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MATPRO – UPGRADED VERSION 2012: A COMPUTER LIBRARY OF MATERIAL PROPERTY AT CRYOGENIC TEMPERATURE.

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Abstract

For computing of quench propagation in superconducting magnets, a number of material properties from cryogenic to room temperature are necessary. The code MATPRO is a computer library, developed in the LASA lab, to providing thermal and electric properties at cryogenic temperatures of most used materials in superconducting magnets. Specific heat is provided for many materials, too. Although not complete, and with some limitations that are evidenced int eh paper, the library might be useful to be integrated into suitable custom numerical codes., Written in Fortran language, MATPRO library can work also as stand alone and can be interrogated in order to give in output both the required property or tables easy to be plotted. This paper is a description of the updated version of MATPRO released in 2012. The previous edition of MATPRO is described in [1].

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1.   INTRODUCTION

The aim of this work is to describe the code MATPRO, a *Fortran 77* computer library that is able to provide some electrical and thermal properties of the most common materials used for the construction of superconducting magnets. The physical properties dealt by the code are:

1. Density.
2. Specific heat.
3. Electrical resistivity
4. Thermal conductivity.

The last three properties are assumed to be dependent on the temperature, and for some metals (copper and aluminium) the last two properties are also dependent on the magnetic field *B* and the *RRR* of the material. In the case of helium, density, specific heat and thermal conductivity are also pressure dependent.

Originally the code was specifically designed to compute thermal and electrical properties for simulations of the transition from the superconducting to the normal state of superconducting magnet (this phenomenon is usually called "*quench*"). Thermal and electrical properties of the materials composing the coils are needed in quench analysis in order to determine the propagation velocity of the interface between the superconducting and normal states and in order to compute the resistance of the coils once they are gone to the normal state as well as the temperature increase of the coil itself. For these scopes, the accuracy required in the knowledge of the properties doesn't need to be very high, because many others uncertainties are present in the models that are usually adopted (actual thermal exchanges with the environment, exact composition of the materials constituting the coil, etc.). Consequently the database of MATPRO code has been compiled with an accuracy of 10-20%. Such a level of accuracy might be not sufficient for other type of analysis like, for example, stability of conductor and superconducting magnets.[1]

2.   GENERAL FEATURES

The code MATPRO is written in Fortran 77. The core of the program is constituted by the function XMATPRO, which gives the required property in function of all the parameters necessary (material name, temperature, magnetic field, etc.) The main program MATPRO is constituted only by the instructions necessary to run the function XMATPRO interactively with the user: in fact it allows preparing files or to display directly in the monitor the property requested in the input. The data necessary for the input can be easily inserted by following the instruction and choices that are presented in the menu of the program. When the *end* option is chosen, before to stop the program, the file MATPRO.INI is written, which contains the data

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[1] L. Rossi is very gratefully to the many students that, as a part of their physics thesis on applied superconductivity in the LASA lab, have contributed to the code. In particular it should be acknowledged the essential work of Gabriele Varieschi, who wrote the first version with, the contribution of Giorgio Ambrosio for high field corrections and the excellent work of Ferdinando Ametrano who did the present computer interface with XMATPRO.

of last input. When the code is run again, this file is open (if present), in order to re-load the last input data that were been used.

The options given in the menu window are:

1. *Physical properties*: the user can select the property he requires among specific heat, electrical resistivity, thermal conductivity, and density.

2. *Output data*: the user can select whether to have the punctual *value* or the *integral* value respect the temperature. This feature is not active for most materials, and for the material for which it is active, the integral values cannot be considered accurate. Consequently it is <u>recommended</u> to use the punctual *value* only (option = *value*), unless authors are contacted.

3. *Reference direction*: a few materials (*G10* and *G11*) are non isotropic, the thermal conductivity is different whether it is considered in the *parallel* or in the *normal* direction respect to the woven that composes the material. Put 3 for parallel direction and 4 for normal direction. For the other materials and for the other properties, the results are independent by whatever value is assigned for this option.

4. *Material name*: the user can select the material type. The list of all available materials is reported in the Table I, with the indication of the parameters used for the calculation of the properties. The material name has to be inserted in the uppercase and the string length has not to contain more than 8 characters.

5. *RRR range*: this option is applicable for some materials (see Table I) for which the electrical resistivity and thermal conductivity depend on the RRR of the material. Three values are expected to be input by the user: *low* value, *high* value and *step*. If the *low* value and *high* value are different, the property required is calculated from the *low* value to *high* value, with the given *step*. The *step* value must be always different from zero. For the other materials and for the other properties not dependent on *RRR*, the results are independent on the RRR value assigned to this option. The RRR (Residual Resistivity Ratio) is defined as the ratio between the room temperature resistivity and the resistivity at 4.2 K: Rho(295 K)/Rho(4.2 K).

6. *Temperature range*: with this option, the user can select the temperature range for the calculation. Three values are expected to be input by the user: *low* value, *high* value and *step*. If the *low* value and *high* value are different, the property required is calculated from the *low* value to *high* value, with the given *step*. The *step* value must be always different from zero. For the properties not dependent on temperature, the results are independent on the particular temperature value assigned to this option.

7. *Magnetic field (or Pressure for helium)*: with this option, the user can select the value of the magnetic field for those materials and those properties that depend on the field (see Table I) or the pressure (in atm) in the case of helium. Three values are expected to be input by the user: *low* value, *high* value and *step*. If the *low* value and *high* value are different, the property required is calculated from the *low* value to *high* value, with the *step* input. The *step* values must be always different from

zero. For the other materials and for the other properties not dependent on the magnetic field, the results are independent on the value is assigned to this option.

Table I : List name of the materials and ranges for the parameters.

Material name	Density	Spec. heat	Electrical resistivity			Thermal conductivity		
		Temp. range (K)	Temp. range (K)	Field range (T)	RRR range	Temp. range (K)	Field range (T)	RRR range
ALUMINUM	Yes	0-300	0-300	0-6	28-30675	2-300	0-5	10-30000
BECU	N.A.	N.A.	N.A.	N.A.	N.A.	2-300	-	-
BRASS	N.A.	N.A.	0-300	N.A.	N.A.	2-300	-	-
BRONZE	Yes	0-300	0-300	-	-	0-300	-	-
BSCCO	N.A.	0-300	0-300	-	-	≥ 2	-	-
COPPER	Yes	0-300	0-300	0-15	0-200	≥ 0	≥ 0	0-200
LEAD	Yes	0-300	N.A.	N.A.	N.A.	2-300	-	-
NIOBIUM	Yes	0-300	20-300	-	-	2-300	-	-
NBSNSUP	N.A.	0-18	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
NB3SN	Yes	0-400	0-300	-	-	2-300	-	-
NBTISUP	N.A.	0-300	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
NBTI	Yes	0-310	0-300	-	-	2-300	-	-
PHBR	N.A.	N.A.	0-300	-	-	N.A.	N.A.	N.A.
PHCU	N.A.	N.A.	N.A.	N.A.	N.A.	2-300	-	-
SILVER	Yes	0-300	0-300	0-Bmax[1]	0-Rmax[1]	2-300	-	5-1790
AISI	N.A.	0-300	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
AISI304	Yes	N.A.	0-300	-	-	2-300	-	-
AISI316	Yes	0-366	0-300	-	-	2-300	-	-
TANTALUM	Yes	0-300	0-300	-	-	2-300	-	-
SN	Yes	0-300	≥ 0[2]	-	-	2-300	-	-
TIN-LEAD	Yes	0-300	≥ 0[2]	-	-	≥ 0[2]	-	-
TITANIUM	Yes	0-300	N.A.	N.A	N.A	N.A.	N.A.	N.A.
TIALSN	N.A.	N.A.	0-300.	-.	-	2-300	-	-
TIALV	N.A.	N.A.	N.A.	N.A.	N.A.	2-300	-	-
TUNGSTEN	Yes	0-350	N.A.	N.A.	N.A.	2-1000	-	-
VANADIUM	Yes	N.A.	N.A.	N.A.	N.A.	2-300	-	-
V3GA	Yes	0-24	0-300	-	-	N.A.	N.A.	N.A.
YBCO	N.A.	0-300	0-300	-	-	1.2-300	-	-
EPOGLASS	Yes	0-300	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

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[1] Bmax × Rmax ≤ 10000 T
[2] Data could not be accurate

(*continued*)

Material name	Density	Spec. Heat Temp. Range (K)	Electrical resistivity Temp. Range (K)	Field range (T)	RRR range	Thermal conductivity Temp. Range (K)	Field range (T)	RRR range
GLASS	N.A.	0-300	≥ 0	-	-	2-300	-	-
G10	Yes	4-300	0-300	-	-	2-300	-	-
G11	N.A.	N.A.	0-300	-	-	2-300	-	-
NYLON	N.A.	N.A.	N.A.	N.A.	N.A.	2-300	-	-
PERSPEX	N.A.	N.A.	N.A.	N.A.	N.A.	2-300	-	-
TEFLON	N.A.	0-310	N.A.	N.A.	N.A.	2-300	-	-
KAPTON	Yes	4-300	N.A.	N.A.	N.A.	4-300	-	-
SPACER	C	0-300	0-300	-	-	≥ 0	≥ 0	0-200
HELIUM[3]	Yes	1-300	N.A.	N.A.	N.A.	1-300	-	-
MNCU	Yes	0-300	0-300			0-300		
DECOPPER	N.A.	N.A.	2-900[4]	≥ 0	≥ 0	N.A.	N.A.	N.A.
CRCOPPER	Yes	1-300	1-300	0-30	10-3000	1-300	0-30	10-3000
CRSNPB	Yes	1-300	1-300	-	-	1-300	-	-
CRG10	Yes	1-300	1-300	-	-	1-300	-	-
CACOPPER	Yes	0-999[5]	0-300	0-15	0-200	≥ 0	≥ 0	0-200
FALSOSN	Yes	0-350[2]	$\geq 0^2$	-	-	$\geq 0^2$	-	-
CAEPOGL	Yes	0-999[5]	≥ 0	-	-	4-300	-	-
CANBTI	Yes	0-999[5]	0-999[5]	-	-	4-300	-	-
AL5083	N.A.	N.A.	0-300	N.A.	N.A.	N.A.	N.A.	N.A.
AL1100	N.A.	N.A.	0-300	N.A.	14-32.6	N.A.	N.A.	N.A.
CRALUMIN	Yes	1-300	1-300	0-30	10-30000	1-300	0-30	10-30000
CRAIS304	Yes	1-300	1-300	-	-	1-300	-	-

8. *Write into file*: in this option the name of the file can be chosen, where the calculated data are printed. Also the extension of the name is required.

9. *Display on video*: by selecting this option, the calculated data are directly displayed on the screen.

10. *End*: it allows closing the program, by saving all the last input data in the file MATPRO.INI.

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[3] All helium properties are pressure dependent (1-25 atm). Also the density is temperature dependent (1-300 K). The value of pressure has to be indicated instead of the Magnetic Field value.

[4] 4 K - 295 K if magnetic field is >0.

[5] When T > 300 K, the data are approximated

The simplest way to get some physical properties is using the menu described above. On the other hand, in some cases, the properties are needed during the run of a program. In this case it is useful to link the function XMATPRO with a program, and so the program will ask directly the physical properties to XMATPRO. The following chapter will illustrate how to use the function XMAPTRO.

3.   THE FUNCTION *XMATPRO*

The function XMATPRO, when it is linked to another program, returns directly the requested material property. The function is in the form: XMATPRO(*igrand, nfl, idir, mat, rrr, temperature*, *bfield*). In the following, it is described the meaning of the variables and how to use them.

1. *igrand*: with this integer variable, the user can select what property wants to require: 1 for specific heat, 2 for electrical resistivity, 3 for thermal conductivity, 4 for density and 0 in order to display the list of materials on the video.

2. *nfl*: with this integer variable, the user can select whether to have the punctual value (*nfl*=1) or the integral value (*nfl*=2) respect the temperature. This feature is not active for most of the material, and for the material for which it is active, the integral values cannot be considered accurate. Consequently it is recommended to use the punctual value only (*nfl* = 1).

3. *idir*: integer variable. For some materials (*G10* and *G11*), the thermal conductivity can be different whether it is considered in the *parallel* or in the *normal* direction respect to the woven that compose the material. Put *idir*=3 for parallel direction and *idir*=4 for normal direction. For the other materials and for the other properties, the results are independent by whatever value is assigned for this variable.

4. *mat*: it is a character variable, by which the user can select what material is considering. The material name has to be inserted in the uppercase and the length of the string has not to contain more than 8 characters. The list of all available materials, updated at the present time, is reported in the Table I, with the indication of the parameters used for the calculation of the properties. For some material slightly different values, originating from different sources, are offered: refer to section 4. "Origin of data" for more information).

5. *rrr*: real variable, which is the RRR of the material. This option is applicable for some materials (see Table I) for which the electrical resistivity and thermal conductivity vary in function of the RRR of the material. For the other materials and for the other properties not dependent by *RRR*, the results are independent by whatever value is assigned for this variable.

6. *temperature*: with this real variable, the user can select the temperature (in kelvin) for the calculation. For the properties not dependent by temperature, the results are independent by whatever value is assigned for this variable.

7. *bfield*: with this real variable, the user can select the value of the magnetic field (in tesla) for those materials and those properties which are sensitive to the field (see

Table I). In the case of helium, this input value is used to select the value of pressure in atmospheres. For the materials and for the properties not dependent by the magnetic field, the results are independent by whatever value is assigned for this variable.

When all parameters are inserted, the value of the returned function XMATPRO is the value of the physical property requested. The density is reported in $g \cdot cm^{-3}$, the specific heat in $J \cdot kg^{-1} \cdot K^{-1}$, the electrical resistivity in ohm·m and the thermal conductivity in $W \cdot m^{-1} \cdot K^{-1}$.

4. ORIGIN OF THE DATA

The data used to compile the electronic library of MATPRO, come from many different sources. In some cases, more then one source has been used to obtain the property of one material, in order to extend the temperature range or the range of other variables like the magnetic field or the RRR. For some materials (like copper, aluminium and G10), more than one source is available for the full range, so more than one curve per material is available, with somehow different value. These curves are available as separate functions, with different names and the user can select a different name for the material, in order to select different sources (for example COPPER, CRCOPPER, DECOPPER).

The code contains also "artificial material, namely "SPACERS" that simulate the properties relevant for quench calculation of composite materials. However the properties implemented for such fictitious material might not be correct for use different than intended. See the description of the material before using.

In the following paragraphs the description of the original sources for each material will be reported.

1. *AISI*: this is stainless steel type 310S. Only the specific heat is reported. See p. 8184 of [2] and parag. VIII-Q-5 of [3].
2. *AISI304*: this is stainless steel type 304L. It is reported the density, the electrical resistivity [4] p.197, [2] and thermal resistivity [2]. The data of the electrical resistivity have been extrapolated between 273 K and 300 K.
3. *CRAIS304*: this is stainless steel type 304L, whose data come from [5]. *Warning*: the properties of this material come from the commercial Company *CRYODATA INC.* [5]. The data can be used <u>only</u> under a written agreement and license with the Company CRYODATA INC.
4. *AISI316*: this is stainless steel type 316L. It is reported the density, the electrical resistivity [4] p.197, [2] and thermal resistivity [2] and the specific heat [26] p.1-4. The data of the electrical resistivity have been extrapolated between 273 K and 300 K.
5. *AL1100*: this is the aluminium alloy 1100-0. It is reported only the electrical resistivity [2] parag. 4.1.4-7.1 (11/76).
6. *AL5083*: this is the aluminium alloy 5083-0, H113. It is reported only the electrical resistivity [2] parag. 4.3.1-15 (11/74).

7. ***ALUMINUM***: this is aluminium. It is reported the density, the specific heat [3] parag. VIII A.1-A.3, the electrical resistivity [2], [6] p.101, and the thermal conductivity [2]. For the evaluation of magneto-resistivity some data have been extrapolated from [7].

8. ***CRALUMIN***: this is aluminium whose data come from [5]. It is reported the density, the electrical resistivity and the thermal conductivity. *Warning*: the properties of this material come from the commercial Company *CRYODATA INC.* [5]. The data can be used <u>only</u> under a written agreement and license with the Company CRYODATA INC.

9. ***BECU***: this is beryllium copper alloy. Only the thermal conductivity is reported [3].

10. ***BRASS***: this is commercial bronze with 90% of copper, that is the standard US terminology for brass. The thermal conductivity [8] p.50 and the electrical resistivity [4] p.197 are reported. The resistivity between 273 K and 300 K has been extrapolated.

11. ***BRONZE***: It is reported the density, the specific heat [2] p.5531-5533, the electrical resistivity [26] p. 3-14 and the thermal conductivity [26] p. 3-15. The specific heat above 20 K has been averaged from the data of the specific heat of copper and tin.

12. ***BSCCO***: it is reported the specific heat [9] and the electrical resistivity [10] of Bi_2-Sr_2-Ca-Cu_2-O_8, known also Bi-2212 superconductor. The discontinuity due to the superconducting transition at 85 K of the specific heat has been obtained by extrapolating the data at 84.95 K in the superconducting state and at 85.05 in the normal state. The electrical resistivity is intended in the normal state.

13. ***COPPER***: this is copper. It is reported the density, the specific heat, the electrical resistivity and the thermal conductivity. The specific heat, whose data come from [3] parag. VIII B.1-B.5, is calculated by an analytical expression from 0 to 10 K. The electrical resistivity and thermal conductivity, which are dependent by temperature, RRR and magnetic field, are calculated with analytical expressions in all the temperature range, with data that come from [11] p. 50, 146. The magneto-resistance of the electrical resistivity has been corrected with some other data coming from the source of the *DECOPPER*. The data of specific heat are less accurate when RRR is lower than 11.

14. ***CACOPPER***: this is copper, with properties for the specific heat and electrical resistivity in an old version. The specific heat, whose data come from [3] parag. VIII B.1-B.5, is calculated by an analytical expression from 0 to 10 K. The electrical resistivity and thermal conductivity, which are dependent by temperature, RRR and magnetic field, are calculated with analytical expressions in all the temperature range, with data that come from [11] p. 50, 146.

15. ***CRCOPPER***: this is copper whose data come from [5]. It is reported the density, the electrical resistivity and the thermal conductivity. *Warning*: the properties of this material come from the commercial Company *CRYODATA INC.* [5]. The data can be used <u>only</u> under a written agreement and license with the Company CRYODATA INC.

16. ***DECOPPER***: this is copper, whose data come from [12]. Only the electrical resistivity is available.

17. ***EPOGLASS***: this is epoxy resin. The density and the specific heat are reported. From 0 K to 100 K the data come from [3] parag. VIII N.1; from 100 K to 300 K come from [27].

18. **CAEPOGL**: this is epoxy resin, with properties for the specific heat, electrical resistivity and thermal conductivity in an old version. The properties are approximated to the ones of *GLASS* (see the material *GLASS*). The specific heat above 300 K has been considered constant.

19. **G10**: this is G10 sheet. It is reported the density, the specific heat [28], the electrical resistivity [13] and the thermal conductivity [13]. The thermal conductivity can be calculated either in the parallel or in the *normal* direction respect to the woven that compose the material (parameter *idir* for the function *XMATPRO*).

20. **CRG10**: this is G10 sheet whose data come from [5]. It is reported the density, the electrical resistivity and the thermal conductivity. *Warning*: the properties of this material come from the commercial Company *CRYODATA INC.* [5]. The data can be used <u>only</u> under a written agreement and license with the Company CRYODATA INC.

21. **G11**: this is "glass-cloth-reinforced epoxy laminates", denominated G11. It is reported the electrical resistivity [13] and the thermal conductivity [13]. The thermal conductivity can be calculated either in the parallel or in the *normal* direction respect to the woven that compose the material (parameter *idir* for the function *XMATPRO*).

22. **GLASS**: this is quartz glass (vitreous silica, silica glass). It is reported the specific heat ([3] VIII M.1-M.2 and [14] p.53), the electrical resistivity and the thermal conductivity [3]. For the thermal conductivity, either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

23. **HELIUM**: these are the properties of helium. They are temperature and pressure dependant, with the pressure expressed in atmospheres (1-25 atm). Under the lambda-point (that is also pressure dependent), the thermal conductivity is set to a conventional large value (10^9 W·m^{-1}·K^{-1}.) because of superfluidity. To obtain a better interpolation, the peak in specific heat at lambda-point is neglected. The reference is [29].

24. **KAPTON:** this is the commercial name for polyimide film. It is reported the density, the specific heat [28] and the thermal conductivity [30]. The thermal conductivity dataset refers to the sample of Kapton H.

25. **LEAD**: this is lead in the normal state. It is reported the density, the specific heat (the source of the data is internal at LASA Lab.) and the thermal conductivity [3]. For the thermal conductivity the data below 6 K have been extrapolated. Moreover either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

26. **MNCU**: This is copper-manganese metallic compound used as matrix for superconducting strands, to limit ac losses. The resistivity is linearly scaled form measurements of bulk at 10 K and 295 K (Luvata, privat communication), and increased of 15-20% to take into account the increase of resistance from bulk to matrix. The thermal conductivity is calculated from the Weidman-Franz law. The density and the specific heat is set equal to COPPER.

27. **NB3SN**: This is the inter-metallic compound Nb$_3$Sn in the normal state. It is reported the density [32], the electrical resistivity [15] p.434, the thermal conductivity [15] p.434 and

the specific heat. The specific heat dataset from 20 K to 400 K comes from [31], while the values from 0 K to 20 K come from [32] and they are interpolated with a pseudo-analytical formula (see [33]).

28. *NBSNSUP*: This is the inter-metallic compound Nb_3Sn in the superconducting state. It is reported the specific heat from 0 to 18 K, using data from [32] interpolated with a pseudo-analytical formula (see [33]). This material property is magnetic induction dependent.

29. *NIOBIUM*: It is niobium in the normal state. It is reported the density, the specific heat [3] parag. VIII O.1-1, the resistivity [26] and the thermal conductivity [3]. For the thermal conductivity, either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

30. *NBTI*: It is the metal alloy niobium titanium in the normal state. It is reported the density, the specific heat (from 0 to 20 K the data come from [6] p.27, above 20 K the data come from [3] VIII-O-2), the electrical resistivity ([15] p.434) and the thermal conductivity ([15] p.424).

31. *NBTISUP*: It is the metal alloy niobium titanium in the superconducting state. It is reported the specific heat [16].

32. *CANBTI*: this is metal alloy niobium titanium in the normal stat, with properties for the specific heat, electrical resistivity and thermal conductivity in an old version. The data of specific heat come from [3] for temperature between 10 K and 310 K; below 10 K the data are extrapolated whereas above 310 K the specific heat is considered constant. The data of electrical resistivity for temperature below 300 K come from [15] p.434 (like the material *NBTI*); above 300 K the electrical resistivity is considered constant. The data of thermal conductivity come from [15] p.424 (like the material *NBTI*).

33. *NYLON*: this is nylon. It is reported the thermal conductivity [3]; either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

34. *PERSPEX*: this is perspex. It is reported the thermal conductivity [3]. The data above the temperature of 25 K have been extrapolated; either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

35. *PHCU*: this is phosphor de-oxided copper. It is reported the thermal conductivity [3]; either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

36. *PHBR*: this is the phosphor-bronze alloy (95% Cu and 5% Sn). It is reported the electrical resistivity ([4] p.197 and [2]). The data above 273 K have been extrapolated.

37. *SILVER*: this is silver. It is reported the density, the specific heat, the electrical resistivity and the thermal conductivity. The resistivity depends also by the magnetic field and by RRR; the thermal conductivity by the RRR. The source of the data for the specific heat is internl at LASA Lab. The data of electrical resistivity at zero field come from [11] and [3] X-O-3; the dependence of the magneto-resistance is deduced from the Kohler's plot [17]. The data of the thermal conductivity come from [3] VII-C-2 and [18] p.104.

38. **SN**: this is tin in the normal state. It is reported the density, the specific heat, the electrical resistivity and the thermal conductivity. The source of specific heat is [19]; the data below 10 K have been extrapolated. The electrical resistivity is a constant provisional value (not dependent by the temperature) given in 1990ies by the firm Ansaldo (Italy). The source of the thermal conductivity is [3]. For the thermal conductivity, either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

39. **FALSOSN**: this is tin in normal state, with properties for the specific heat, electrical resistivity and thermal conductivity in an old version. The specific heat is approximated to the one of copper (see the material CACOPPER). The electrical resistivity is a constant provisional value (not dependent by the temperature) given in 1990ies by the firm Ansaldo (Italy). The thermal conductivity is calculated with the Widemann-Franz law from the electrical resistivity.

40. **SPACER**: with this material it is intended to simulate the physical properties of the fillers that often are present in dipole and quadrupole magnet for accelerator. If these fillers are in copper, they present the density and the thermal properties of the copper, but they are electrically insulated with polyimide or similar tapes, so they do not carry transport current. Consequently the following physical properties have been assigned: the density, the specific heat and the thermal conductivity are the same of the material *COPPER* (consequently there is also the dependency by the magnetic field and RRR for the thermal conductivity). The electrical resistivity is the same of the material *G10*. It should be understood this is good for calculations where the eddy current induced by field variation in the spacer can be neglected, otherwise this schematization of the spacers is not correct.

41. **TANTALUM**: this is tantalum. It is reported the density, the specific heat [3] VIII E.1-E.3, the electrical resistivity [3] and the thermal conductivity [3]. For the thermal conductivity, either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

42. **TEFLON**: this is Teflon. It is reported the specific heat and the thermal conductivity. The source of the specific heat is [3] VIII I.1-I.2; the values below 10 K have been extrapolated. The source of the thermal conductivity is [3]. For the thermal conductivity, either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

43. **TITANIUM**: this is titanium. It is reported the density and the specific heat [19],[20].

44. **TIALSN**: this is the titanium-aluminium-tin alloy (Ti-5Al-2.5Sn). It is reported the electric resistivity [2] and the thermal conductivity [2].

45. **TIALV**: this is the titanium-aluminium-vanadium alloy (Ti-6Al-4V). It is reported the thermal conductivity [2].

46. **TINLEAD**: this the alloy tin lead (90%Sn-10%Pb). It is reported the density, the specific heat, the electrical resistivity and the thermal conductivity. The specific heat is calculated from the data of material *LEAD* and *SN*. The electrical resistivity and thermal conductivity have been assumed equal to ones of material *FALSOSN*.

47. **CRSNPB**: this is the alloy tin lead, whose data come from [5]. It is reported the density, the electrical resistivity and the thermal conductivity. *Warning*: the properties of this material come from the commercial Company *CRYODATA INC.* [5]. The data can be used <u>only</u> under a written agreement and license with the Company CRYODATA INC.

48. **TUNGSTEN**: this is sintered tungsten with RRR 15. It is reported the density, the specific heat [34] and the thermal conductivity [18].

49. **VANADIUM**: this is vanadium. It is reported the density and the thermal conductivity [3]. For the thermal conductivity, either the punctual value or the integral value can be computed respect the temperature (parameter *nfl* for the function *XMATPRO*).

50. **V3GA**: this is the inter-metallic compound V_3Ga in the normal state. It is reported the density, the specific heat [3] and the electrical resistivity [2].

51. **YBCO**: this is the ceramic compound YBCO (1,2,3,7-X) for superconducting application. The properties are supposed for the material in the normal state. It is reported the specific heat, the electrical resistivity and the thermal conductivity. The source of specific heat is [21] p.872 for temperature between 1.7 K and 20 K; for temperature between 20 K and 170 K the source is [22]; below 1.7 K and above 170 K the data are extrapolated. The source of the electrical resistivity is [21] p.868, 824 and the value at 0 K has been extrapolated. The source of the thermal conductivity is [21] p.868, 872.

5. CONCLUSION

The computer library MATPRO has been introduced. The main features have been presented and limitation discussed. It can useful for different types of cryogenic calculation, however it has certainly limitations that are inherited by the fact that the original scope was only quench calculations, for highly compact multi-turn solenoid type windings. Furthermore it is not complete since it has been built upon the needs encountered in the magnet design and quench calculation of the Superconductivity group of INFN-LASA, with no attempt to make it complete.

6. DISCLAIMER

With the present paper the authors want to put the library at disposal of the community after it has been used for years in the LASA lab. (where it has been employed for the design of the high field solenoid SOLEMI [23],[24], for the protection of the ATLAS toroid [25] and for the protection of CRIS-Napoli high field solenoids), in the Fermilab for preliminary calculations of the high field magnets for the VLHC and in BNL for a computation on superconducting Siberian snake.

However the authors warn that they are not computer specialists and the software employed might not be optimized or fully standardize, so they decline any inconvenient derived by a non proper running of the code on other machine, as well as by a mistake of evaluation generated by errors in the basic data or in their fitting. In case of problem please contact the authors.

7. REFERENCES

(1) L. Rossi, M. Sorbi, MATPRO: a computer library of material property at cryogenic temperature, INFN/TC-06-02, 2006.

(2) Handbook of Materials for Superconducting Machinery, Columbus, Ohio: Metals and Ceramics, Information Centre Battelle (1977)

(3) Bubble Chamber Group Data Handbook – Selected Cryogenic Data Notebook, compiled and edited by: J.E. Jensen, R.B. Stewart, W.A. Tuttle, Brookhaven National Laboratory, N.Y., U.S., (1966)

(4) Richard P. Reed and Alan F. Clark, "Materials at Low Temperatures", American Society for Metals, Metals Park, OH (1983)

(5) Cryocomp Libraries 1995: from Cryodata Inc. (Horizon Technologies, www.htess.com).

(6) M.N. Wilson, Superconducting Magnets, Claredon Press Oxford, (1983).

(7) LASA Internal data on measurements on the Zeus conductor with RRR 1330 performed by E. Acerbi.

(8) R. G. Scurlock, "Low temperature behaviour of solids", in Solid State Physics series edited by L. Jacob, published by Routledge and Kegan Paul Ltd., London 1966

(9) Hoechst Company: "High temperature superconducting bulk material for current leads" special edition of "Materials for superconducting" October 1993.

(10) Physica C 209 (1993) p.456-462

(11) F. Broggi, Progetto dei passanti di corrente per il ciclotrone superconduttore dell'Università di Milano, Graduated Thesis, Physics Department of Milan University, 1983

(12) Copper electrical resistivity: fortran subroutine by Arnaud Devred, "Quench Origins", KEK report 89-25, March 1990, based on data from N.G. Simon and R. P. Reed, preliminary draft of "Cryogenic properties of copper and copper alloy, Part II electromagnetic properties", NBS, Boulder Colorado, USA, August 1987.

(13) M.B.Kasen et al.,Mechanical,electrical and thermal characterization of G-10CR, Adv. in Cry. Eng. Materials vol.26, Planum Press, New York (1980), pp.235-244.) and vol. 32 p.235

(14) P.M. Clintock, D.J. Meredith and J.K. Wigmore, Matter at Low Temperature, Blackie, 1984 (out of print)

(15) H. Brechna, Superconducting Magnet System, Springer-Verlag, Berlin (1973)

(16) Zong-Ping Zhao, Thermo-electrodynamics of the resistive transition of superc. in epoxy-resin impregnated superc. Magnets, Doctoral thesis, M.I.T. December 1990, p.7-8)

(17) Cryogenics, vol.33 p.836 (1993)

(18) Thermal Conductivity of Solids at Room Temperature and Below, edited by G. E. Childs, L. J. Ericks, and R. L. Powell, Natl. Bur. Stand. (U.S.) Monograph No. 131 (U.S. GPO, Washington, D.C., 1973).

(19) Handbook of Chemistry and Physics, 70th edition, CRC Press Inc., Boca Raton-Florida (1989)

(20) Advance in Cryogenic Engineering Materials, vol. 8, p.268

(21) ICEC 13 Proceedings - supplement of Cryogenics vol.30 (1990)

(22) Physica C vol.194 (1992) p.97-104

(23) E.Acerbi, F.Alessandria, G.Baccaglioni,C.Birattari, E.Fabrici, L.Rossi, A.Sussetto, High field superconducting solenoid for the LASA in Milan, IEEE Trans. On Ma., Vol.24, N.2, March 1988, p.1417-1420

(24) G. Baccaglioni, M. Canali, L. Rossi, M. Sorbi, Measurements of quench velocity in adiabatic NbTi and Nb3Sn coils. Comparison between theory and experiments in small model coils and large magnets, IEEE Trans. on Magnetics, Vol. 30, n.4, July 1994, p. 2677-2680.

(25) E. Acerbi, M. Sorbi, G. Volpini, A. Dael, C. Lesmond, The protection system of the superconducting coil of the Barrel Toroid of ATLAS, IEEE Trans. on Applied Superconductivity, Vol. 9 N.2, June 1999, p. 1101-1104

(26) P. Bauer, H. Rajainmaki, E. Salpietro, EFDA Material Data Compilation for Superconductor Simulation, EFDA CSU, Garching, 2007

(27) IE Evseeva and SA Tanaeva. Thermophysical properties of epoxy composite materials at low temperatures. Cryogenics , 35(4):277-279, 1995.

(28) Material properties database of National Institute of Standards and Technology (NIST), available at http://cryogenics.nist.gov/MPropsMAY/materialproperties.htm

(29) Steven W Van Sciver. Helium Cryogenics. International cryogenics monograph series. Plenum, New York, NY, 1986.

(30) D. L. Rule, D. R. Smith, and L. L. Sparks. Thermal conductivity of polypyromellitimide film with alumina filler particles from 4.2 to 300 K . Cryogenics , 36(4):283-290, August 1990.

(31) G. S. Knapp, S. D. Bader, and Z. Fisk. Phonon properties of A15 superconductors obtained from heat-capacity measurements. Phys. Rev. B , 13(9):3783-3789, May 1976.

(32) V. Guritanu, W. Goldacker, F. Bouquet, Y. Wang, R. Lortz, G. Goll, and A. Junod. Specific heat of Nb3Sn: the case for a second energy gap. Phys. Rev. B, 70:184526, Nov 2004.

(33) G. Manfreda, Nb_3Sn Specific Heat Fit Function for Quench Simulation, TE-MSC Internal Note 2011-22, CERN.

(34) G.K. White and S.J. Collocott, Heat Capacity of Reference Materials: Cu and W, J. Phys. Chem. Ref. Data, Vol. 13, No. 4, 1984.