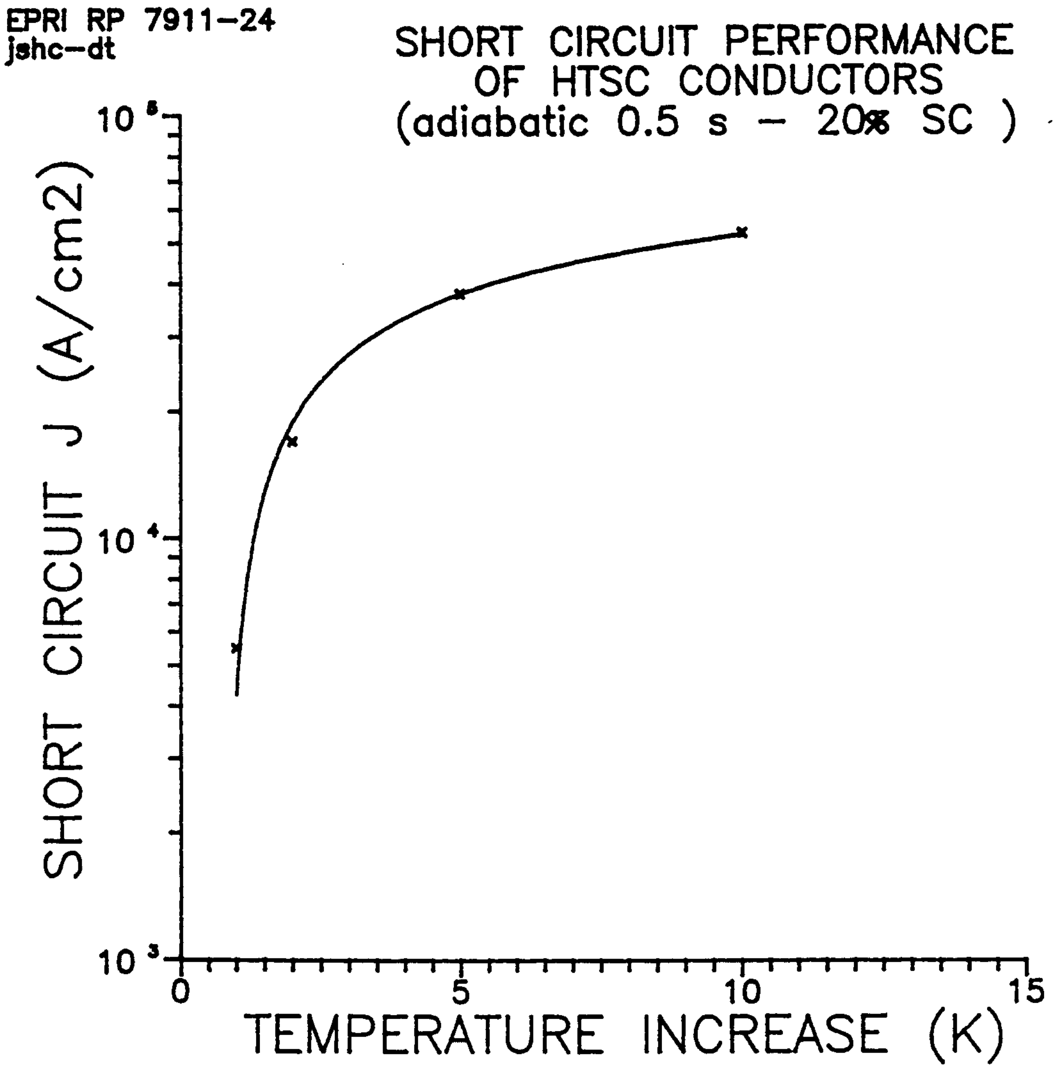


Fig. 4-10

Thermal short circuit performance of HTS conductors versus the adiabatic temperature increase.

to the critical current level, it has been already discussed in 4.1.2, the generated losses would not exceed levels not compatible with an acceptable surface heat exchange rate (around 0.1 W/cm^2) and a temperature increase likely to be tolerable [39],[40].

In the case of a short circuit at 50 kA/cm^2 (r.m.s.) during 0.5 s, the temperature increase calculated in adiabatic conditions for the conductor assembly (**Fig. 4-9, 4-10**) would be equal to 8 K, therefore still keeping the HTS tapes at a current capability likely in excess of the rated current (Fig. 4-8) at the end of the short circuit.
The amount of heat accumulated in the conductor, corresponding to that generated during approximately 10 minutes at full load, is likely to be removed without any uncontrollable perturbation to the cable operation, even immediately after the short circuit.

In the unlikely case of a complete stop of the coolant flow, with the cable operated at full load, the heating of the cold components of the cable (LN, conductor and cold corrugated tube) at the calculated amount of losses (4W/m) would increase the temperature at the rate of 15 K/hour; the rate would be reduced to 1.9 K/hour for the cable at no load, with only thermal losses (0.5 W/m) present.

This leaves sufficient time to exclude the cable from service and, if necessary, to discharge the LN from the cable (2 hours approximately if discharged at both ends of a 1 km section) before the critical point of LN (126 K-33 bar) is approached.

Experimental verification of the discussed transients should be planned to determine the actual capability of the conductor and of the cable in anomalous conditions, and in particular to verify that an electrical and thermal stabilization of the conductor may not be necessary to obtain a full stabilization in a reasonable overload range and an adiabatic stabilization in short circuit.
This analysis might result in a reconsideration of the optimum filling factor of the tapes and/or of the possible use of a stabilizing layer, if more stringent performances than the "intrinsic" one of the selected tape assembly had to be achieved.

For the <u>cryostat</u> the final thickness of the superinsulation layers, which have been assumed to be crinkled alluminated mylar films [25],[41], has been fixed to obtain a distributed amount of thermal losses of 0.2 W/m .
This level of losses is expected to be achieved by a number of 45 layers of 6.4 μm tapes softly wound in the 12 mm gap between the corrugated tubes.
The required level of vacuum, in the range of 10^{-4} torr, is to be obtained by means of a preliminary evacuation of the space between the tubes and by the subsequent activation of suitable getters [42] in this permanently sealed environment during the appropriate manufacturing phase (for example the drying of the electrical insulation).

Table 4-5

Thermal calculations for the warm components of the room temperature dielectric cable specified in Table 4-4.

THERMAL CALCULATIONS FOR THE WARM COMPONENTS OF THE CABLE			
CURRENT	(A)	1500	2000
LOSSES	(W/m/ph)		
"conductor"		-0.5	-0.5
warm tube		0.47	0.85
dielectric		0.93	0.93
shield		0.24	0.43
pipe		46.3/3	83.4/3
TEMPERATURE	(K)		
dielectric		52	75
shield		51	75
pipe		51	73
ambient		20	20

The spacer between the two corrugates tubes will be made by a tightly applied, helically wound plastic cylindrical rod (ϕ= 11 mm, lay pitch 76 mm), which will keep in place the tubes in the axial direction and will support the lateral pressure (12 kN/m) during the short circuit.

This structure and this process require some assumptions that will need an extensive experimental verification on cryostat models before manufacturing a cable prototype:

- the actual achievement of the expected level for the vacuum;

- its stability and durability in time;

- the total amount of thermal losses;

- the practical aspects of sealing of the ends and, if necessary at intervals along the cable lengths;

- the practical aspects to install the cable and to join it without breaking the vacuum.

For the <u>electrical insulation and pipe</u>, the thermal calculation has been carried out as for conventional cables [3],[22],[23],[34],[37], considering the warm tube losses, the dielectric losses, the shield losses, the pipe losses and a value of -0.5 W/m for the conductor losses to account for the thermal inleak from the conductor shield to the LN circuit.

From this standard calculation carried out for the specified dimensions, the temperature of the dielectric and of the pipe at different loads have been determined (**Table 4-5**) and found to be approaching the limit acceptable values for the 2000 A rating.

Some uncertainty has to be kept on this likely thermal limit, since experimental data for the pipe losses, which are the main responsible of the cable heating, are at present limited to substantially lower ratings at the level of 1 kA.

A significant reduction of actual losses with respect to the extrapolated equations from [22],[23] may be in fact expected [3], mainly due to the possible saturation of the magnetic pipe.

For an optimized cable design, the dielectric temperature should not exceed that in use for conventional cables; as a consequence of the very small temperature drop inside the pipe, the total heat dissipated in the environment from the pipe would in the end be higher than for conventional cables installed in the same pipe and operated at their full (lower) load, even if the usual pipe temperature is not exceeded.

4.1.5 Cable performances

The losses calculated for each element (or layer) of the cable are listed either in Table 4-4, for both WI and CI-a solutions and in **Fig. 4-11** and **4-12** for the WI and CI-a solutions, respectively.

In addition **Fig. 4-13** compares directly the losses for the two solutions.

In both cases the cooling losses have been calculated as 14 W/W, neglecting any minor variation of efficiency to be expected depending on the actual size of the coolers [35]; this refinement has not been performed because the final value of this size would be determined to a large extent also by the requirements for accessories and, more important, by operation, maintenance and reliability considerations.

Therefore a standard size of coolers of the order of 1000 kW, leading to cooling losses around 14 W/W has been retained.

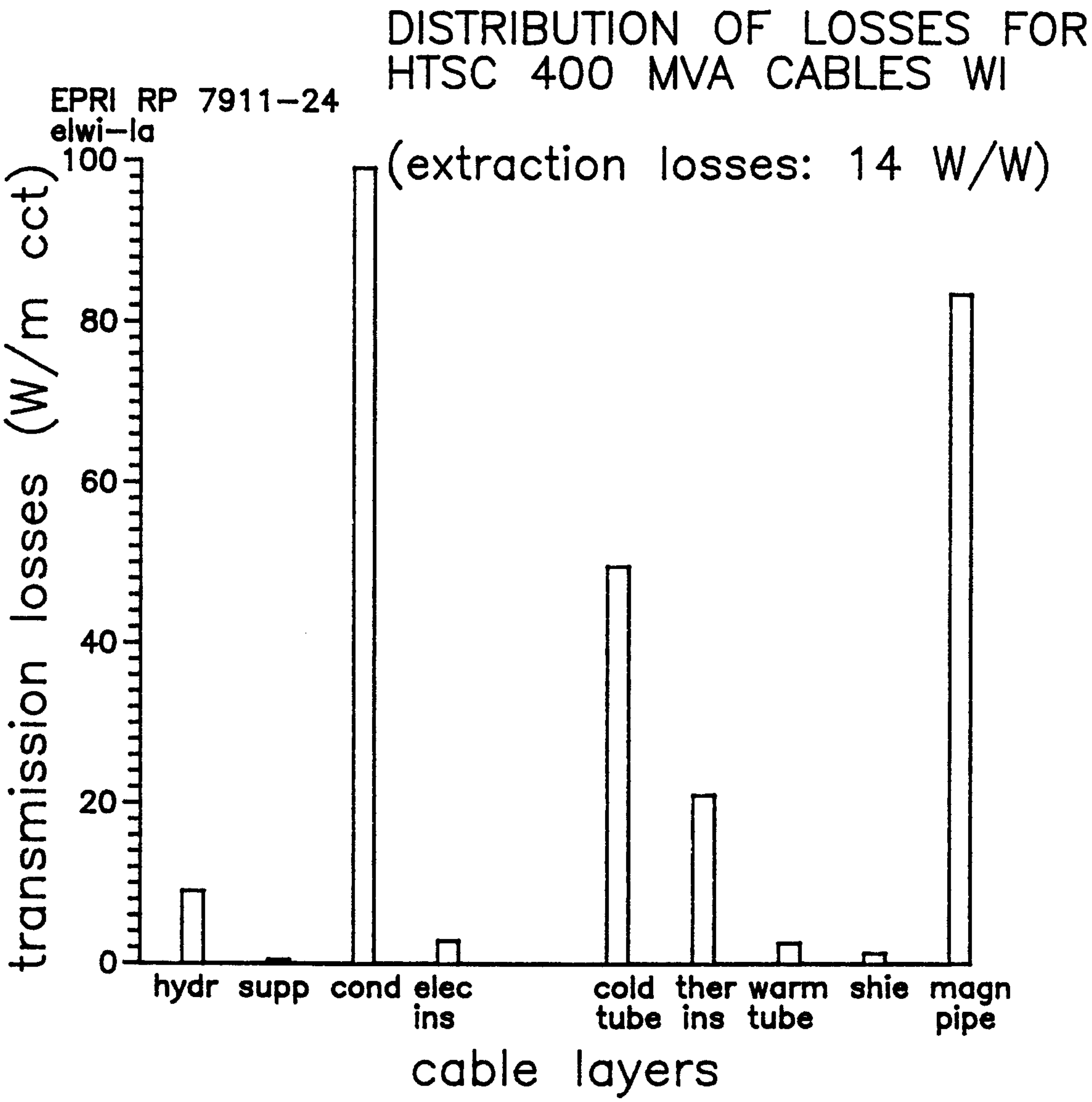


Fig. 4-11

Repartition of transmission losses among the various elements of the cable calculated for the room temperature dielectric solution. All cold losses have been added with cooling losses at 14 W/W.

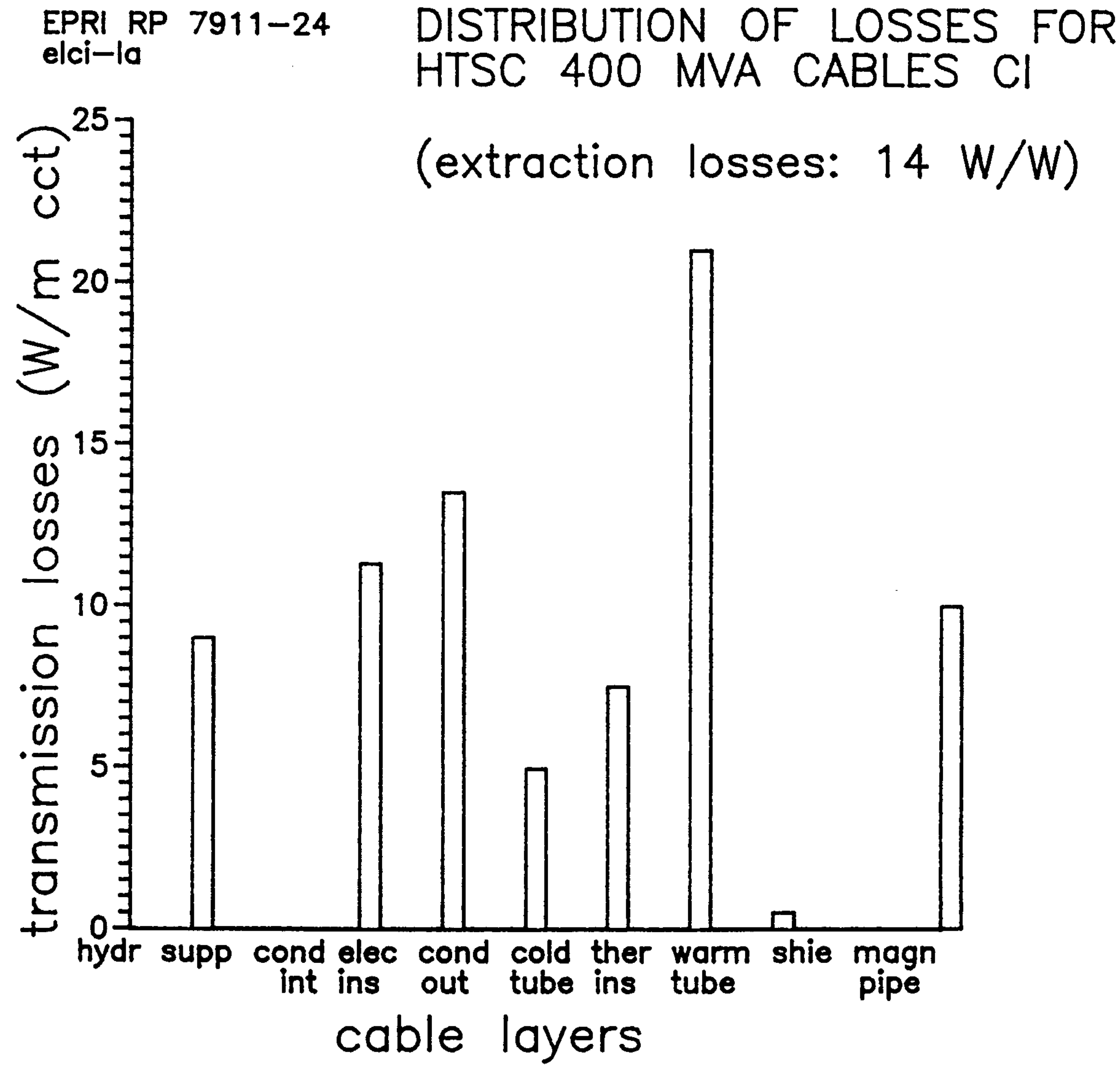


Fig. 4-12

Repartition of transmission losses among the various elements of the cable calculated for the cryogenic dielectric solution.
All cold losses have been added with cooling losses at 14 W/W.

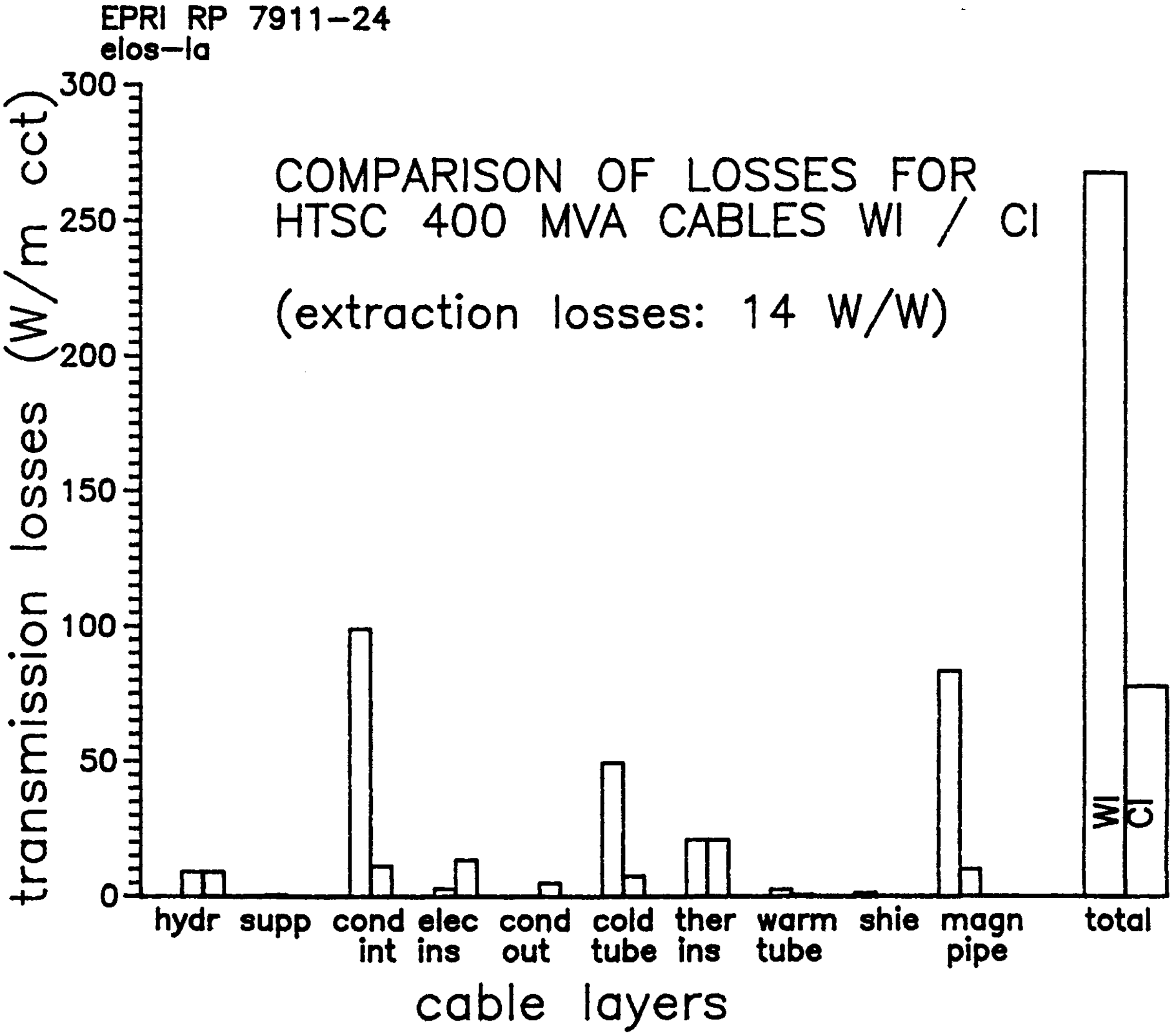


Fig. 4-13

Comparison of transmission losses for each element of the cable between the room temperature and the cryogenic dielectric solutions.
All cold losses have been added with cooling losses at 14 W/W.

4.2 Final design specifications

In parallel with the definition of the geometrical requirements, also the calculation of losses and of the other performances, the final geometrical, electrical, mechanical and thermal specifications have been defined.
The following paragraphs will list these data for the cable components, for the case of the warm dielectric retrofit solution.

4.2.1 Elementary wires

The specifications of the elementary conductors from the finalized design are listed in **Table 4-6.**

4.2.2 Conductor

The conductor specifications derived from the finalized design are listed in **Table 4-7.**

4.2.3 Cryostat

The cryostat specifications derived from the finalized design are listed in **Table 4-8.**

4.2.4 Electrical insulation

The electrical insulation specifications derived from the finalized design are listed in **Table 4-9.**

4.2.5 Installation

The installation specifications derived from the finalized design are listed in **Table 4-10.**

4.3 Cable performances

4.3.1 Warm dielectric design

The results from the final calculations of the 115 kV-400 MVA HTS cable losses at full load are reported in **Fig. 4-14,** for the room temperature dielectric solution.

4.3.2 Comparison with cryogenic dielectric design

The same data are reported in **Fig. 4-15** for the cryogen dielectric solution and the direct comparison of losses for the two HTS alternatives is shown in **Fig. 4-16.**

4.3.3 Comparison with conventional cables

The comparison of the 400 MVA HTS cable specific transmission losses at full load with conventional 200 to 300 MVA HPFF cable losses is shown in **Fig. 4-17.**

Table 4-6

Specifications for the HTS tapes to be used for the conductor of the WI cable.

shape	tapes
size	0.25 mm (0.010") thick x 4.3 mm (0.170") wide
filling factor	20 t0 25% of superconductor over the total cross section
material	HTS 2223 BSCCO
a.c. critical current density (10^{-4} V/m)	12 kA/cm^2 (r.m.s.)
a.c. losses in self field	10^{-4} W/m at the rated current
strain tolerance	0.4% without appreciable degradation of the critical current, after repeated bending (10 times), simulating the manufacturing and installation effects.
manufacturable lengths	at least 100 m for conductor prototypes, extendable to >1 km for actual cables and suitable to be supplied of bobbins having ϕ= 250 mm.

Table 4-7

Specifications for the HTS conductor of the WI cable.

- Geometry	pitch (mm)	width (mm)	thick. (mm)	diameter (mm)
internal channel for LN	-	-		27.6
spiral support, stainless steel (1.0×10^{-7} Ωm) R=0.11 Ω/m	10	7.0	1.2	30.0
HTS tapes 10 layers, 15 tapes each, 160 mm^2 $R_{Ag}=3.1\ 10^{-5}$ Ω/m	110	4.3	10 x 0.25	35.0
reinforcement SS tape R= 0.27 Ω/m	22	19	2 x 0.05	35.2
bedding layer			0.5	36.2

- Performances		
critical current at 10^{-4} V/m		2.5 x 2000 A (r.m.s)
a.c. losses at 2000 A, self field		0.4 W/m
short circuit current	thermal	20 kA (r.m.s.) x 0.5 sec
	dynamic	50 kA (r.m.s.)
bending diameter		2 m
pulling tension		1500 N

Table 4-8

Specifications for the cryostat of the WI cable.

- Geometry	pitch (mm)	width (mm)	thick. (mm)	diameter (mm)
cold stainless steel corrugated tube (corr. depth 1.4 mm) R= 1.3 10^{-3} Ω/m	10	-	0.7	40.4
superinsulation tapes (45 double metallized 6.4 μm tapes				
spacing helical rod and gas getter	76	11.5	11.5	64.0
warm stainless steel corrugated tube (corr depth 1.4 mm) R= 5.0 10^{-3} Ω/m (7.0 x 10^{-7} Ωm)	15	-	0.7	68.2

- Performances	
thermal losses ambient-LN	0.5 W/m
bending diameter	2 m
pulling tension	10 000 N
operating pressure in/out	20/15 bar
eddy losses at 2000 A-3 phase	2 W/m/phase

Table 4-9

Specifications for the electrical insulation of the WI cable.

- **Geometry**	pitch (mm)	width (mm)	thick. (mm)	diameter (mm)
- conductor shield				
stainless steel wire =1.4 mm in grooves R= 5.6 Ω/m	15			68.2
one stainless steel tape + three conducting tapes R= 1.5 Ω/m	33 33	30 30	0.10 0.30	68.4
two conducting tapes and one duplex tape	33	30	0.30	69.6
- insulation				
PPP tapes, graded thick. 0.10, 0.14, 0.17 mm	33	30	7.25	84.1
- insulation shield				
one duplex tape and two conducting tapes	33	30	0.30	84.7
two metallized tapes	33	30	0.20	85.1
one stainless steel tape interleaved with one mylar tape R= 1.2 Ω/m	33	30	0.25	85.6
skid wires, double entry 5 x 2.5 mm$_2$ R= 4.7 10^{-2} Ω/m	76	5	2.5	90.6
- impregnant				
standards polybuthene for HPFF cables				

- **Performances**	
a.c. operation voltage	115/√3 kV
" " max stress	10.1 kV/mm
" " min stress	8.4 "
B.I.L. voltage	650 kV
" max stress	83 kV/mm
" min stress	69 "
operating dielectric losses	0.93 W/m/phase
shield losses at 2000 A - 3 phase	0.43 W/m/phase

Table 4-10

Specifications for the installation of the WI cable.

- Geometry	thick. (mm)	diameter (mm)
three core assembly		192
clearance	14	206
8" x 5/8" carbon steel pipe R= 2.1 10^{-5} Ω/m	6.4	219
cable core weight 8 kg/m		

- Performances	
operating pressure	15 bar
pulling force for 1000 m	10 kN/phase
pipe losses at 2000 A	83 W/m cct

The comparison of specific transmission losses versus the transmitted power for the above cases is shown in **Fig. 4-18.**

Dimensional data and further data on performances are reported in Table 4-4.

4.3.4 Assessment of calculation

A critical analysis of the calculation, in terms of both theoretical and experimental factors involved has finally been carried out, with the intent of assessing the reliability of the calculated performances, the need for experimental confirmation of data and/or calculation methods and the level of importance of each parameter with respect to the overall design and development.
The results of this analysis are reported in **Table 4-11.**

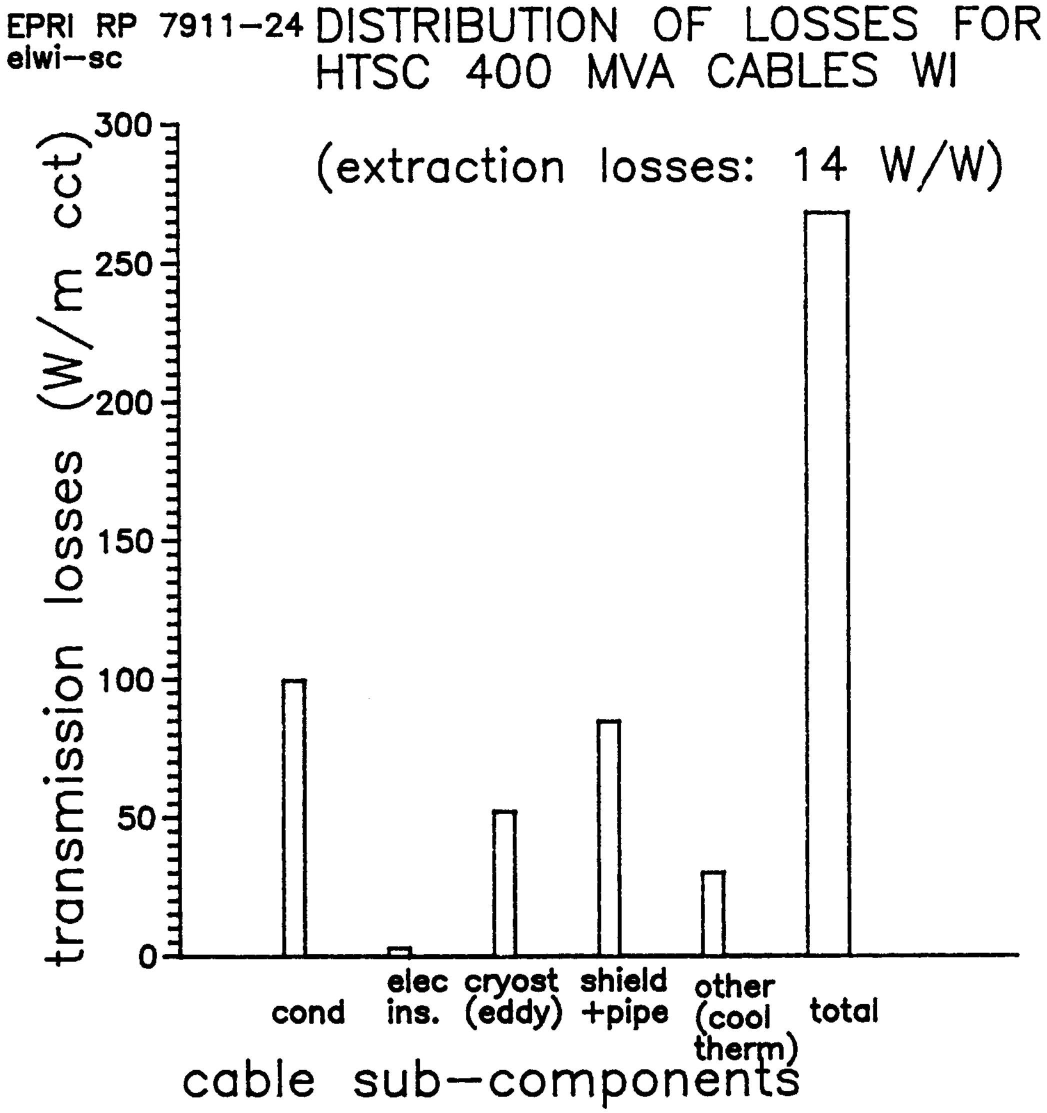


Fig. 4-14

Repartition of transmission losses among the various elements of the cable calculated for the room temperature dielectric solution of Table 4-4.
All cold losses have been added with cooling losses at 14 W/W.

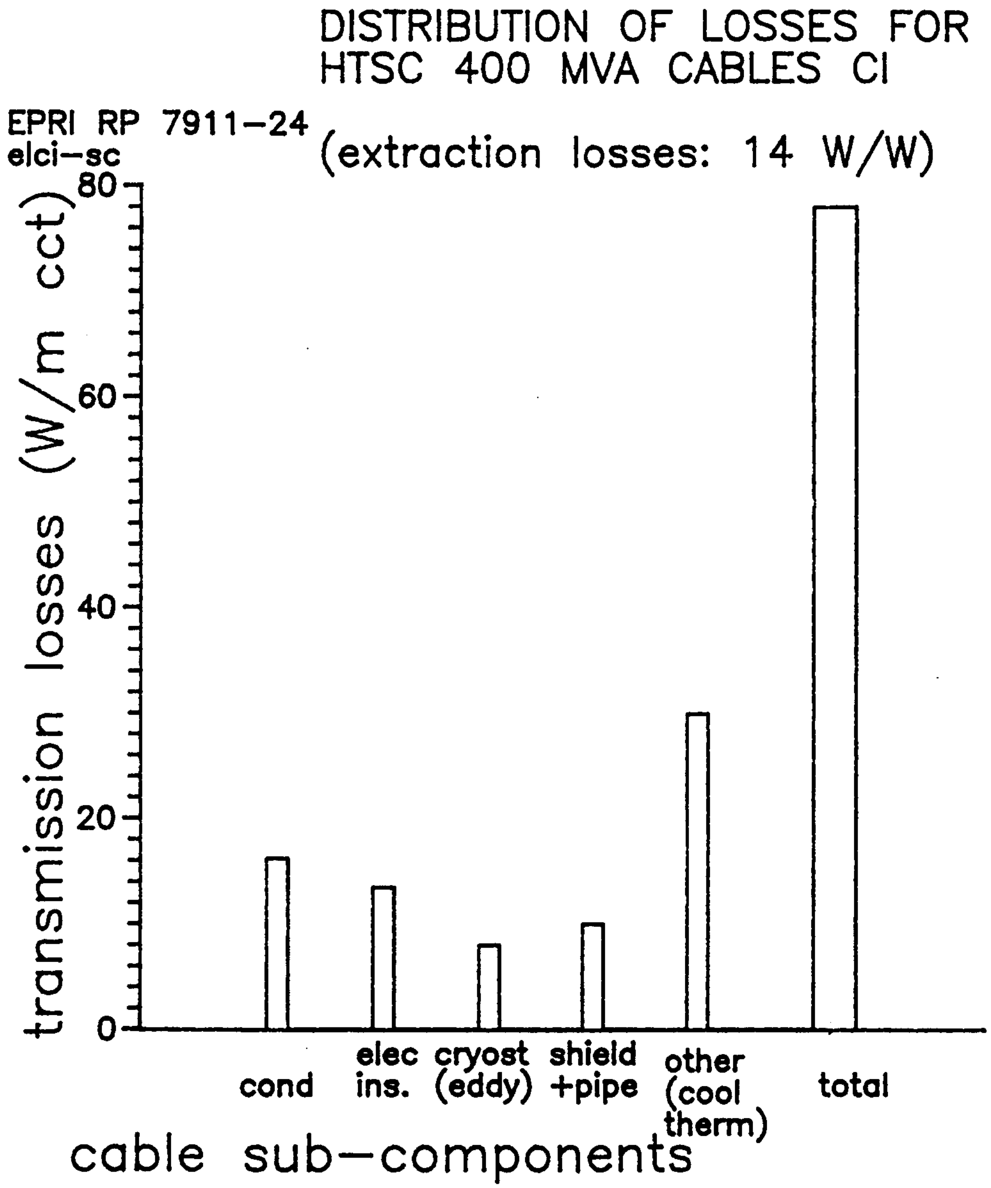


Fig. 4-15

Repartition of transmission losses among the various elements of the cable calculated for the cryogenic dielectric solution of Table 4-4. All cold losses have been added with cooling losses at 14 W/W.

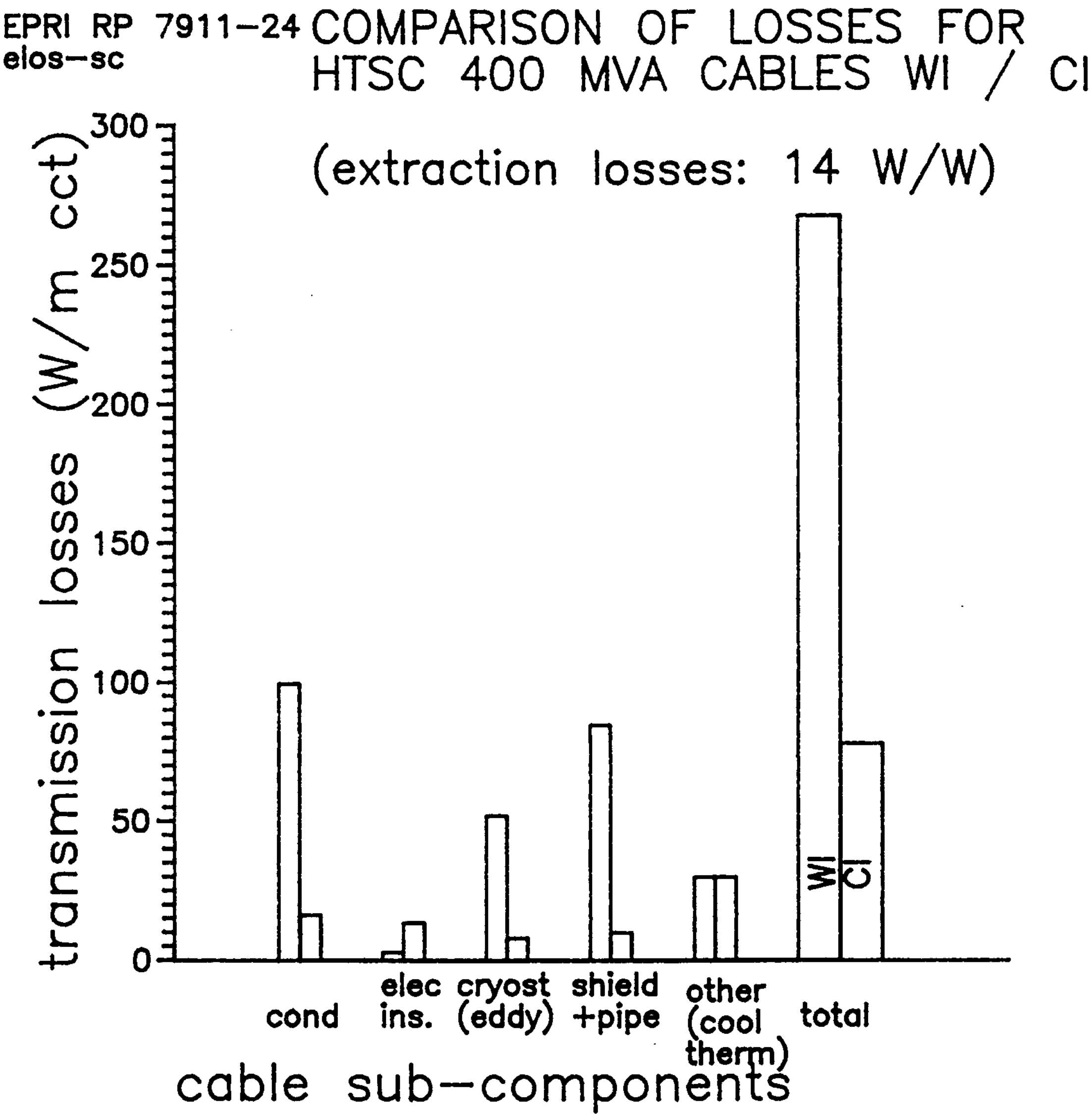


Fig. 4-16

Comparison of transmission losses for each element of the cable between the room temperature and the cryogenic dielectric solutions of Table 4-4.
All cold losses have been added with cooling losses at 14 W/W.

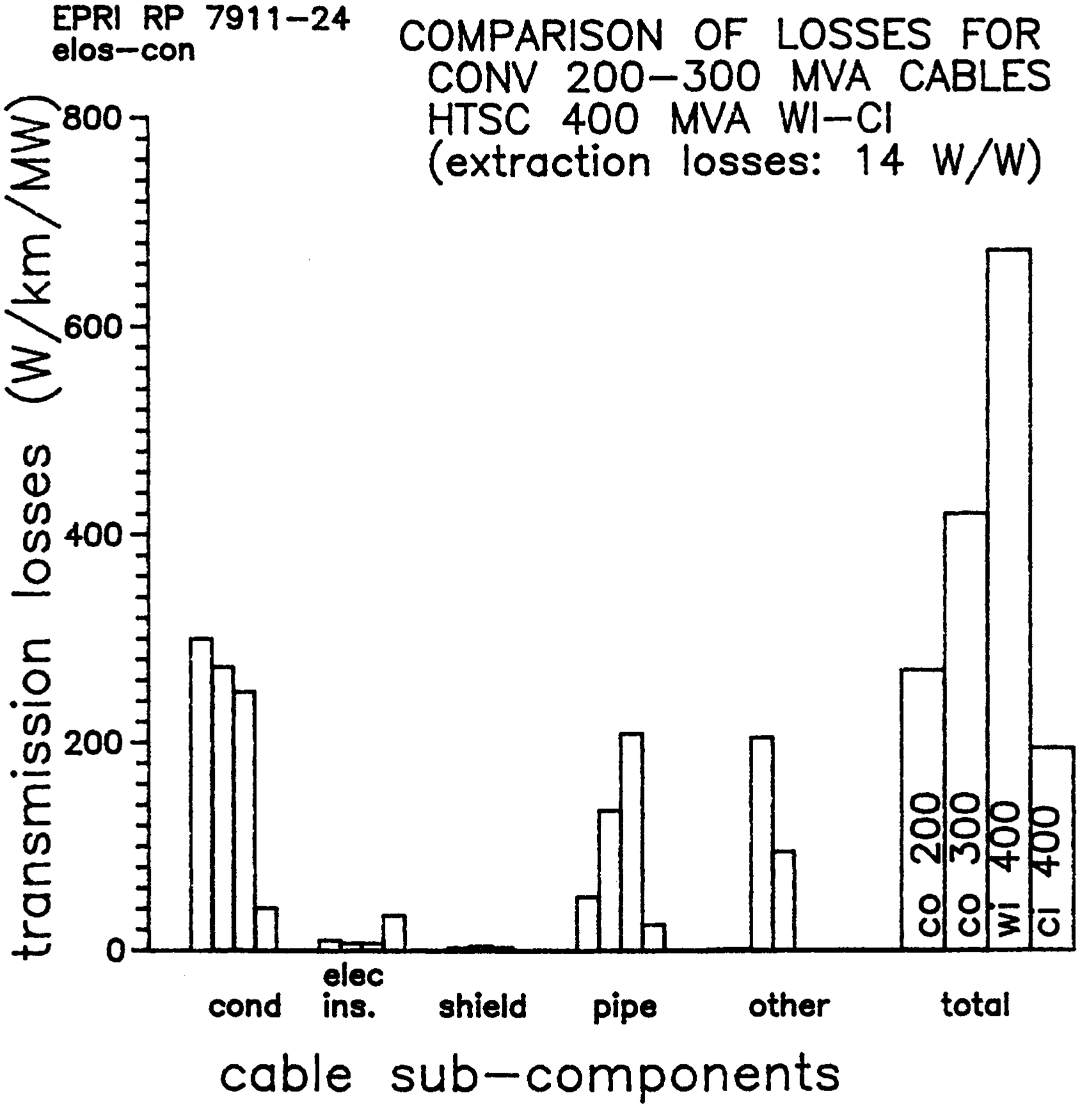


Fig. 4-17

Comparison of transmission losses at full load of HTS 400 MVA cables and of 200 to 300 MVA conventional HPFF cables.
All cold losses have been added with cooling losses at 14 W/W.

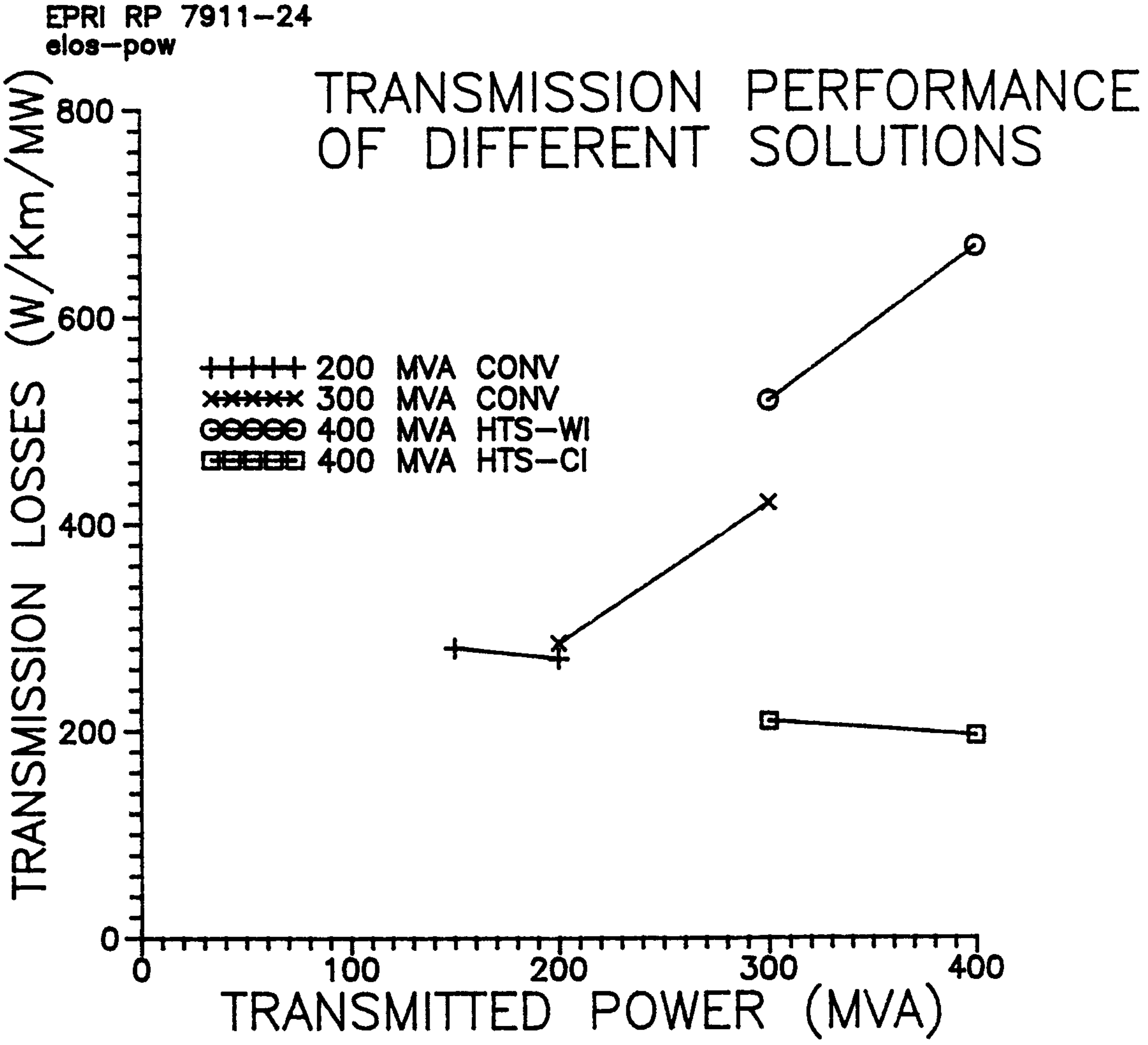


Fig. 4-18

Comparison of transmission losses versus load for HTS 400 MVA cables and for 200 to 300 MVA conventional HPFF cables.
All cold losses have been added with cooling losses at 14 W/W.

Table 4-11

Assessment of calculation reliability, of the need for experimental data and of the overall importance of the cable performances with respect to the development.

ITEM	CALCULATION RELIABILITY	EXPERIMENTAL NEED	CRITICAL IMPACT
B.I.L.	H	L	M
Rated current	M	H	H
Short circuit level	M	H	M
Current losses	L	H	H
Voltage losses	H	L	L
Thermal losses	M	H	H
Hydraulic losses	H	M	L
Cooling losses	M	M	L
Flexibility	M	H	H
Pulling tension	M	H	H
Lateral pressure	M	H	M

H = high
M = medium
L = low

Section 5

COOLING SYSTEM

5.1 Principle of operation

As already anticipated in section 3.3.6, the cooling of the room temperature dielectric cable will be ensured by a closed-cycle forced flow of sub-cooled liquid nitrogen (see Fig. 3-5) through the conductor channels.

The components of the cooling system will be coolers, tanks, pumps and control elements suitable to perform for the correct operation of the cable and accessories in both normal and exceptional conditions.

Normal condition have been assumed to be the continuous operation of the system at full transmitted load, while exceptional conditions will mean operation of the system at a given overload and/or after a defined perturbance.

For the purpose of this study the overload up to the critical current level (i.e. approximately twice the rated current) and the recovery from short circuit have been explicitly considered for the preliminary design of the cooling system.

5.2 Specifications and outline of the cooling system

A schematic representation of a cooling section for the 115 kV-400 MVA system is given in Fig. 5-1, where also different possibilities for the operation of the cooling system are outlined.

The selected input and output conditions of the coolant and its operational parameters are collected in Table 5-1 for the typical situation of a 1000 m long cooling section of the 115 kV-400 MVA system.

5.3 Operation and control requirements

5.3.1 Normal operation

During normal operation at full load, as it appears from the data in **Fig. 5-1**, any of the considered cooling system configurations is capable of keeping the coolant (and conductor) temperature within the design range for continuous operation.

However, in consideration of the effect of the temperature on the performance of the HTS tapes and of the small amount of the pumping losses, it would be preferable to operate permanently the system at the maximum flow rate, taking advantage of both the reduced maximum temperature and the safer situation with respect to any possible temperature disuniformity and/or sudden anomaly.

COOLING CIRCUIT

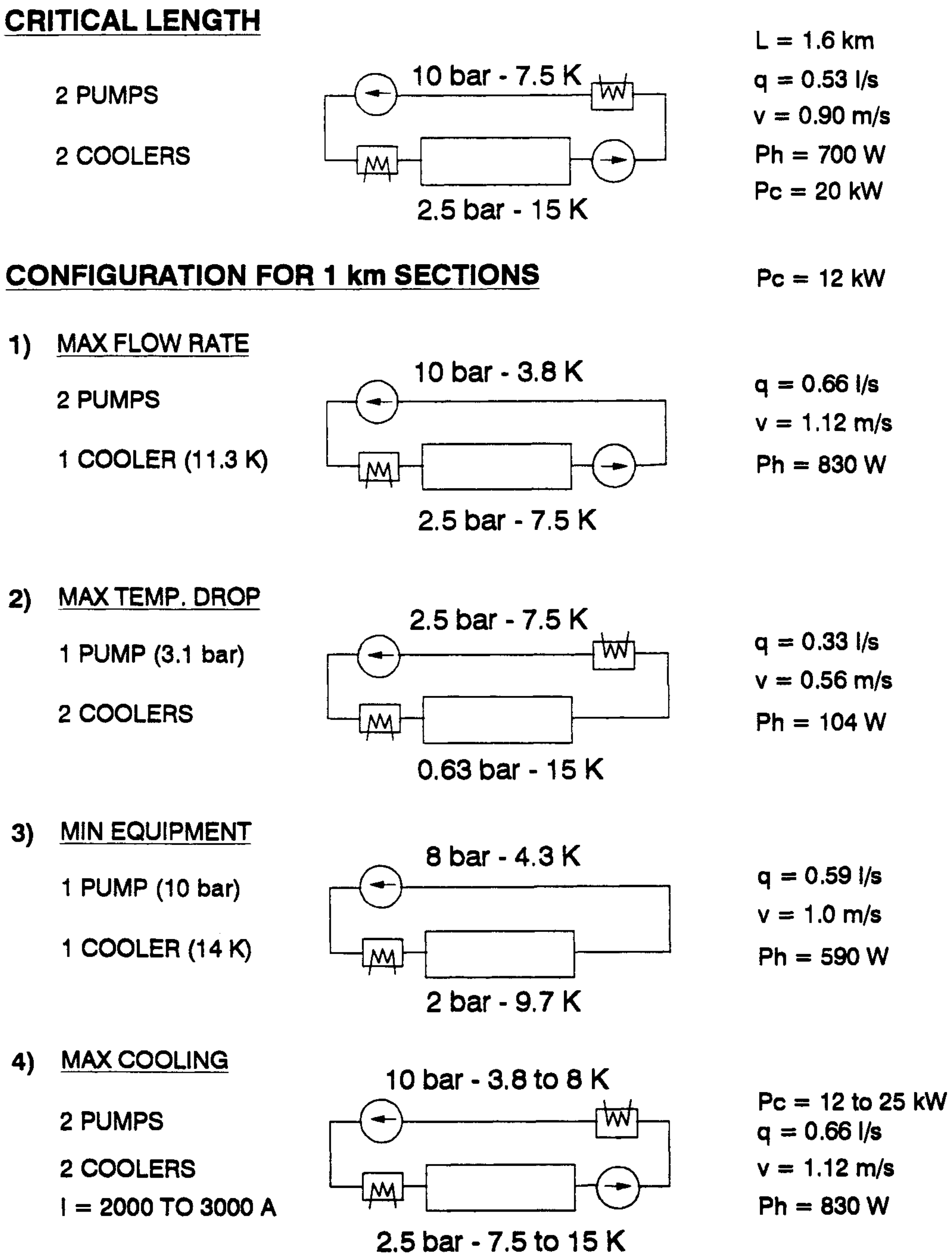


Fig. 5-1

Schematic representation of a 1 km long cooling section for the 400 MVA-115 kV system, with different possible configurations of the cooling system.

In fact it would be of little use to operate the system with the conductor at the limit of the design thermal conditions, at a reduced flow rate or, apart from the required maintenance periods, to exclude from the circuit one cooler, which should be kept ready for operation to ensure the continuity of the cooling in any contingency.

The same considerations may apply to the operation at reduced load, (e.g. at 1500 A), in which case, however, the margin with respect to the limit temperature becomes so large that a less effective cooling configuration might be preferable (or could be safely adopted for any maintenance purpose).

5.3.2 Overloads

In the case of an overload a first consideration is to calculate the thermal conditions in steady state, to verify the possibility to operate the transmission system for a long time at the considered level, at least in the most effective cooling configuration.

From **Table 5-1** it appears that, even by adopting the best configuration, it would be difficult to keep the temperature within the acceptable range for permanent overloads in excess of 150% of the rated current, the main limitation arising from the flow rate allowed by the hydraulic resistance of the conductor channel.
Any further increase of the current would not reach any critical level for the heat exchange along the conductor channel at least up to the assumed critical current of 5000 A; however it would require special features to be permanently accepted (increased channel size design, separate LN flow from an additional reservoir through the third phase).
On the other hand, for a limited duration of the overload, the heat capacity of the cold assembly of the cable and of the coolant should be taken into consideration, in addition to the coolant flow, to evaluate the acceptable range of overload versus time.
In this respect, if an overcurrent at 5000 A is assumed, starting from full load condition with the most efficient cooling configuration, a temperature gradient of 50 K/hour can be estimated, which allows for about 10 minutes before the limit of 82 K is reached for the maximum temperature of the coolant.
The above considerations should of course be complemented by the verification of the thermal transient for the warm part of the cable, which might be, mostly for long durations, the more severe limitation.

In the case of the recovery from a short circuit, which is supposed to increase the conductor temperature by 8 K, the system is expected to operated without any critical perturbance, since the maximum temperature would be 82.5 K, starting from the full load conditions in Table 5-1.
The cooling of the system from room temperature to LN is assumed to be carried out by controlled feeding from LN at atmospheric pressure from a tank and has been estimated to require approximately 0.5 kg/m/phase of nitrogen to be evaporated, in addition to approximately the same amount for filling the conductor, for a total of 3000 kg, or about 3.8 m^3.
The pumps are capable to provide this quantity in a few hours, which time is considered to be acceptable and not to be a limitation with respect to the

Table 5-1

Operating conditions of the cooling system for a 1 km long section of the 400 MVA-115 kV system for steady state calculation at different loads in the configuration for the maximum cooling efficiency.

400 MVA - 115 kV cable - 1 km section
Coolant flow : 0.66 l/s, input at 67 K
Pumping losses : 830 W
(max cooling configuration, 4 in Fig. 5-1)

Load current (A)	1500	2000	3000	(5000)
Total cooling power (kW)	6.6	12	24.6	(64)
LN temperature drop along the Go path (K)	2	3.8	9	(20)
LN temperature drop along the RETURN path (K)	4	7.5	15	(40)
Max LN temperature (K)	71	74.5	82	(107)

cooling rates expected to be required to avoid excessive thermal constraints to the cable structure.

5.3.3 Accessories

From the preliminary design of accessories (Section 6), the cooling requirements can be summarized as follows:

Joints:	resistive losses at the level of	20	W/each
	additional thermal losses	500	"
Terminations:	resistive and thermal losses through connector	150	W/phase
	additional thermal and eddy losses	500	"

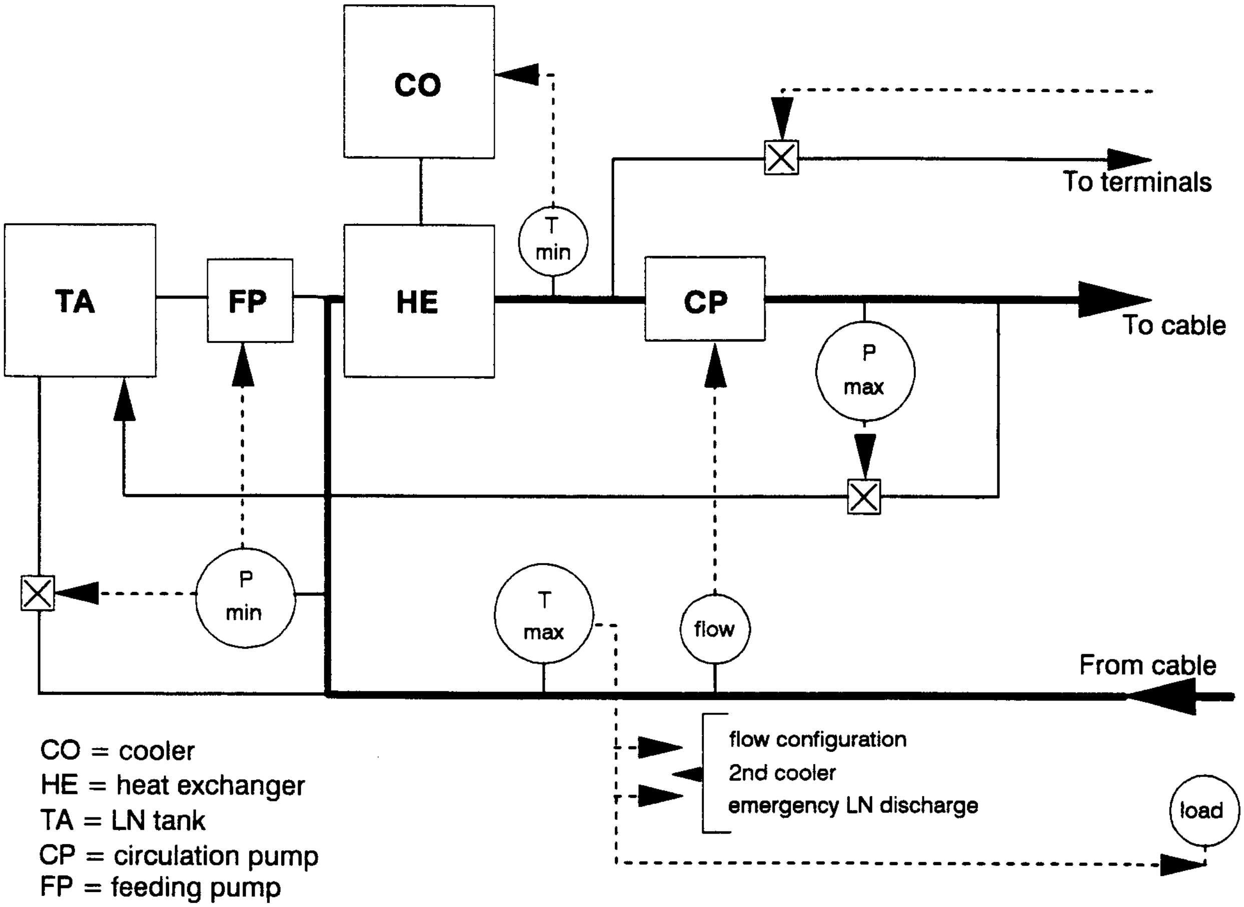


Fig. 5-2

Schematic outline of the components and of the controls for a cooling station of the system.

Table 5-2

Controlled levels for the parameters of the cooling system and main action to be provided by controls.

parameter	low load	normal	overload	controlled through
flow rate (l/s)	0.33 to 0.66	0.66	(>)= 0.66	circulation pumps
min pressure	10 bar	10 bar	10 bar	pressurizing pumps
max pressure	≤20 bar	20 bar	(>)= 20 bar	circulation pumps
T coolant	67 K	67 K	67 K	coolers
T max cable	< 82 K	74.5 K	82 K	coolers

Joints would have to be cooled by the coolant flowing along the cable, and their losses should be added to the cable losses in the calculation of the cooling system. In the case of a 1 km cooling section it can be assumed that no joints are included; for longer sections or in the presence of joints in a 1 km section, their losses are in the range of 4% of the total cable losses and might even be neglected at a preliminary stage for the estimation of the required performance of the cooling system.

Terminations are assumed to be cooled by a circuit separate from that of the cable in order both to limit the heat load to the main flow along the cable and to have a better flexibility of the system in case of anomalies and maintenance.
In addition part of the termination cooling is to be obtained by LN evaporation, which could be better controlled with a separate LN circuit.

In conclusion an additional heat load of 2 to 2.5 kW per section, to be obtained by a separate local LN circuit is assumed to account for the cooling of accessories.

5.3.4 Controls

Based on the above considerations and on previous analysis of thermal transients (see 4.1.4), the functional controls to operate the system have been examined.

The main parameters to be controlled for the cooling system are:

- flow rate;
- minimum pressure;
- maximum pressure;
- feeding temperature for the coolant;
- maximum coolant temperature.

This would be accomplished for the system configuration in Fig. 5-1 with the arrangement of components as in **Fig. 5-2** and according to the principles and parameters shown in **Table 5-2.**

In addition emergency features should be provided to perform the following:

- Pressure relief at the output of the feeding and circulation pumps;
- Automatic shift to maximum efficiency cooling configuration in case of overload;
- Automatic insertion of reserve pumps and of available cooling capability in case of failures and of increased demand for overloads;
- Emergency discharge of LN from the cryostat in case of uncontrolled overheating.

5.4 Cooling units and other components

From the analysis of the required cooling power, the size of the cooling units is suggested in the range of 60 kW cooling power, which would provide 25 kW for the continuous cooling of one cable section (up to the 150% I_n overload level) and >2.5 kW for accessories, with a 100% capability available for the adjacent section in case of maintenance or failure of the relevant cooler.
Such size of coolers is in a practical range from the available experience [35], **Fig. 5-3** and the following specifications can be identified.

cooling unit:	cooling power 60 kW continuous at ≤ 67 K
(to be combined with the associated heat exchanger): closed cycle LN	in at ≤ 82 K out at 67 K flow rate 2.4 m^3/h
circulation pumps:	2.4 m^3/h 20 bar out 10 bar in
feeding pumps:	1 m^3/h 20 bar out 0 bar in
LN tanks:	5 m^3 at 67 to 82 K

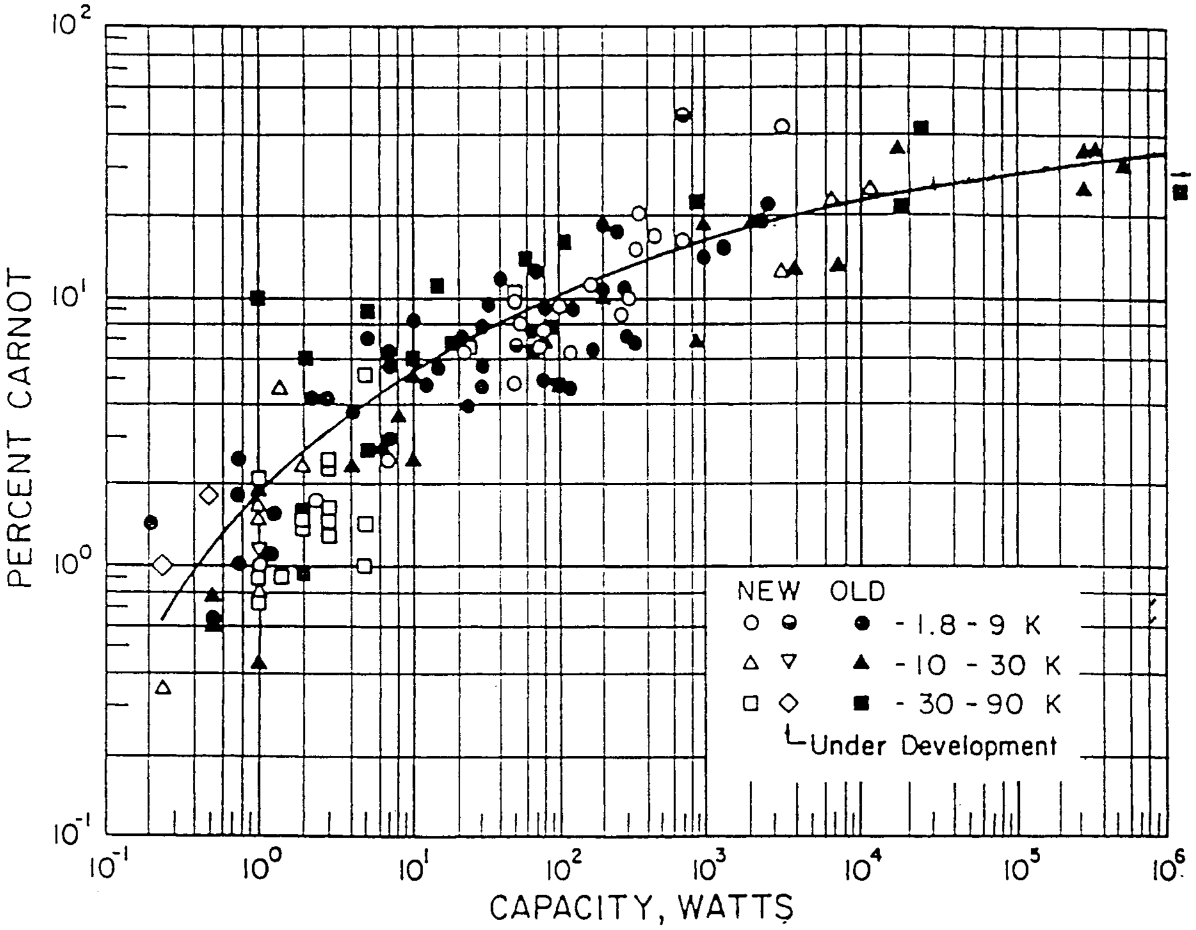


Fig. 5-3

Energetic efficiency versus cooling power of practical coolers [35].

Carnot efficiency = $(T_{out}-T_{in}) / T_{in} = (P_{out}-P_{in}) / P_{in}$

5.5 Energetic efficiency

The energetic efficiency of the cooling system is largely dominated by the efficiency of the coolers, which depends from both their working temperature and their effectiveness.

The theoretical (Carnot) efficiency for the operation from 67 to 300 K can be calculated at 3.5 W/W [35].

For the envisaged size of coolers of this type the practical data (Fig. 5-3) support the possibility to achieve 30% of this efficiency, which leads to a final practical efficiency of 11.6 W/W.

This value has been rounded up to 14 W/W for use in the design of the system to account also for additional losses due to the efficiency of pumps and to the thermal losses of the components of the cooling system.

Section 6

ACCESSORIES

6.1 Basic Problems

With respect to the accessories used in conventional HPFF cable systems, the accessories for HTS conductor based cables with room temperature dielectric would have some additional requirements related to their structure, installation and operation.

In particular the following features shall be considered:

- the connection of the superconducting to normal conductor for the termination;
- the control of the thermal field and of the associated losses for the resistive conductor end of the terminations;
- the feeding of LN at the high voltage end of the termination;
- the connection of two superconducting conductors for the joint.

The scope of the present preliminary study of accessories will include open air terminations and straight joints, as the fundamental elements required for the installation and the operation of the system.
Stop joints, which might be required along the line for total lengths significantly in excess of 1.5 km, have not been analyzed at this preliminary stage.

6.2 Electrical, Thermal and Mechanical requirements

The specific requirements to achieve the electrical, thermal and mechanical performances of the accessories are considered in the following paragraphs.

6.2.1 Electrical requirements

The voltage performance of the accessories will be required at the very same level as for conventional cables: standard B.I.L. levels are to be considered for the design (650 kV for the 115 kV system).

The current performance of the accessories, with a rated current of 2000 A for continuous operation and up to 3000 to 4000 A for overloads will be in excess of the usual levels; this might significantly affect the level of eddy losses in the structure of the terminations and in the joint enclosure.

The short circuit current will not significantly exceed the usual levels, in the range of 20 kA(r.m.s) or slightly higher.

6.2.2 Thermal requirements

For the joint the continuity of the cooling channel between the two adjacent cable lengths will have to be obtained with negligible hydraulic losses.

The heat generated by the connector of the conductors will have to be evacuated with an acceptable local temperature increase and without significantly affecting the overall thermal balance of the cooling section.
The radial heat inleak to the conductor assembly will also have to be limited to a level not affecting both the local temperature and the overall thermal balance to a significant extent.

For the termination the temperature of the superconducting end of the conductor will have to be firmly kept at the LN level, while along the normal conductor the temperature drop to the ambient level will have to be controlled to an appropriate gradient.

The thermal losses, mostly flowing along this connector from ambient to LN, and the resistive and eddy losses generated in it and in the surrounding cold enclosure will have to be evacuated with an acceptable temperature drop with respect to the coolant and will have to be reduced to a minimum, acceptable value.

6.2.3 Mechanical requirements

The operating pressure for the terminations and for the joint will be the same as for conventional system (15 bar) on the side of the dielectric fluid.
Higher pressure will have to be accomodated for the cooling circuit, up to 20 bars for continuous operation.

For the termination an unusually large size will be required for the warm end connector as well as for the high voltage electrode along the insulator.

Also the joint will have a "conductor" size exceeding the normal diameter and will need a local reconstruction of the thermal insulation, without exceeding the overall size allowed by the enclosure box.

The dynamic short circuit performance will have to be verified, although it is not expected to be significantly different from the standard levels.

6.3 Guidelines for Design

On the basis of the particular requirements identified in section 6.2, guidelines for the design of specific accessories for the retrofit room temperature dielectric 115 kV cable have been developed.
They have been based as far as possible on the modification and implementation of existing standard components, for the achievement of the required performances and capabilities.

6.3.1 Termination

A standard termination assembly for the 115 or 138 kV class can be assumed as the basic element for the HTS room temperature dielectric cable termination.

Such a component, for instance the High Pressure Oil Filled Terminator type ATA 140N from G&W in **Table 6-1** and **Fig. 6-1** can suitably perform the function of voltage stress control at the end of the electrical insulation applied onto the cryostat assembly, which is performing as the normal conductor (or as the high voltage electrode) of a conventional cable
A verification of the impulse performance will be advisable, because of the large "conductor" diameter (70 mm over the conductor shield), which might depress to some extent the effectiveness of the stress control device, which is designed for a smaller size range.

The current performance will require the design of a suitable connector and the verification of the level of eddy losses, while mechanical performances are likely to be fully satisfied by the original assembly.

The thermal requirements will pose the need for some additional components of the terminations for the control of the thermal field and for the LN circuit.
The envisaged provisions to achieve the thermal control could consist of an additional element including the transition connector from superconductor to normal metal (copper) and its extension from the low temperature side to the warm side (**Fig. 6-2**).

The available soldering techniques and materials are considered to be suitable to connect the HTS tapes to the copper rod or tube with sufficient electrical and mechanical performances to transmit the required high current [43].
From the typical resistivity of the soldering alloys and from preliminary data it can be estimated that the resistance should be in the range of 10 to 30 $\mu\Omega$/tape.
With this value the total amount of losses at the connection would be less than 1 W at 2000 A and 3.2 W at 4000 A; the temperature increase would be of the order of 2 K in overload conditions and < 1 K for the adiabatic short circuit, with the surface heat exchange rate which is allowed by the 10 cm length assumed for the soldering zone.

Table 6-1

Specifications for conventional terminations for high voltage cables (G&W Electric Co.).

ATA/ATL Terminations

ORDERING INFORMATION

The following information is needed for ordering:

a) Select the termination by catalog number based on voltage, BIL and conductor size.
b) Provide a complete description of the cable including the conductor material, and diameters over insulation, shielding system and overall diameter.
c) Specify aerial lug required (flat bus or clamp type)
d) Specify nominal operating pressure of cable.

Catalog numbers include porcelain terminator, connector, aerial lug, stress cone and paper roll assembly kit, top corona shield, inner stress control porcelain, base plate, checkplate and pipe stub assembly with baseplate insulators. Valves, oil line insulators, high strength designs (up to 400 psi nominal), external filters, pressure switches, connectors for aluminum cable and diffusion chambers are available.

For typical specifications, see page 8.

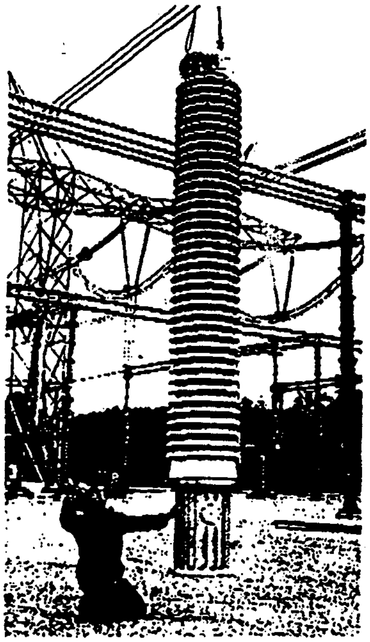


Photo shows an ATA199NC 500kV termination being installed for field testing.

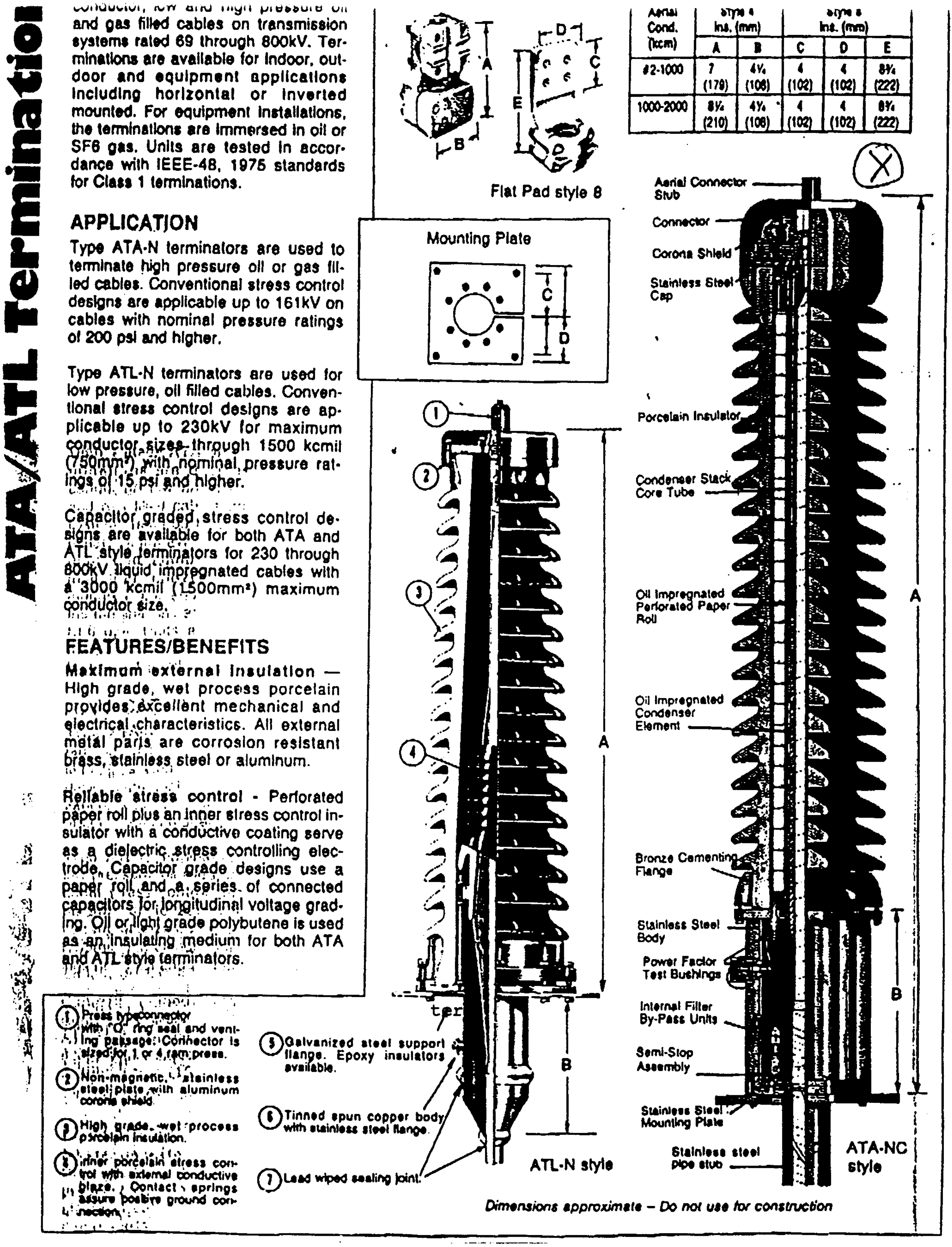
INTERNAL PRESSURE CHARACTERISTICS

Item	ATA Design STD	ATA Design High Strength	ATA Design Extra High Strength	ATL Design	ATL Design High Strength	ATL Design Extra High Strength
Nom. Operating Pressure - psi	200	300	400	15	40	100
Max. Continuous Operating Pressure (over 10 hr.) - psi	275	410	750	22	55	138
Max. Transient Pressure (up to 10 hr.) - psi	300	450	840*	24	60	150
Max. Peak Transient - psi	400	600	—	32	80	200
Max. Field (proof) - psi	350	525	—	28	70	175
Factory Test (1 hr.) - psi	500	750	1000	40	100	250

*Up to 8 hours

Voltage (kV)	Catalog* No.	BIL (kV)	Max. Conductor (kcmil)	Creepage Ins. (mm)	Strike Ins. (mm)	Shpg. wt. lbs (kg)	Approximate Dimensions - Ins. (mm) A	B	C	D	Approx. Oil Volume Gal. (L)
ATA-N Terminators (High Pressure Oil Filled)											
69	ATA 119N	350	1500	52 (1321)	25⅞ (656)	600 (272)	50 (1270)	16 (406)	6.7 (170)	7.7 (196)	2 (7.6)
69	ATA 110N	350	3000	61 (1549)	28 (711)	650 (295)	53 (1346)	15 (381)	6.7 (170)	7.7 (196)	7 (27)
115	ATA 139N	550	1500	80 (2032)	37 (940)	800 (363)	62 (1575)	15 (381)	6.7 (170)	7.7 (196)	8 (30)
115	ATA 130N	550	3000	98 (2489)	42 (1067)	900 (408)	68 (1727)	15 (381)	6.7 (170)	7.7 (196)	8 (30)
138	ATA 149N	650	1500	98 (2489)	42 (1067)	900 (408)	68 (1727)	15 (381)	6.7 (170)	7.7 (196)	11 (42)
138	ATA 140N	650	3000	120 (3048)	52 (1321)	1100 (499)	78 (1981)	16 (406)	7.5 (190)	9 (229)	15 (57)
161	ATA 159N	750	1500	120 (3048)	52 (1321)	1100 (499)	78 (1981)	16 (406)	7.5 (190)	9 (229)	15 (57)
161	ATA 150N	750	3000	138 (3505)	58 (1473)	1250 (567)	84 (2134)	16 (406)	7.5 (190)	9 (229)	15 (57)
230	ATA 160NC	1050	3000	193 (4902)	77½ (1968)	2200 (998)	115 (2921)	21 (533)	9.5 (241)	11 (279)	40 (152)
345	ATA 180NC	1300	3000	237 (6020)	98 (2489)	3500 (1589)	145 (3683)	29 (737)	10 (254)	11 (279)	50 (190)
500	ATA 199NC	1675	3000	352 (8941)	140 (3556)	5000 (2265)	196 (4978)	29 (737)	10.5 (267)	12.5 (317)	65 (246)
800	ATA 209NC	2450	3000	425 (10,795)	163 (4140)	8000 (3632)	222 (5639)	42 (1067)	10.5 (267)	12.5 (317)	82 (311)
ATA-N Terminators (High Pressure Gas Filled)											
69	ATA 119NG	350	1250	52 (1321)	25⅞ (656)	650 (295)	56 (1422)	22 (559)	6.7 (170)	7.7 (196)	—
69	ATA 110NG	350	2500	61 (1549)	28 (711)	700 (317)	63 (1600)	25 (635)	6.7 (170)	7.7 (196)	—
92	ATA 129NG	450	1250	61 (1549)	28 (711)	700 (317)	63 (1600)	25 (635)	6.7 (170)	7.7 (196)	—
92	ATA 120NG	450	2500	80 (2032)	37 (940)	850 (385)	75 (1905)	28 (711)	6.7 (170)	7.7 (196)	—
115	ATA 139NG	550	1250	98 (2489)	42½ (1079)	900 (408)	81 (2057)	28 (711)	6.7 (170)	7.7 (196)	—
115	ATA 130NG	550	2500	120 (3048)	52 (1321)	1050 (476)	90 (2286)	28 (711)	7.5 (190)	9 (229)	—
138	ATA 149NG	850	1250	120 (3048)	52 (1321)	1200 (544)	90 (2286)	28 (711)	7.5 (190)	9 (229)	—
138	ATA 140NG	650	2500	138 (3505)	58 (1473)	1300 (590)	96 (2438)	28 (711)	7.5 (190)	9 (229)	—
ATL-N Terminators (Low Pressure Oil Filled)											
69	ATL 119N	350	1250	52 (1321)	25⅞ (656)	450 (205)	35 (889)	10 (254)	8 (203)	9 (229)	2 (7.6)
69	ATL 110N	350	3000	61 (1549)	28 (711)	600 (272)	39 (991)	17 (432)	10 (254)	11 (279)	5 (19)
92	ATL 129N	450	1250	61 (1549)	28 (711)	600 (272)	39 (991)	17 (432)	10 (254)	11 (299)	5 (19)
92	ATL 120N	450	3000	80 (2032)	37 (940)	750 (350)	48 (1219)	17 (432)	10 (254)	11 (279)	7 (27)
115	ATL 139N	550	1250	80 (2032)	37 (940)	750 (350)	48 (1219)	17 (432)	10 (254)	11 (279)	7 (27)
115	ATL 130N	550	3000	98 (2489)	42 (1067)	800 (363)	54 (1372)	17 (432)	10 (254)	11 (279)	7 (27)
138	ATL 149N	850	1250	98 (2489)	42 (1067)	800 (363)	54 (1372)	17 (432)	10 (254)	11 (279)	10 (38)
138	ATL 140N	650	3000	120 (3048)	52 (1321)	1050 (476)	63 (1600)	17 (432)	11.5 (292)	12.5 (317)	11 (42)
161	ATL 159N	750	1250	120 (3048)	52 (1321)	1050 (476)	63 (1600)	17 (432)	11.5 (292)	12.5 (317)	11 (42)
161	ATL 150N	750	3000	138 (3505)	58 (1473)	1100 (499)	69 (1753)	17 (432)	11.5 (292)	12.5 (317)	15 (57)
230	ATL 160NC	1050	2500	193 (4902)	77½ (1968)	1800 (726)	109 (2769)	24 (610)	12 (305)	13 (330)	30 (114)

*Low and high pressure oil filled terminations are also available for oil filled equipment mounted applications up to 230 kV.



ATA/ATL Terminatio

conductor, low and high pressure oil and gas filled cables on transmission systems rated 69 through 800kV. Terminations are available for indoor, outdoor and equipment applications including horizontal or inverted mounted. For equipment installations, the terminations are immersed in oil or SF6 gas. Units are tested in accordance with IEEE-48, 1975 standards for Class 1 terminations.

APPLICATION

Type ATA-N terminators are used to terminate high pressure oil or gas filled cables. Conventional stress control designs are applicable up to 161kV on cables with nominal pressure ratings of 200 psi and higher.

Type ATL-N terminators are used for low pressure, oil filled cables. Conventional stress control designs are applicable up to 230kV for maximum conductor sizes through 1500 kcmil (750mm²) with nominal pressure ratings of 15 psi and higher.

Capacitor graded stress control designs are available for both ATA and ATL style terminators for 230 through 800kV liquid impregnated cables with a 3000 kcmil (1500mm²) maximum conductor size.

FEATURES/BENEFITS

Maximum external insulation — High grade, wet process porcelain provides excellent mechanical and electrical characteristics. All external metal parts are corrosion resistant brass, stainless steel or aluminum.

Reliable stress control - Perforated paper roll plus an inner stress control insulator with a conductive coating serve as a dielectric stress controlling electrode. Capacitor grade designs use a paper roll and a series of connected capacitors for longitudinal voltage grading. Oil or light grade polybutene is used as an insulating medium for both ATA and ATL style terminators.

Aerial Cond. (kcm)	Style 4 Ins. (mm)		Style 8 Ins. (mm)		
	A	B	C	D	E
#2-1000	7 (178)	4¼ (108)	4 (102)	4 (102)	8¾ (222)
1000-2000	8¼ (210)	4¼ (108)	4 (102)	4 (102)	8¾ (222)

Flat Pad style 8

Mounting Plate

① Press type connector with "O" ring seal and venting passage. Connector is sized for 1 or 4 ram press.

② Non-magnetic, stainless steel plate with aluminum corona shield.

③ High grade, wet process porcelain insulation.

④ Inner porcelain stress control with external conductive glaze. Contact springs assure positive ground connection.

⑤ Galvanized steel support flange. Epoxy insulators available.

⑥ Tinned spun copper body with stainless steel flange.

⑦ Lead wiped sealing joint.

ATL-N style

ATA-NC style

X

Dimensions approximate – Do not use for construction

Fig. 6-1

Schematic view of conventional terminations for high voltage cables (G&W Electric Co.).

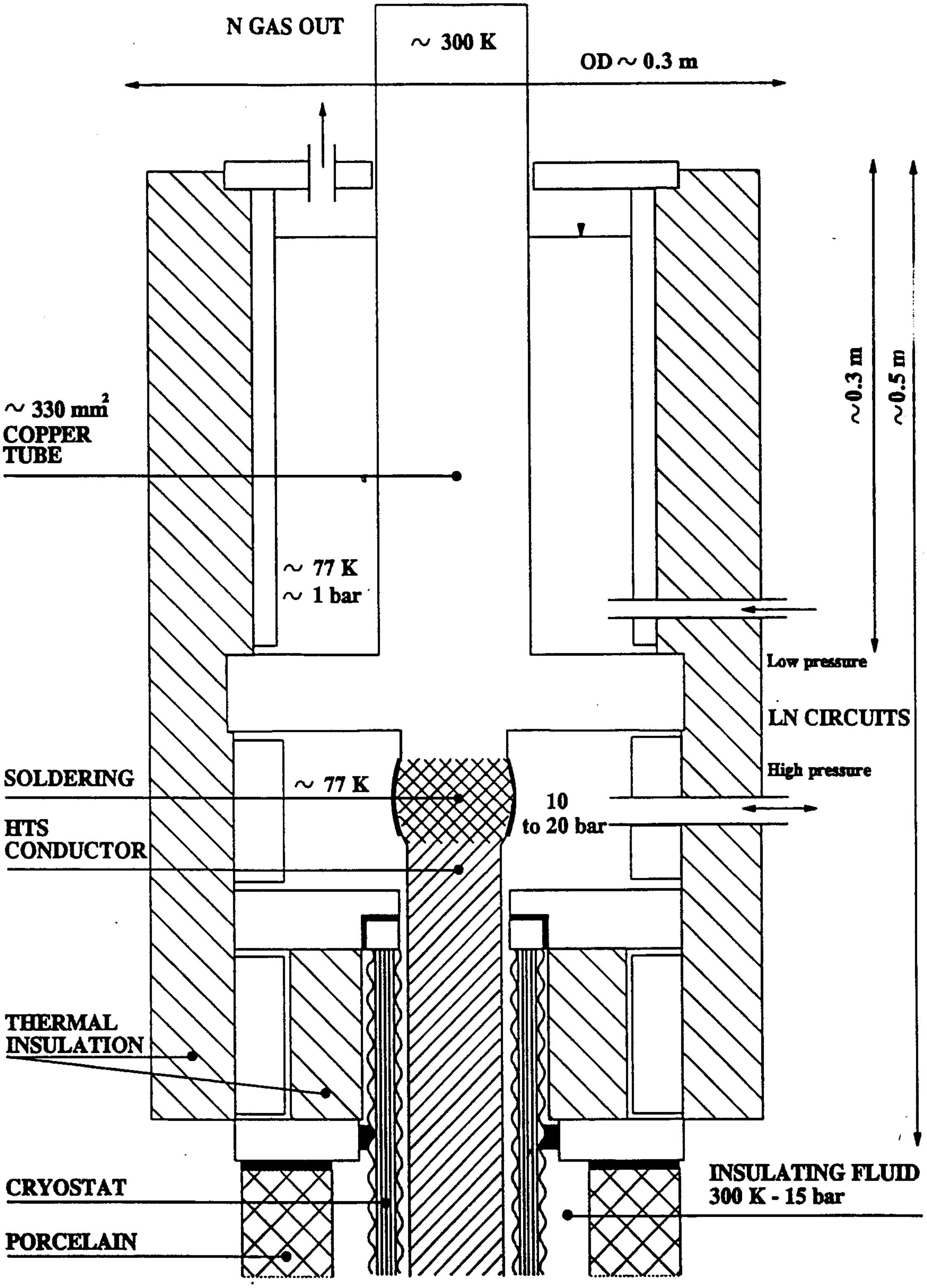


Fig. 6-2

Schematic representation of the "thermal box" to be connected at the end of the normal pothead, including the superconductor-to-normal connector and the provisions for LN feeding and for the control of the thermal gradient.

The length and cross section of the normal conductor leading the current from the LN ambient to room temperature should be optimized for the minimum of losses (total of resistive losses and thermal losses).

On the basis of the suggested methods for optimization [44],[45] a suitable value for the copper cross section has been evaluated at around 300 mm^2.
Preliminary calculation of losses in the 300 mm^2 copper tube result in 60 W for thermal losses and of 40 and 160 W for resistive losses at I_n and $2I_n$ respectively.

The amount of losses generated along the copper tube can be evacuated by an LN auxiliary flow to be finally evaporated at the warm end, following the same principles as for LTSC high current ends [45].
This flow is effective enough to this purpose, because the steady state temperature increase with respect to the coolant, calculated from the cooling capability of LN and of gaseous nitrogen [39],[40],[46], would be up to 4 K in the liquid bath and up to 115 K at the gas cooled warm end, in the extreme condition of overload at 2 I_n.
The adiabatic temperature increase for the 20 kA-0.5 sec short circuit is anticipated to be of 11 K.

The element to connect the termination and the cable to the cooling circuit is envisaged to include an electrically and thermally insulated LN line from ground to the high voltage side and should be designed to withstand the voltage and to carry separately the high pressure main flow to the cable and the auxiliary low pressure flow for the end connector.
Provisions will be necessary to avoid water condensation on the outer surface if, as it is likely to be, this element could not be incorporated in the main body of the termination, but it would have to be included in a separate supporting insulator.

Additional thermal losses from heat inleak through the structure of the termination are very difficult to be anticipated; for the purpose of dimensioning the cooling system a maximum value of 500 W/phase has been extrapolated from low temperature systems [45].

6.3.2 Joint

A standard joint box would be used to enclose the cable straight joint.

The superconductor-to-superconductor connection is assumed to be of the resistive type and to be obtained by soldering the tapes from each side, if necessary with the aid of a metal support and reinforcement.
The conductor joint would be included in a short section of cryostat, to be applied and evacuated on the site, up to an external diameter which would not significantly exceed the size of common conductor ferrules.

This arrangement, which seems to be the simplest solution allowed by the mechanical properties of the HTS material, would permit to use the conventional technique to reconstruct the electrical insulation over the cryostat for the completion of the cable joint structure.

By using the same principles and parameters as for the terminal connector, the resistance of the joint would be around $2\ 10^{-7}\ \Omega$, with losses and overheat quite comparable to the terminal connector.

The total dissipated power, of the order of a few W at nominal load, including estimated eddy losses in the support, being at the same level of the total heat load of the coolant per meter of cable, could be easily evacuated by the coolant flowing through the support and around the HTS tapes.

For the heat transmission from the connector to the fluid, again a length of 100 tO 200 mm would be enough to limit the thermal drop within a few K in overload conditions.

From these estimations it can be anticipated that neither the diameter of the connector nor its length would pose problems from sizes largely exceeding the usual values of ferrules in conventional joints.

The reconstruction of the section of cryostat over the connector will have to be made on the site.The possible use of pre-fabricated elements will have to be carefully considered in order to simplify the installation, while avoiding an eccessive increase of the high voltage electrode diameter.

As for terminations, a method to prepare the ends of the cable cryostat at the correct position without affecting the performance of the vacuum along the cable will also have to be developed.

In the end it is very likely that it will be possible to use standard sizes for the electrical insulation and for the joint enclosure, the radial and longitudinal dimensions of the conductor joint being in a well normal range.

Section 7

CONCLUSIONS

The results of the studies performed during this project lead to the following conclusions:

1) At the preliminary stage of the analysis of different cable concepts for retrofit application:

   - A range of system requirements for retrofit application of existing pipes of HPFF cable routes has been identified and discussed;
   - Design criteria for the cable components (conductor, thermal insulation, electrical insulation) have been selected, based on materials and technologies either in use or susceptible to be developed in a few years;
   - Two practicable options, one with room temperature dielectric and one with cryogenic dielectric, have been identified and designed at a preliminary stage for a cable structure to be used as a >=400 MVA retrofit application in the 69 to 230 kV range;
   - The main performances (rating, losses, cooling section length) of these solutions have been estimated;
   - The advantages and disadvantages of the two alternatives have been discussed for each cable component and in the whole;
   - The room temperature dielectric solution has been selected as being the shortest step towards a feasible application, although pipe losses are intrinsically limiting its performances at around twice the rating of conventional cables (400 MVA at 115 kV in 8" pipes);
   - The cryogenic dielectric solution has been established to have the potential for intrinsically better performances, up to twice the rating of the room temperature dielectric solution, provided further specific development is carried out.

2) In the case of the room temperature dielectric solution for 115 kV-400 MVA, the following conclusions have been achieved:

   - Constructional and dimensional details of the conductor, of the cryostat and of the electrical insulation have been defined;
   - The specifications for the elementary wires to be assembled in the cable conductor have been defined;
   - The performances of the cable have been anticipated from the available data as a function of the load and for overload and short circuit conditions;

- The performances calculated for the room temperature dielectric cable have been compared to those estimated for the cryogenic dielectric cable and to those typical of conventional cables; the doubling of the transmissible power with conventional cables at slightly higher specific losses with cooling sections largely exceeding 1 km has been confirmed;

- The calculations for the cryogenic dielectric cable on the basis of the same performance of the HTS materials, show the possibility to achieve a level in the range of four times the rating of conventional cables, and even higher with better HTS, with much lower specific losses;

- The most critical experimental evaluations needed to confirm the specifications, the manufacturing processes and the performances have been identified.

3) For the cooling system needed to operate the 115 kV-400 MVA room temperature dielectric cable:

   - The outline for a typical 1 km section and the specifications for the main components of the cooling system have been defined;

   - The operating parameters and the principles for control procedures have been defined for normal and abnormal conditions;

   - The energetic efficiency of the cooling system has been evaluated.

4) For the accessories of the 115 kV-400 MVA room temperature dielectric cable:

   - The peculiar problems related to terminations and normal joints for cables with HTS conductors have been analyzed;

   - Guidelines for the design of terminations and joints based on modification and extension of standard components have been defined;

   - The basic dimensions and the overall outline of terminations and joints have been evaluated, with respect to accessories for conventional cables.

Section 8

REFERENCES

1. E.B.Forsyth The High Voltage Design of Superconducting Power Transmission Systems IEEE Electr. Insul. Magaz., Vol.6, N.4, Jul/Aug 1990

2. J.S.Engelhardt, D.V.Dollen, R.Samm, Application Considerations for HTSC Power Transmission Cables 5th Ann. Conf. on Superc., Buffalo N.Y., Sept 24-25, 1991

3. EPRI RP 7911-10 Technology base document (draft)

4. T.Hara et al. Feasibility Study of Compact High-Tc Superconducting Cables IEEE/PES 1990 WM, paper 90 WM 075-2 PWRD

5. A.P.Malozemoff et al. Progress in the Development of Bismuth-Based High-Temperature Superconducting Tapes ICMC Conf., Kiev, June 1992

6. A.Otto et al. Multifilamentary Bi-2223 Composite Tapes Made by a Metallic Precursor Route Appl. Sup. Conf., Chicago, Aug 1992

7. EPRI RP 7911-10 Variations of Conductor Assembly Cross-sections Presented to EPRI/DOE meeting , Redbank N.J., Aug 1990

8. EPRI RP 7911-10 Cable Concepts Revised Jan 1991

9. EPRI RP 7911-10 Perspectives for Cable Application Presented at DARPA workshop, Santa Fe, N.M. Jan 1991

10. EPRI RP 7911-10 Conductor Assembly Options for Tapes and Wires Presented to EPRI/DOE meeting , Naval Reas. Lab., Virginia,Apr 1991

11. EPRI RP 7911-10 Perspectives for Cable Application Presented at EPRI workshop, Palo Alto, Ca, Aug 1991

12. AEIC Specifications for Impregnated Paper-Insulated Cable, High - Pressure Pipe-Type AEIC-CS2

13. AEIC Specifications for Cross-Linked Polyethylene Insulated Shielded Power Cables rated 46 through 138 kV AEIC CS7

14. E.Dorison et al. Changes in the Specifications of HV and EHV Cables Associated with Installation and Operating Conditions CIGRE paper 21-03, 1984

15. Development of Optimized PPP Insulated Pipe-Cable Systems in the Commercial Voltage Range EPRI Report TR-100416, May 1992, Cablec Corporation

16. H.Suzuki et al. Dielectric Insulation Characteristics of Liquid-Nitrogen-Impregnated Laminated Paper-Insulated Cable IEEE/PES 1992 WM, paper 92 WM 046-3 PWRD

17. Development of Cross-Linked Polyethylene Insulated Cable for Cryogenic Operation EPRI Report EL-3907, Feb 1985, CTL Inc.

18. M.Kosaki et al. Development of Extruded Polymer Insulated Superconducting Cable Cryogenics 1992 Vol 32,No 10

19. Glossary of Terms Relating to Superconductors IEC document 90(Secretariat)4, July 1992

20. AC Losses in the New High-Temperature Superconductors EPRI Report EL-6277, March 1989, Iowa State Univ.

21. J.Orehotsky et al. AC Losses in $YBa_2Cu_3O_7$ and $Bi_2Sr_2Ca_2Cu_3O_{10}$ Superconductors at Power Frequencies Adv. in Supercond.,vol.IV, 1992

22. J.H.Neher, M.H.McGrath. The Calculation of the Temperature Rise and Load Capability of Cable Systems AIEE Trans.,vol 76, Oct 1957

23. Calculation of the Continuous Current Rating of Cables IEC Standard 287

24. E.B.Forsyth Energy Loss Mechanism of Superconductors Used in Alternating-Current Power Transmission Systems Science, vol.242, Oct 1988

25. Thermal Insulation Options for the Superconducting Transmission Initiative Project LANL Report LA-UR-91-850

26. A.M.Wolsky,T.P.Sheaen. The Status of Progress Toward HTS High-Amperage Conductor Argonne Nat. Lab Report, Jan 1992

27. R.F.Giese,A.M.Wolsky. Published Assessment Bearing on the Future Use of Ceramic Superconductors by the Electric Power Sector Argonne Nat. Lab Report, Aug 1992

28. H.Mukai et al. Multifilamentary Bismuth (2223) Multilayer-Wound Conductors for Power Transmission Lines Mat. Res. Soc. meeting, S.Francisco,CA, Apr 1992

29. H.Kikuchi et al. Preparation of Power Conductors Using Bi-Based Superconducting Tapes ISS '92, Kobe,Jap, Nov 1992

30. B.Hensel et al. Microstructure,Resistivity and Critical Currents of Ag-Bi/Pb(2223) Tapes Appl. Sup. Conf., Chicago, Aug 1992

31. C.P.Bean Magnetization of High Field Superconductors Rev. Mod. Physics, Jan 1964

32. R.Hancox Calculation of AC Losses of a Type II Superconductor IEE Proc. vol. 113,No 7, July 1966

33. K.Edney Longitudinal Temperature Distribution in Low Temperature Cables with Counterflow Cooling Cryogenics, Dec 1967

34. Determination of AC Conductor and Pipe Losses in Pipe-Type Cable Systems EPRI Report EL-2256, Feb 1982, Pirelli Cable Corp.

35. Refrigeration Options for the Superconducting Transmission Initiative Project LANL Report

36. R.C.Rifenburg Pile-Line Design for Pipe-Type Feeders AIEE paper 53-389, Dec 1953

37. Designer`s Handbook for Forced-Cooled High-Pressure Oil-Filled Pipe-Type Cable Systems EPRI Report EL-3624, July 1984, Underground System Inc.

38. E.C.Rogers Internally Force-Cooled Power Cables; Optimum Working Temperature in the Range 70-358 K Proc.IEE Vol.122,N.9, Sept 1975

39. E.W.Collings Design Considerations for High Tc Ceramic Superconductors Cryogenics, 1988,vol 28 Nov 1988

40. A.Abeln et al. Stability Consideration for Design of a High Temperature Superconductor Cryogenics 1992,Vol.32,N.3,Mar 1992

41. NCR-2 Superinsulation Specifications, Metallized Products Inc., 1991

42. Technical data , SAES Getters SpA, 1992

43. Arconium Special Alloys Technical Data, 1991

44. M.Rechowicz <u>Electric Power at low Temperature</u> Oxford University Press, 1975

45. <u>Superconducting Machines and Devices- Chap.8 :Transmission of Electrical Energy by Superconducting Cables</u> Plenum Press, New York,1974

46. J.R.Hull <u>High Temperature Superconducting Current Leads for Cryogenic Apparatus</u> Cryogenics 1989, Vol.29, Dec 1989

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Printed on recycled paper in the United States of America

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com