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COMMISSION OF THE EUROPEAN COMMUNITIES

FILLING ALLOYS FOR FAST BREEDER FUEL ELEMENT CONDITIONING

by

P.R. HEYLEN
(CEN)
J.G. WURM and A. AVOGADRO
(EURATOM)

1972

Report prepared by CEN
Centre d'Etude de l'Energie Nucléaire - Mol (Belgium)

Euratom Contracts No. 014-65-1 RAPB
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It is shown that with the filling alloy concept most of the unit operations along the Head-end flow-sheet will be less complicated and expensif.

Finally also transportation of the conditioned fuel elements should be much safer.

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KEYWORDS

MELTING POINTS
ALUMINIUM ALLOYS
MANGANESE ALLOYS
COPPER ALLOYS
MAGNESIUM ALLOYS
VANADIUM ALLOYS
CORROSION
SODIUM
FLOWSHEETS
FAST REACTORS
BREEDER REACTORS
SPENT FUEL ELEMENTS
IRRADIATION
TRANSPORT
BRITTLENESS
FUEL CANS
HEAT TRANSFER
LEAKS
REPROCESSING
CASTING MOLDS
FISSION PRODUCTS
SAFETY

C O N T E N T S

I.	General considerations	5
II.	Criteria for the choice of the filling alloy	6
III.	Proposed " Filling Alloys "	8
IV.	Results	9
V.	Filling and casting equipment	12
	Conclusions	15
	Abstract	17
	References	18
	Figures - I .... Flow diagram	19
	II .... Phase diagrams	20
	III .... Phase diagrams	21
	IV .... Filling device	22
	Micrograph 1	23
	Micrograph 2	

I. GENERAL CONSIDERATIONS

The highly irradiated fast breeder fuel elements must be handled with great care after the reactor discharge. Beside the brittlenes of the structural material and particularly the fuel can, there are other problems of concern such as the presence of sodium, the gazeous fission products, and the heat removal. The Head-end treatment unit operations, as well as the handling and transfert operations from the unloaded fuel element down to the HNO_3 dissolution unit (Fig.I.) are carried out in the following order :

- storage at the reactor site under Na
- transfert to the transport container under inert gas
- transport under Na
- reception at the reprocessing plant under inert gas
- sorting of the damaged fuel elements and conditioning
- storage under Na or inert gas
- elimination of Na
- preparation prior to decanning
- decanning chopping, electrocutting, etc.
- can-fuel separation by disaggregation
- HNO_3 dissolution.

In principle, the fast breeder fuel elements are handled and transferred in vertical position. Handling those elements in horizontal position is always accompanied by a certain risk of pin rupture and lack of cooling, a consequence of which could be a temperature rise followed by a fission gas pressure increase and their escape.

In order to avoid this kind of accidents, leaktight and cooled casks are necessary. However such an infrastructure is relatively expensive. For the transport of fast breeder fuel elements, even sodium cooling is considered. [1] The safety regulations impose an absolutely leaktight double containment transport container, which increase the transportation costs. Moreover, only the undamaged elements are transported, while the damaged elements (estimated at 2 %) have to be submitted to a conditioning, a storage and a special treatment, which results in a useless Pu hold-up.

In the case of mechanical cutting the sodium must be removed. This requires a relatively expensive and cumbrous equipment. For the mechanical chopping of an entire fuel element, the free space between individual pins do not allow sharp cutting. The pin fragments are more or less crushed and torn and even sometimes half closed at their ends, which involves a more difficult oxidization and dissolution procedure.

All afore-mentioned disadvantages can be avoided by a special treatment of the element as soon as it leaves the reactor. For instance : in order to improve the mechanical resistivity of the irradiated fuel element, a metal or a special alloy is poured into its interior. Thanks to this solid and massive coating the risk of pin fracture is diminished and all unit operations of the elements, from the storage zone of the reactor down to the HNO_3 dissolution unit are simplified. The material which fills up the free space is called the " Filling Alloy ".

II. CRITERIA FOR THE CHOICE OF THE FILLING ALLOY

An optimized filling alloy should meet following criteria :

1) Melting point above 700 °C
   The melting point of an ideal "Filling Alloy" should be located between 700 °C and 800 °C.

2) Boiling point of the filling alloy above 1000 °C.
An alloy with a very low vapour pressure below 1000 °C must be chosen in order to avoid difficulties during the filling operation.

3) Very high fluidity of the filling alloy.
The alloy must be very fluid at the moment of pouring in order to avoid formation of cavities. In principle, the eutectic alloys are the most appropriated ones.

4) Very good thermal conductibility.
The filling alloy must ensure a great radial heat removal in order to avoid liquid metal pockets in the inner part of the element. Only the outside wrapper wall will be cooled.

5) The filling alloy should have low interactions on the structural materials (no diffusion and dissolution during filling).

6) The filling alloy must resist reasonably well to the oxidizing medium required for disaggregation, as e.g. molten nitrate salts at 600 °C.

7) The filling alloy should not introduce penalities for the Head-end operations.

8) The filling alloy must be compatible with the long-term storage of the solid waste.

9) The filling operation costs and the price of the alloy should not penalize the fuel cycle cost.

III. PROPOSED " FILLING ALLOYS "

Taking into account the afore-mentioned criteria and more particularly the factor price/volume unit, following metals can be considered : Al, Cu, Mg. Since no individual metals satisfy entirely the criteria, there are only binary alloys of these metals which might be suitable.

Al-Mn alloy

According to the phase diagram of Fig.II, alloy Al-Mn(10 %), melting point 700 °C, meets all conditions. It is characterized by a very good fluidity during casting and by a good conductibility.

Cu-Mg alloy

Alloy Cu-Mg shows an eutectic with 9.7 wt.% Mg, the melting point of which is 722 °C. The only restriction to this alloy is related to the reducing power of Mg in regard to UO_2 and PuO_2 in case of fuel contact with Cu-Mg. (Fig.III)

Al-V alloy

In the Al-V phase diagramme there exists a peritectic point at 735 °C with only 1,8 wt % of V should be very favorable as for as its properties are concerned. Furthermore it could be produced in a very inexpensif way. The adequate quantity of V_2O_5 in added to the molten Al which produces the Al-V, 2 wt.% alloy in situ by Aluminothermie. (Fig.II)

Cu-Sn alloy

At 30 wt. % Sn, an eutectic is found, the melting point of which is 755 °C, more known as γ bronze. This alloy is relatively expensive and would not present an advantage over Cu-Mg. (Fig.III)

Cu-Zn alloy

This alloy is mentioned pro memorie. The dissolution kinetic of the zinc at the casting temperature is not to high. However Zn penetrates between the grain boundaries of the austenitic structure and makes it brittle. Another negative point of Zn will be its already high vapour pressure a 800 °C. (Fig.III)

In short, the first three filling alloys Al-Mn, Cu-Mg, Al-V, are considered as the most suitable ones, and their feasibility will be tested in the laboratory. The last three, all copper alloys Cu-Mg, Cu-Sn, Cu-Zn, will be kept in reserve unless the first series proves inadequate.

IV. RESULTS

Theoretical and practical investigations of the filling alloy concept have been directed in three different directions :

- theoretical evaluation of the heat transfert caracteristics of a short cooled fuel element with and without a filling alloy ;
- laboratory investigations of the cladding corrosion, the Na behaviour and the physical caracteristics of the filling alloys ;
- conceptual study and lay-out of a hot cell facility.

Heat transfer caracteristics

The purpose was to calculate the heat transfert caracteristics of a high burn-up (100.000 Mwd/T) short cooled core fuel element loaded with either Al or Cu as a reference filling alloy.
Details are given in a " Technical Annexe " written by W.Detavernier, Technology Department, C.E.N./S.C.K., Mol.

The main features are follows :
It is well known that the heat transfert characteristics of such a fuel element are relatively poor and without inside forced cooling the temperature would rise quickly up to the melting point of the stainless steel. Calculations have shown that such a fuel element filled with Al filling material, in vertical position in stagnant air, would reach the melting point of Al (660 °C) even after 200 days cooling. This means that a filling alloy with a somewhat higher melting point (around 750 °C) should be more satisfactory. But in any case the fuel element could not remain without cooling of the outer wrapper wall. The simplest cooling procedure would be forced air convection.

In theory Cu has a better thermal conductivity than Al, and its behaviour as a filling alloy should be improved, which is also shown from the radial temperature distribution curves. However its melting point is to high for practical purposes. Therefore only copper alloys with melting temperatures around 750 °C would be suitable. (exemple Cu-Mg 10 wt.%). Also in such a case forced air convection cooling would be necessary.

Laboratory results obtained at Euratom, Ispra

Stainless steel (304) tubes of 10 mm Ø closed at one end with a 2mm hole have been filled with the filling alloy at an overpressure of 500 Torr. The stainless steel dissolution kinetic in the Al-Mn 10 wt.% at different temperatures has given following results :

Temperature °C	Time min.	Dissolution speed mm/h
700 °	480	0,005
800 °	158	0,080
900 °	5	0,45

Corrosion rates up to 800 °C are well acceptable. There is however a sharp increase if temperature reaches 900 °C. The photomicrograph N° 1 shows the cut view of the cast tube. A needle like structure is observed at the lower part. The photomicrograph N° 2 shows an intermetallic layer at the inox-alloy interface. The penetration of this intermetallic layer depends more on the temperature than contact time. The practical conclusion would be that the casting temperature of the Al-Mn filling alloy should not exceed 800 °C. Since the casting operation takes only a few minutes, such a short contact time between the liquid filling alloy and the stainless steel would not damage the cans. However a forced cooling of the wrapper outside wall would be necessary.

Similar experiments have been performed with the Cu-Mg 10 wt.% alloy. Since it is a pure eutecticum it has a true melting point, exellent flow characteristics, and wets the stainless steel. Furthermore it dissolves about 1,5 wt.% of Na which gives the alloy a red orange color also its wetting properties seem to be increased. The alloy sticks well to the stainless steel, which provides a very leak tight containment for the fission gases.

Graphite behaves badly as a crucible material and should be discarded. A refractory steel or hastalloy or an Al_2O_3 crucible would be more suitable. No noticeable corrosion of stainless steel in a molten Cu-Mg 10 wt.% alloy at 900 °C for a contact time of 2 hours could be observed. However the stainless steel tube surface come out with a black colored very thin oxyde surface layer, but without any visible intergranular penetrating attack. In short the Cu-Mg 10 wt.% presents optimum conditions as a filling alloy, its major drawback will be however the generally high and sometimes oscillatury price of copper.

The investigation of the Al-V 2 wt.% filling alloy is not yet completed. Its general characteristics should be very close to pure Aluminum except for the sharp melting point increase. It might be more suitable and less expensif than the Al-Mn 10 wt.% alloy.

V. FILLING AND CASTING EQUIPMENT

Casting of the filling alloy must be performed right at the reactor discharge of the fuel element. The special equipment (Fig.IV) which must be designed will be composed of the following elements :

- a graphite, cast iron or refractory metal crucible for casting the foot of the element. This crucible is provided with a cooling system in order to favor " de-casting " of the filling alloy ;
- a melting and casting apparatus for the filling alloy composed of a low-frequency or a resistance furnace. In order to prevent contamination of this material, it is stored outside the hot cell, while the liquid filling alloy streams through the wall by means of a liquid metal siphon.

The sequences of the casting procedure are follows :

- transfer and fixation of the fuel element to the filling ramp ;
- filling of the crucible with filling alloy ;
- introduction of the foot of the element in the filling alloy and solidification ;
- the filling alloy is cast into the fuel element through a funnel ;
- after complete solidification of the filling alloy, the element is withdrawn and stored.

Advantages of the filling alloy concept

This fuel element conditioning induces a series of advantages for most of the unit operations which are performed between the reactor discharge and the HNO_3 dissolution.

This advantages are the following :

- strenghthening of the mechanical resistance of the fuel element by the filling alloy which eliminates the risk of pin damage ;
- the solidified alloy provides a total containment of the pins, which are completely drown in a metallic matrix, so that the fission gases remain captured until decanning. Therefore a costly gaz purification system becomes useless;
- owing to the total containment, it is no longer necessary to make a distinction between the damaged and the normal fuel assemblies. All elements, including the damaged ones are submitted to the same treatment, so that the monitoring and special handling equipment become useless;
- the problem of fuel element cooling is thoroughly modified. In fact, the heat transfert coefficient of the filling alloy is much higher than the one of air, the fuel element is cooled at the wrapper outside wall;
- Na elimination.
  Solubility of Na in Al is relatively low (0.15 wt.%). Nevertheless, in most cases the quantity of available Na is greater than its solubility which leads us to the consideration of two possibilities for Na elimination.

  First : during casting of the filling alloy, only a part of the Na is dissolved, while the other part is captured. This technique is valid in the case of electrochemical machining with molten salt electrolytes.

  Second : Na is eliminated before casting of the filling alloy, by immersion in a molten salt bath (nitrate-nitrite mixture). Sodium is oxidized and dissolves in the salt.

→ Intermediary storage before transport.

The fuel element loaded with the filling alloy is not any more stored in a sodium storage pool. It can be transfered and stored temporarily in a storage pool of simpler design using a cheap cooling medium such as air, N_2, or even a molten salt (nitrate - nitrite). A fission gas extraction unit would not be necessary or at least could be very much simplified.

→ Transport.

Similarly to the storage, transportation of these same fuel elements is much less complicated. Since Na is replaced by a more common heat carrier (nitrate-nitrite) all loading and unloading operations can be carried out in air instead of argon. Therefore the risk of fission gas release is diminished and the danger of a Na + H_2O reaction is eliminated.

→ Handling at the reprocessing plant.

Reception, transfert and intermediary storage are also less critical at the reprocessing plant. The storage facility could be the same as described in /2/ /3/

→ Fuel element decladding.

The three potential decladding processes which might be applied to fast breeder fuels are following :

- the mechanical chopping
- the liquid metal decladding
- the electrochemical machining with molten salts.

In each case the filling alloy would have a different role, however it might be also desirable to melt it out before decladding is started particularly in the case of liquid metal Sb-Cu decladding.
Since the decladding procedure is not yet clearly defined it is still to early to examine the simplifications and real advantages which will be induced by the filling alloy.

→ Filling alloy recycling.
If the more expensif Cu-Mg alloy is used, recycling might be considered. In this case the molten-out alloy will be shipped back to the reactor site in the empty fuel transportation cask for reuse. If the less expensif Al-V alloy is used, recycling might not be necessary. In this case the alloy could be used as a solid wrapper material for the conditioning of highly radioactive solide waste either from the Head-end or the Purex plant.

CONCLUSIONS

A general survey of the filling alloy concept for the conditioning of fast breeder fuel elements during the Head-end operations has been given. The filling alloy is poured inside the fuel element right at the reactor site, so that the fuel pins are surrounded by a leak tight metal matrice, which improves the mechanical properties of the fuel element, and firthermore prevents the fission gases to escape. Consequently the fuel element can be moved, transfered and shiped with much less care, also the Head-end gas purification system could be considerably simplified. Therefore at every unit operation along the Head-end line, many technical improvements can be materialized, and the transportation safety considerably increased. The total sum of the savings should largely exceed the equipment and operating expenses of the filling alloy device.

Quantitative data

The expenses for the filling material might be illustrated on hand of the following examples :

	Al-Mn 10 wt.%	Al-V 2 wt.%	Cu-Mg 10 wt.%
- Mean density	3,17	2,77	8
- Free volume	31	31	31
- Weight kg/element	98 kg	86 kg	250 kg
- Price FB/element	2.600	2.186	9.750

Problems still to be solved

This document gives a rather general idea of what can be done with the filling alloy concept. However there are still lots of problems to be solved such as follows :

- fundamental investigation of the stainless steel (and other canning material) dissolution kinetics with the chosen filling alloy ;
- conceptual study of the fuel element casting technique at the reactor site, particularly in the case of high burn-up irradiated fuels with high residual heat ;
- study of the cooling problems during transfer and transportation of the as cast fuel elements ;
- conceptual study of the decasting operation of the filling alloy, at the reprocessing plant, equipment design and optimisation ;
- investigation of the penalties of solid waste problems and filling alloy traces interferences with the flow sheet of the Head-end and the Purex process ;
- economical assesment of the filling alloy concept in regard to the over all fuel cycle costs.

Acknowledgement

The authors are endebted to Dr.Mutzbauer from C.C.R., Euratom, Ispra, who carried out the laboratory experiments on stainless steel corrosion with liquid metals. Details are to be published by Dr. G.Mutzbauer in an C.C.R., Ispra internal report.

The authors express also their gratitude to Mr.W.Detavernier, C.E.N./S.C.K., Mol, Technology Department, for his valuable contribution on heat transfert calculations.

Abstract

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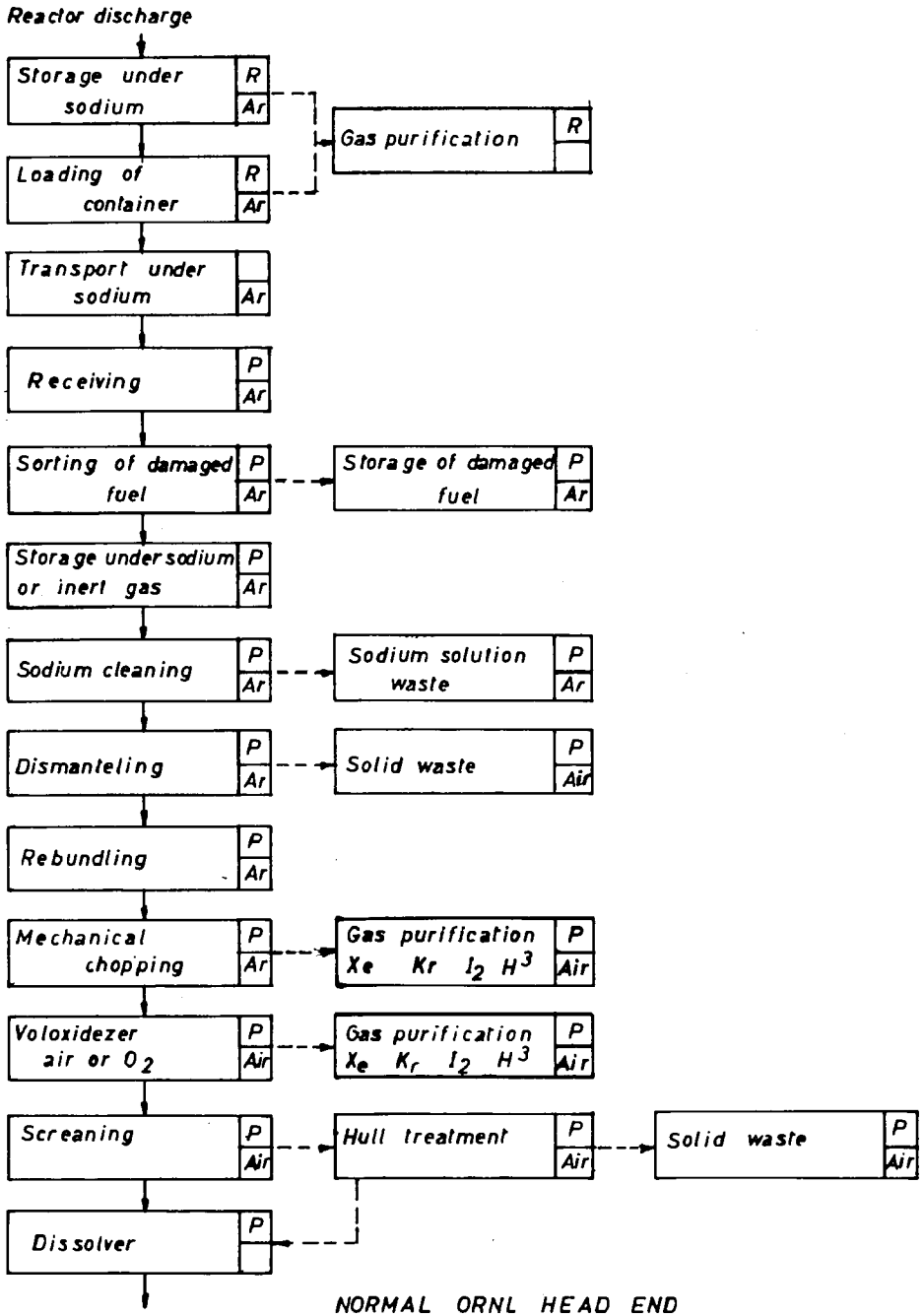
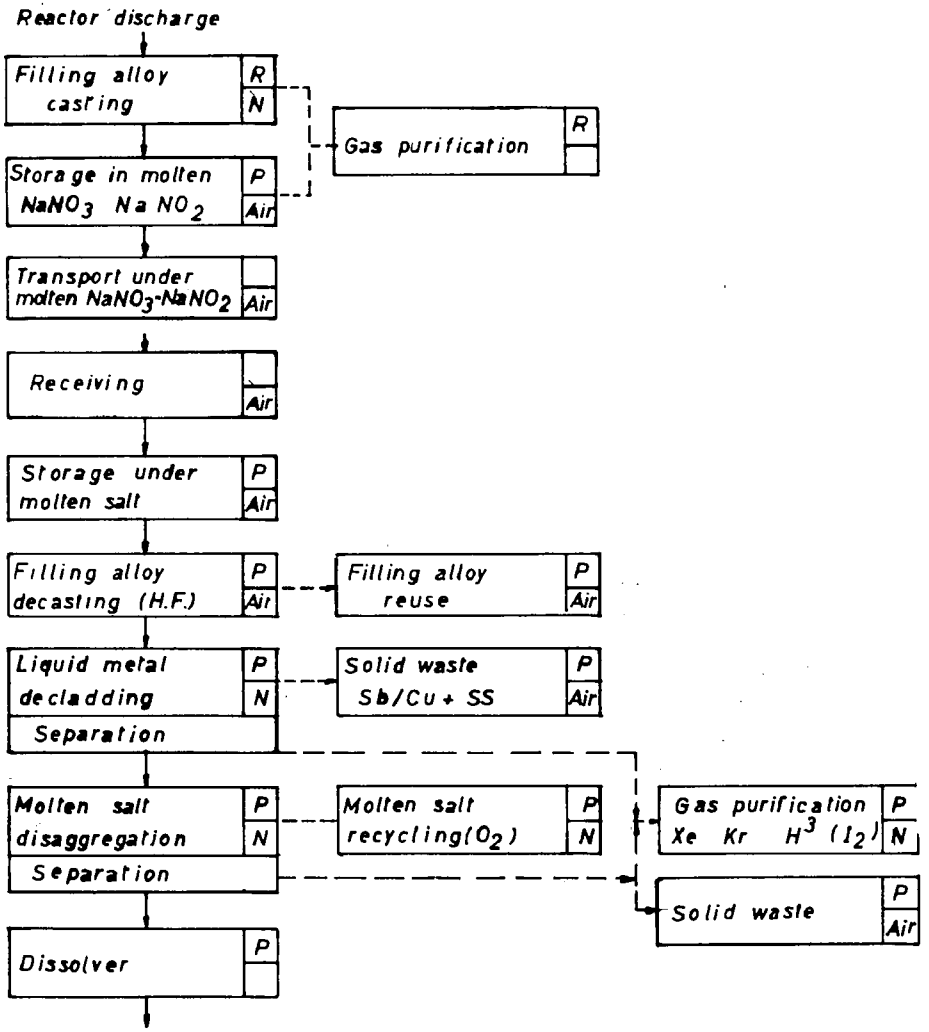


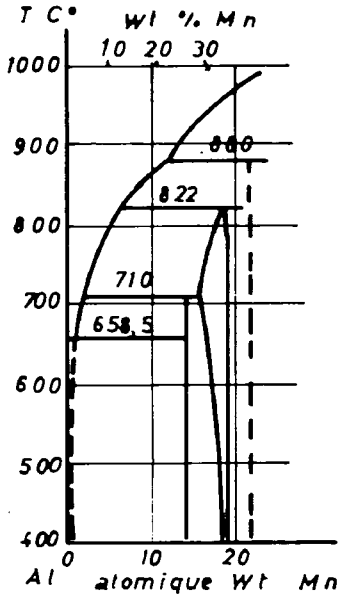
NORMAL ORNL HEAD END



PYROCHEMICAL HEAD END

R: Reactor
P: Reprocessing plant

FIG.: 1 FLOW DIAGRAM



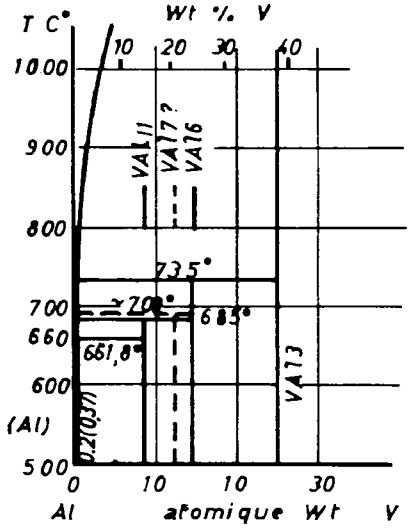
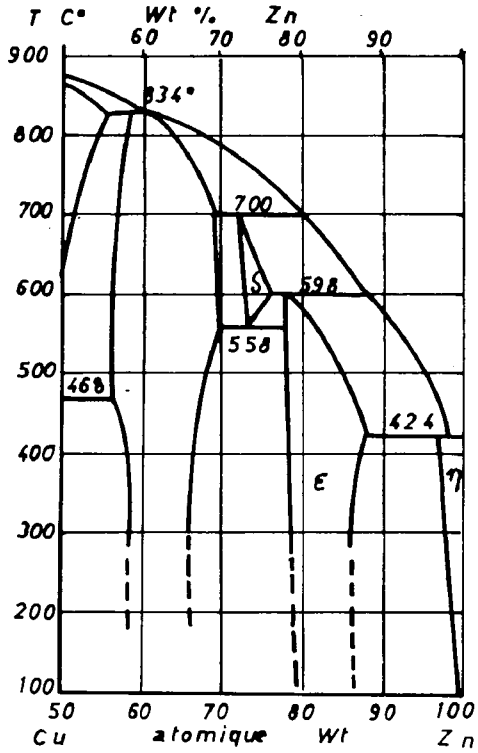
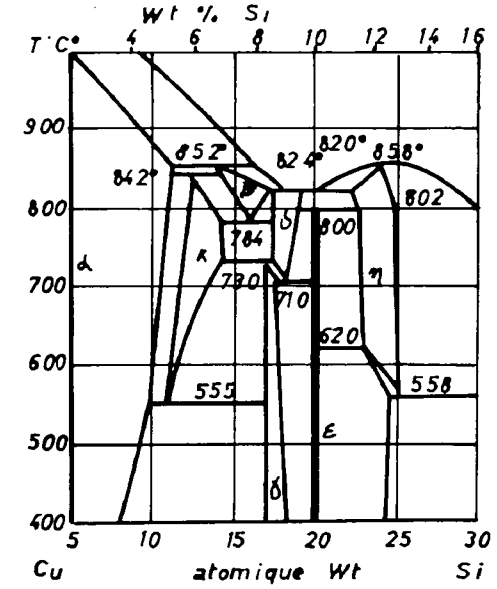
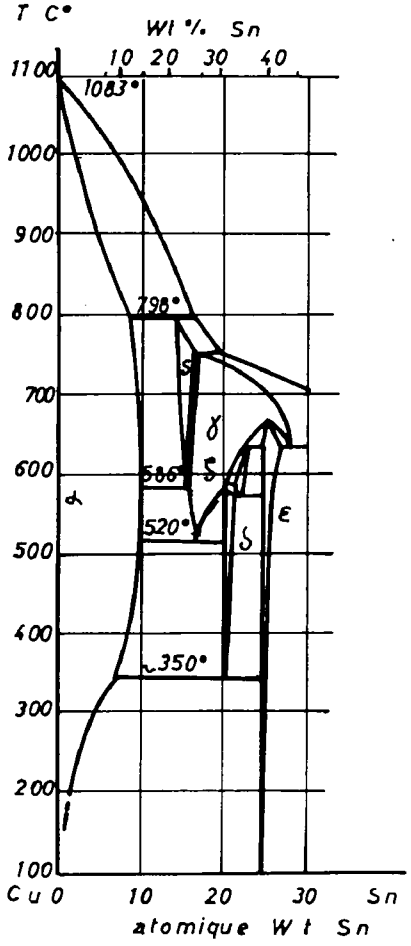


FIG II PHASE DIAGRAMS Al. ALLOYS







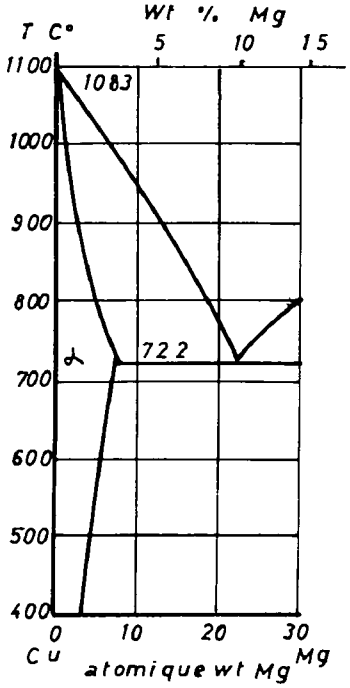
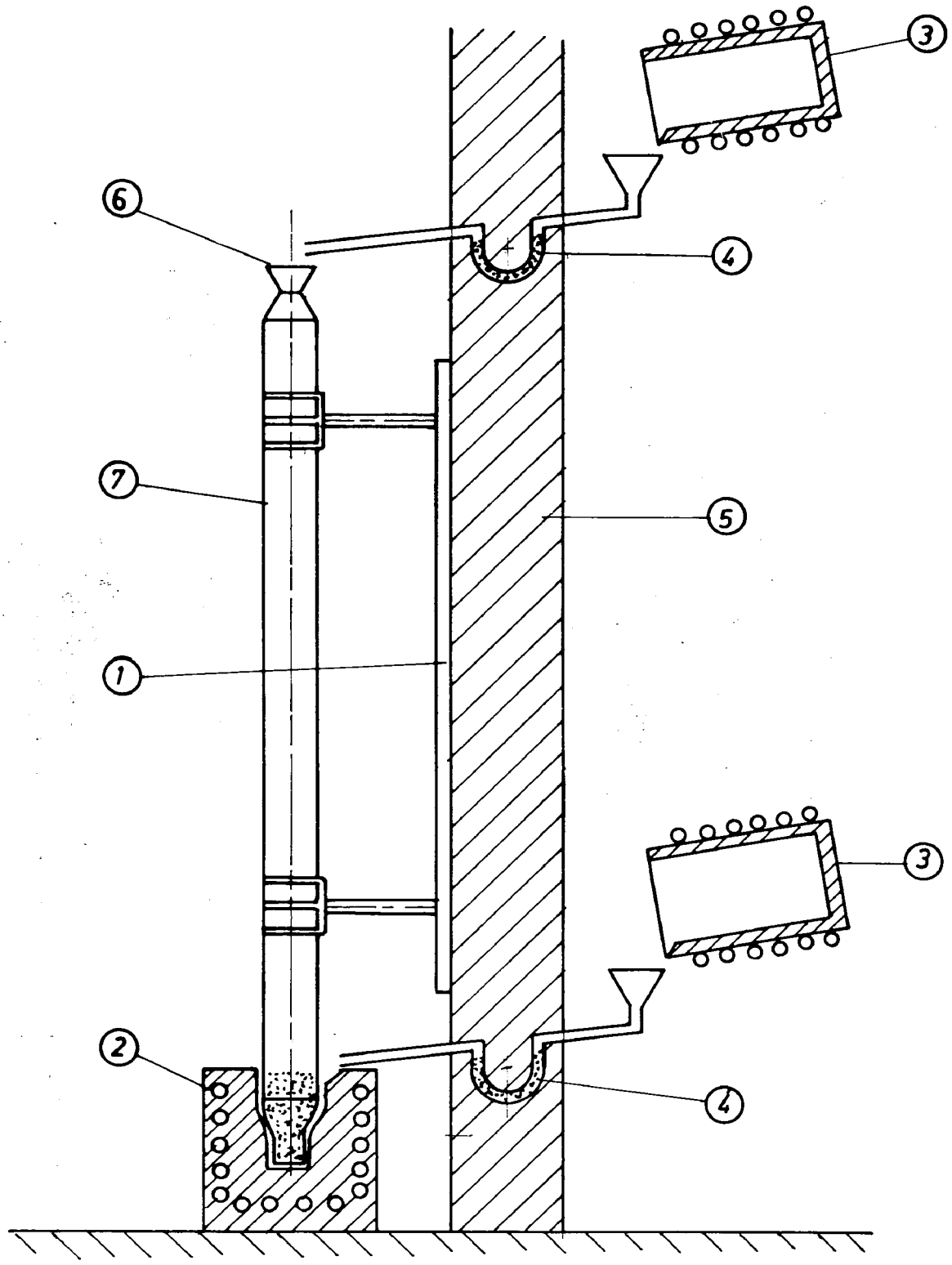


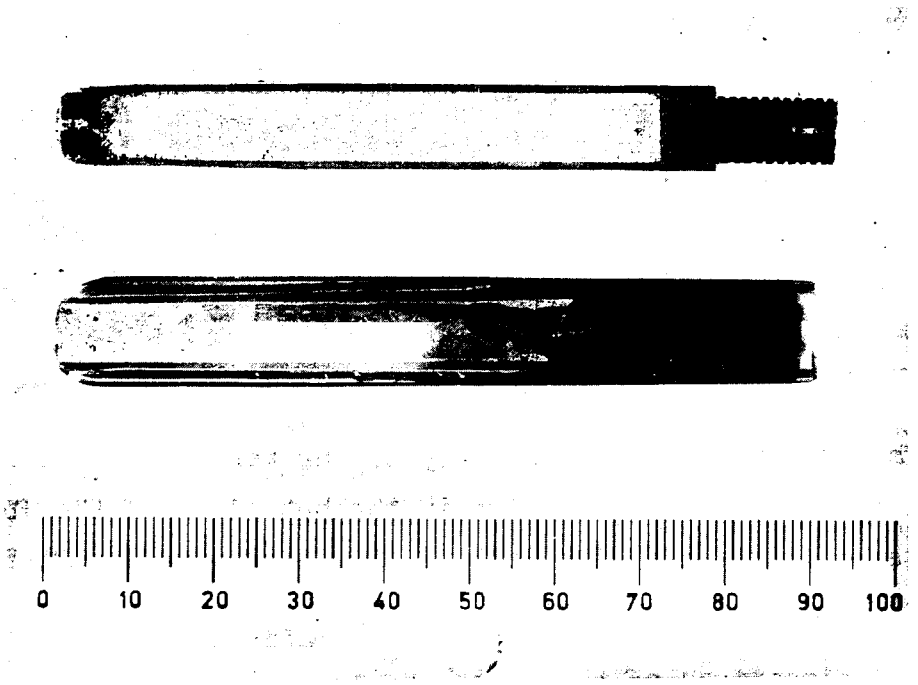
FIG. III

PHASE DIAGRAMS Cu ALLOYS

FIG. IV FILLING DEVICE



1. Filling ramp
2. Casting furnace
3. Melting furnace
4. Liquid metal siphon
5. Cell wall
6. Funnel
7. Fuel assembly



Micrograph 1.

Upper part : filling experiment and S.S. corrosion at 900 °C

Lower part : S.S. corrosion at 800 °C

Micrograph 2.

Corrosion test of Al-Mn 10 wt.% on S.S. tube 304 at 700 °C during 480 min.

100 x

Upper layer : Al-Mn 10 wt.%

Black layer : intermetallic corrosion layer

Lower part : unchanged S.S.

ANNEXE

Calculation of the radial temperatures distribution in the hot plane of the fuel assembly, type Na1, zone 1-3, after irradiation.

This document gives a summary of the results of the calculation of the radial temperature distribution in the hot plane of the fuel assembly type Na1 as a function of the cooling time after the irradiation for the following conditions :

- principal dimentions of the assembly :
  see Fig. 1 and Fig. 2
- the space between the fuel pins in the hexagonal tube is completely filled with copper or aluminium after the irradiation,
- the assembly is cooled in vertical position by natural convection in stagnant air or argon at atmospheric pressure and 20 °C, and by radiant-heat transmission;
- the ratio $\frac{\text{maximum axial linear power}}{\text{mean axial linear power}}$ is

  1,22 for the core zone 1

  1,22 for the blanket zone 3

- the mean heat production in W/kg UO_2-PuO_2 over the length of the zones 1 and 3 as a function of the cooling time in days after the irradiation is given below :

Cooling time after irradiation (days)	Mean heat production in W/kg UO_2-PuO_2	
	core zone 1	outer zones 3
10	320	14,2
20	247	10,9
30	197	8,8
60	139	6,2
90	104	4,6
180	60	2,7

- the weight of UO_2-PuO_2 in the 331 fuel pins of the assembly is :

  85,5 kg over a length of 955 mm for the core zone 1
  73,7 kg over a length of 2 x 400 mm for the blanket zone 3.

- the thermal conductivity of the filling material is about :

  1,8 W/cm°C for aluminium
  3,5 W/cm°C for Cu.

- the melting point of the filling material is :

  660 °C for aluminium
  1083°C for copper.

- the volumetric expansion by melting of the filling material is about :

  + 6,5 % for aluminium
  + 4,2 % for copper

- the radiant heat-transmission from the stainless-steel (AISI 304 L) hexagonal tube has been calculated for an emissivity of 0,35 to 0,53.
  This value is supposed according to ref (3) which give :

  for stainless steel type 304 (8 Cr, 18 Ni)

  ε = 0,36 for a light silvery, rough brown surface after heating at 500 °C, this value can increase to about 0,73 after 42 hr heating at 530 °C.

  for other stainless steel types (types 301, 316...) after repeated heating and cooling one has :

  ε = 0,3 to 0,55 for temperatures up to 1000°C

- the radiant heat-transmission emissivity coefficient for the filling material is about :

  ε = 0,13 to 0,16 for molten copper (1075 up to 1275°C)

  ε = 0,1 to 0,2 for oxidized aluminium (200 up to 600 °C).

- the coefficient of thermal expansion is about :

  25.10^{-6} $°C^{-1}$ for aluminium (20 -- 300°C)
  $19,3.10^{-6}$ $°C^{-1}$ for copper (20 -- 750°C)
  19.10^{-6} $°C^{-1}$ for AISI 304 (20 -- 750°C)
  (see ref.4)

Results of the calculation

The results of the calculations are presented on the diagrams 1, 2, 3 for natural cooling in stagnant air and on diagram 4 for natural cooling in stagnant argon.

Diagram 1

Diagram 1 gives the maximum temperature at the outside surface of the hexagonal tube in the hot plane of the core zone 1 of the fuel assembly Na1 as a function of :

- the maximum heat power evacuation in W/cm assembly or W/kg UO_2-PuO_2 , produced in the hot plane of the core zone 1, to the environment of the assembly.

- the mean heat power production over the length of the core zone 1 in W/kg UO_2-PuO_2 .

- the cooling time in days after the irradiation, corresponding to the mean heat power production over the length of the core zone 1.

The assembly is assumed to be cooled by natural convection and radiant heat-transmission in stagnant air atmosphere.

The heat transfer by natural convection of air is calculated according to ref (1) and (2).

The minimum heat transfer coefficient for natural convection is situated between the midplane level and the upper level of the core zone 1 and can be estimated at about :

$7,3\ 10^{-4}$ W/cm^2°C in the laminar convection zone according to ref. (1)

$5,2\ 10^{-4}$ W/cm^2°C in the laminar convection zone according to ref. (2)

$9,5\ 10^{-4}$ W/cm^2°C in the turbulent convection zone according to ref. (1)

for a surface temperature of 700 °C.

At 700 °C surface temperature the heat transfer by natural convection is about 30 W/ cm assembly

The radiant - heat transmission has been calculated for two different emissivity coefficients : 0,35 and 0,525 which give respectively 108 and 162 W/ cm assembly for 700 °C surface temperature.

Diagram 2

Diagram 2 gives the maximum temperature of the aluminium filling material at the center of the hot plane function of the same parameters as on diagram 1.

The maximum temperature in the center of the hot plane is calculated for 3 cases taking into account the following heat transfer conditions :

case (a)
- maximum emissivity of the hexagonal tube = 0,525
- heat transfer coefficient for turbulent flow motion according to VDI (ref.1)
- good contact between the filling material and the inner surface of the hexagonal tube.

case (b)
- nominal emissivity of the hexagonal tube = 0,35
- heat transfer coefficient for undistorted laminar motion according to VDI (ref. 1)
- good contact between the filling material and the inner surface of the hexagonal tube.

case (c)
- nominal emissivity of the hexagonal tube = 0,35
- heat transfer coefficient for undistorted laminar motion according to VDI (ref. 1)
- heat transfer by conduction and radiant-heat transmission through a formed air gas-gap of about 1,6 mm thickness between the inner surface of the hexagonal tube and the filling material, obtained after solidification of the aluminium filling material (ε Al = 0,15).

The cladding temperature of the fuel pins can be adopted to be the same as the temperature of the filling material.

Case (c) gives the cooling time after the irradiation which allows the filling material to solidify about 250 days for safety reasons if the filling material is aluminium.
It is possible that this time will be much smaller in reality if the cooling conditions turned out to the most favourable ones.

Diagram 3

Diagram 3 gives the maximum temperature of the copper filling material at the center of the hot plane of the core zone 1 of the fuel assembly Na1 (see fig.2) as a function of the same parameters as on diagram 1 and 2.

The maximum temperature in the center of the hot plane is calculated for the same cases as on diagram 1 and 2.

The gas gap which can be formed here has a thickness of about 1 mm after solidification of the copper filling material (emissivity of Cu = 0,15).

The cladding temperature of the fuel pins can be adopted to be the same as the temperature of the filling material.

From cas (c) it can be seen that the cooling time after the irradiation may be choosen much smaller for copper than for aluminium (melting point for copper = 1083 °C).

Diagram 4

Diagram 4 gives the same characteristics as the diagrams 1 to 3 for argon instead of those for air.

From this diagram one can conclude that argon gives a little higher temperatures than air, if the emissivity coefficients of radiant - heat transmission can be considered the same as in air. This is probably not the case if the surfaces cannot be oxidized.

Therefore the use of argon atmosphere is to be avoid.

Enclosure : 2 figures
4 diagrams

REFERENCES

(1) "VDI Wärmeatlas" (1963)
VDI-Verlag (GM-BH) Düsseldorf.

(2) "Convection naturelle en régime turbulent le long d'une plaque plane verticale" (1970) par A. PIROVANO, S. VIANNAY et M. JANNOT .

(3) "Heat transmission" (1954) by William H. Mc.ADAMS.

(4) "Metals reference book" volume II (1955) by Colin J. SMITHELLS.

ASSEMBLY N_a 1 IN NATURAL COOLING POSITION AFTER IRRADIATION

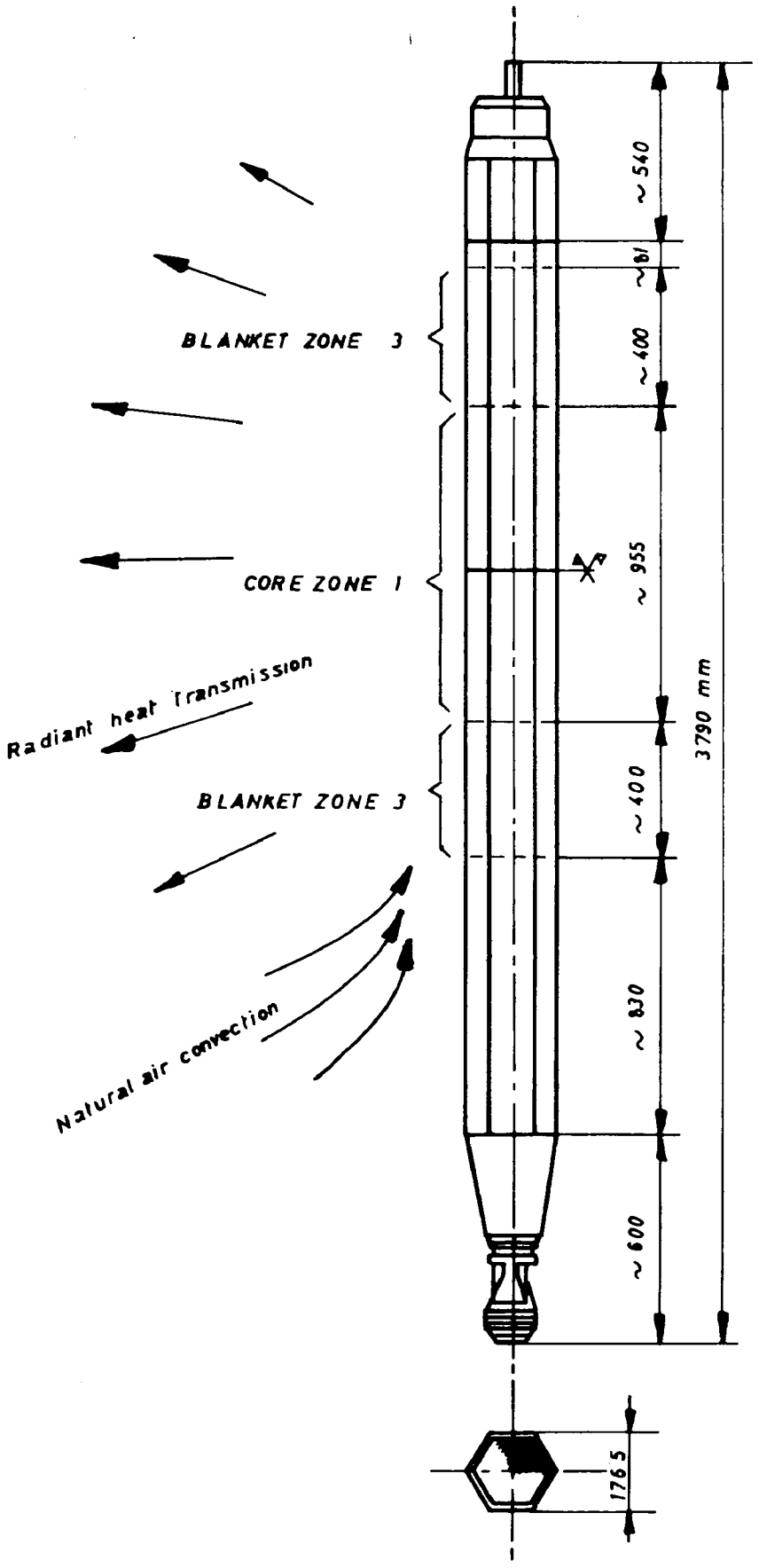
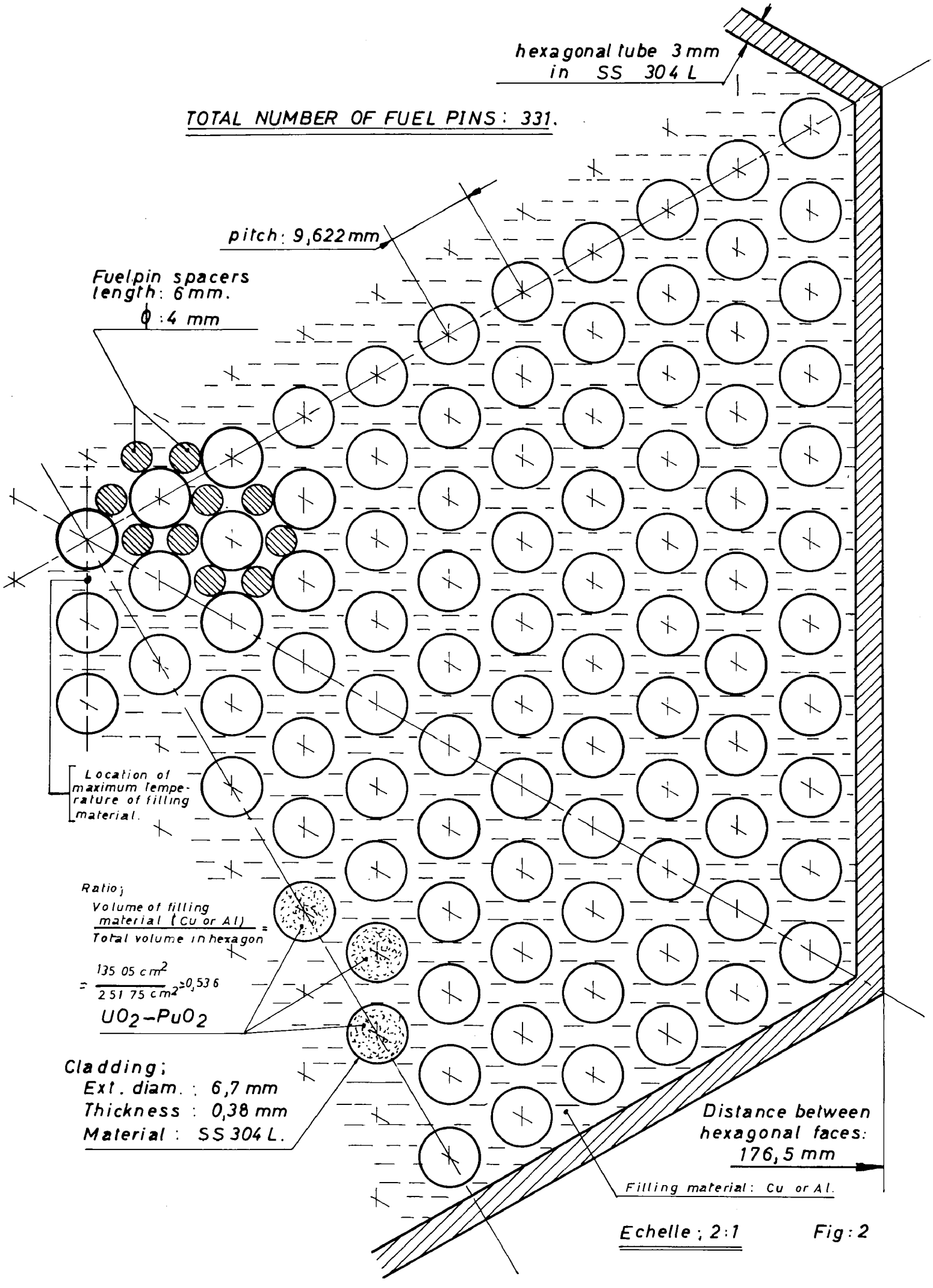
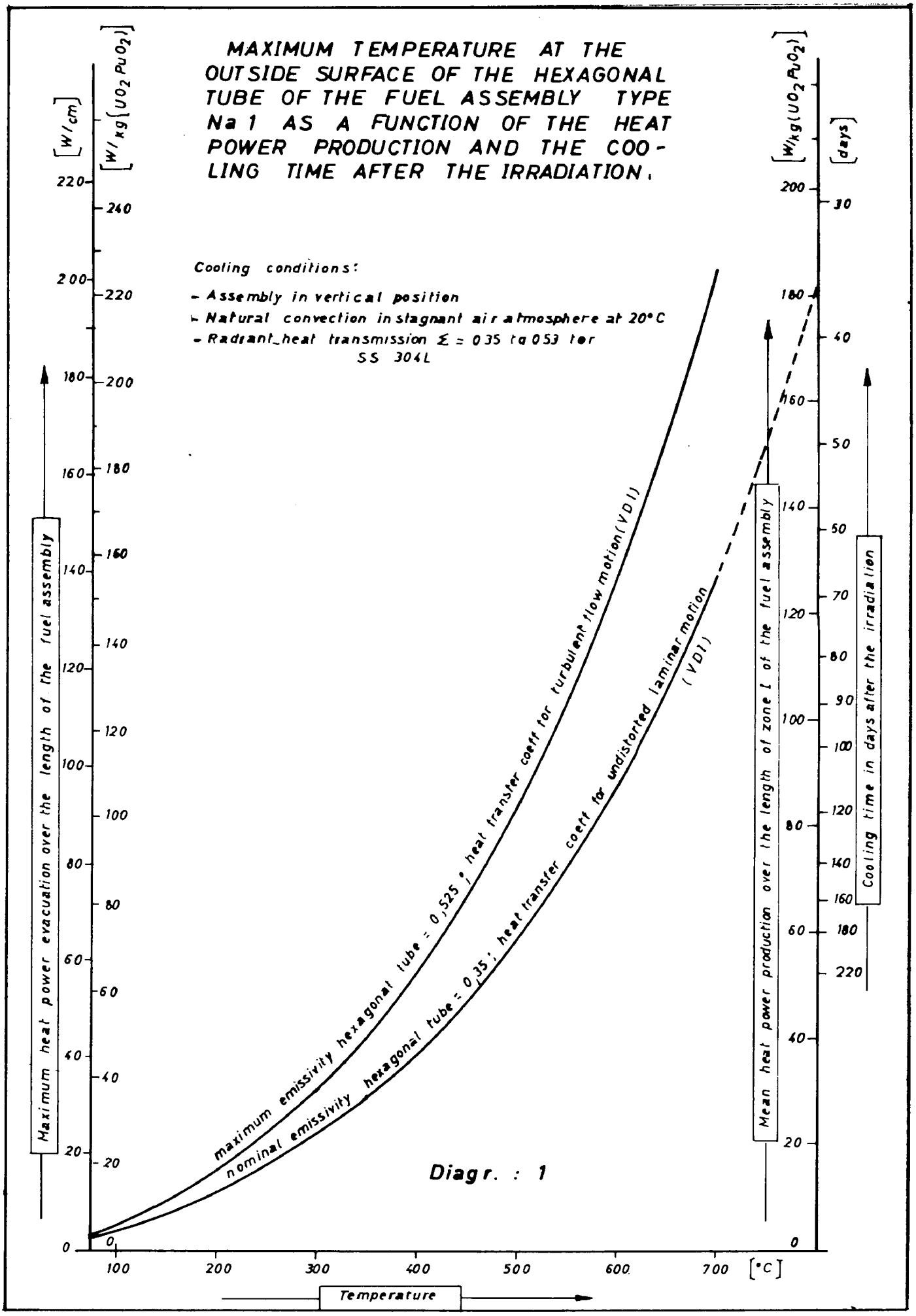
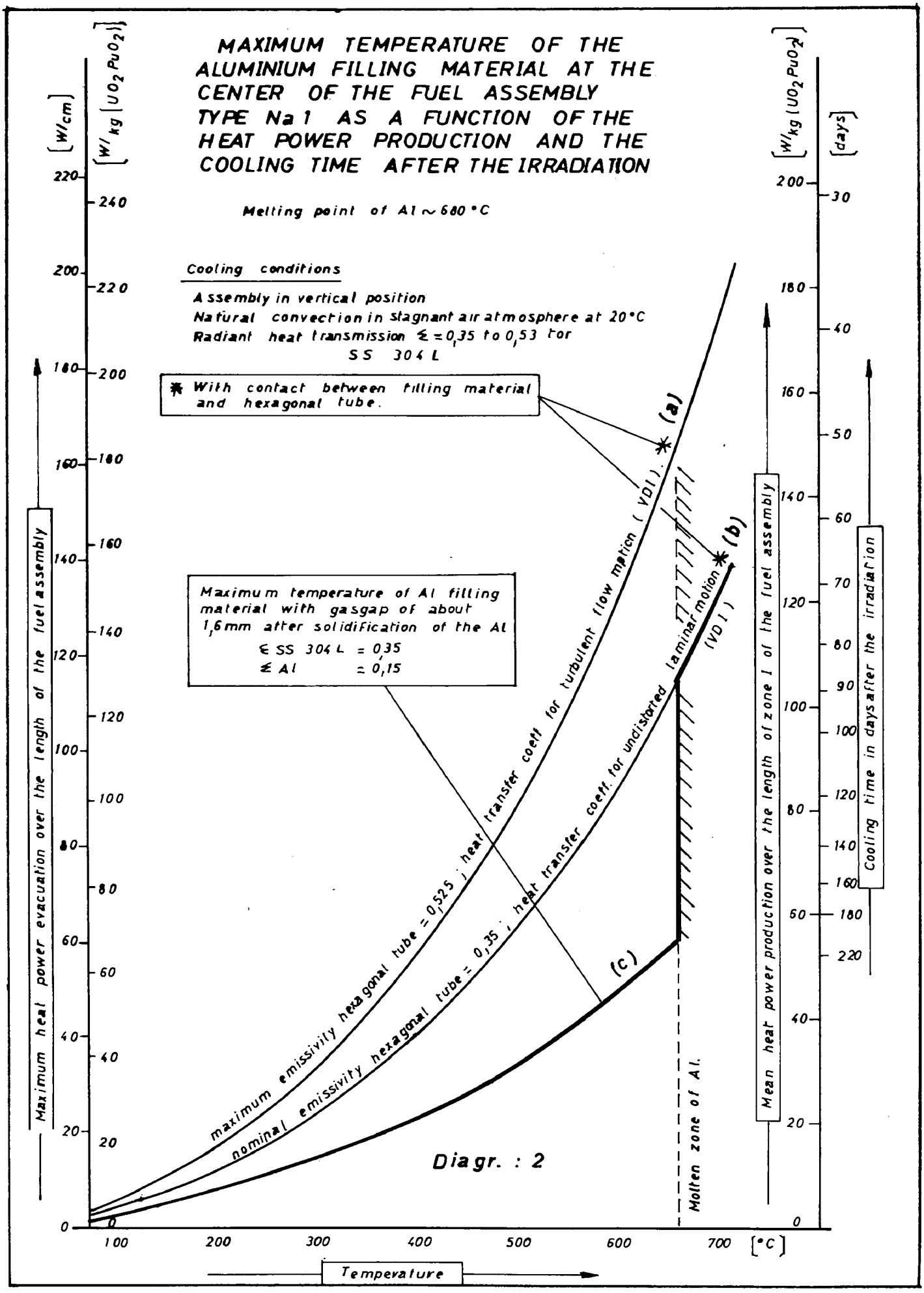
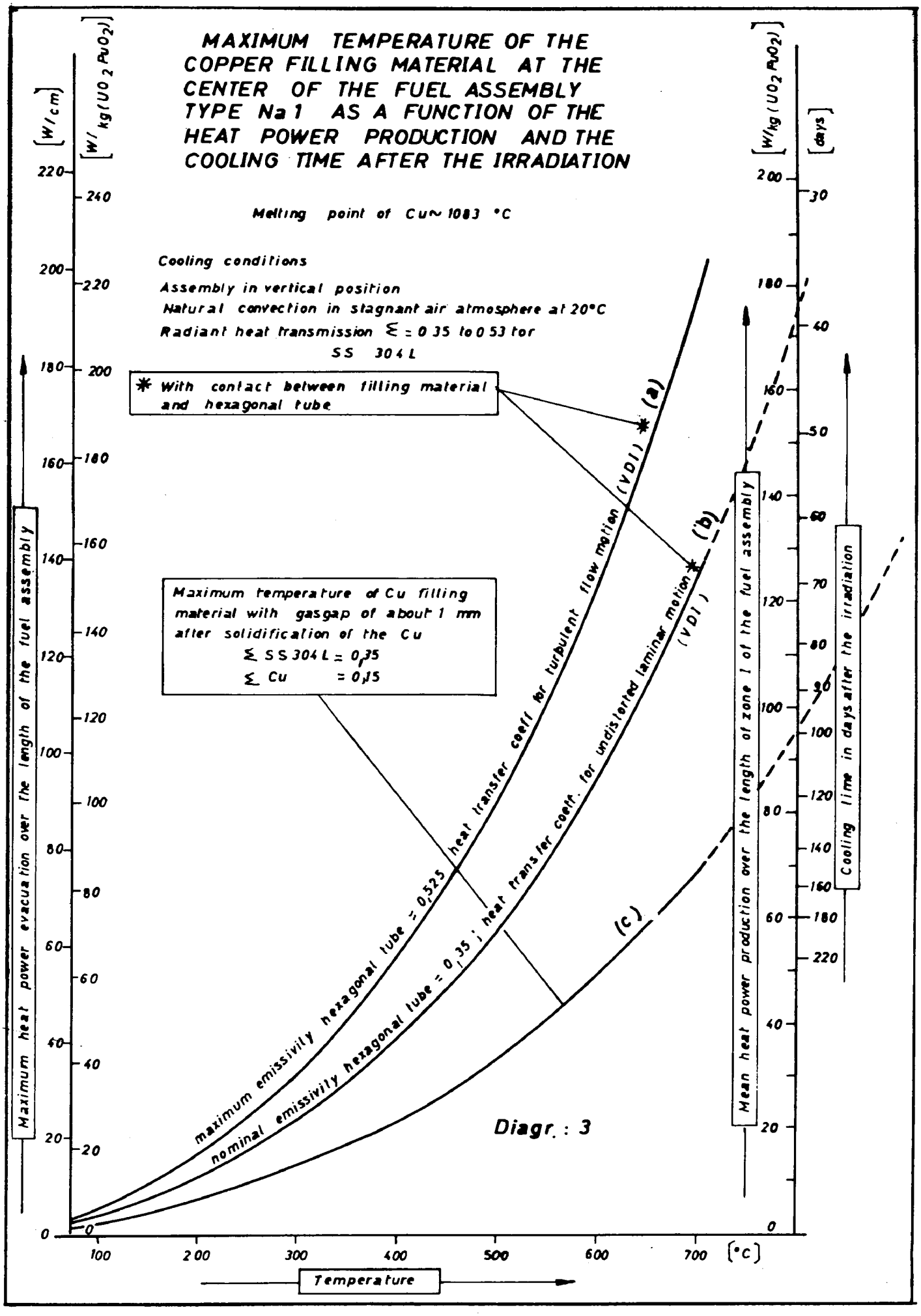


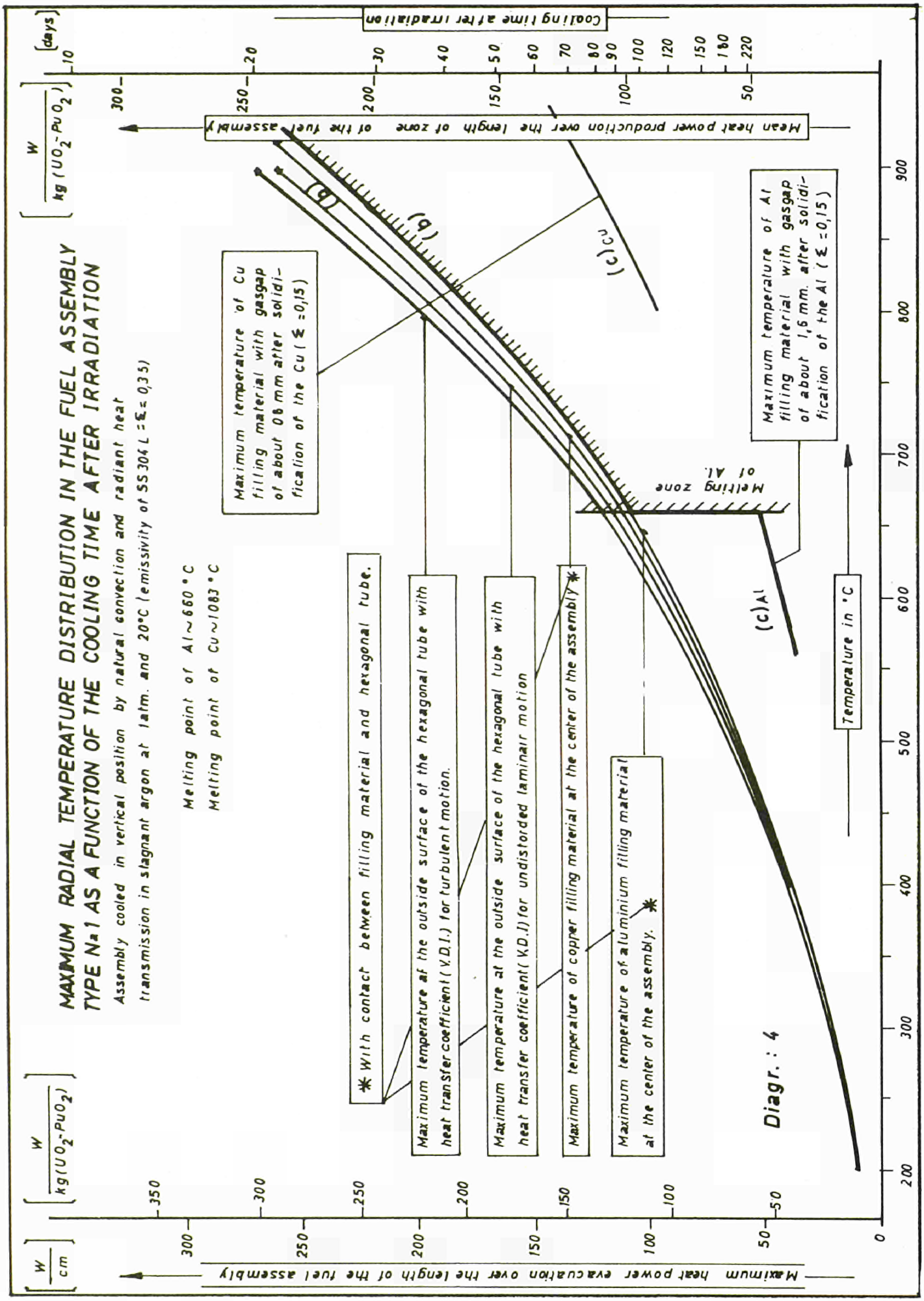
FIG. : 1


hexagonal tube 3 mm
in SS 304 L
TOTAL NUMBER OF FUEL PINS : 331.
pitch : 9,622 mm
Fuelpin spacers
length : 6 mm.
Φ : 4 mm
Location of maximum temperature of filling material.
Ratio ;
Volume of filling material (Cu or Al)
Total volume in hexagon
= 135 05 cm²
251 75 cm²
= 0,536
UO2 – PuO2
Cladding ;
Ext. diam. : 6,7 mm
Thickness : 0,38 mm
Material : SS 304 L.
Distance between hexagonal faces:
176,5 mm
Filling material : Cu or Al.
Echelle ; 2:1
Fig : 2


MAXIMUM TEMPERATURE AT THE OUTSIDE SURFACE OF THE HEXAGONAL TUBE OF THE FUEL ASSEMBLY TYPE Na 1 AS A FUNCTION OF THE HEAT POWER PRODUCTION AND THE COOLING TIME AFTER THE IRRADIATION.
Cooling conditions:
- Assembly in vertical position
- Natural convection in stagnant air atmosphere at 20°C
- Radiant heat transmission ε = 0.35 to 0.53 for SS 304L
[W/cm]
[W/kg(UO2 PuO2)]
[W/kg(UO2 PuO2)]
[days]
Maximum heat power evacuation over the length of the fuel assembly
Mean heat power production over the length of zone I of the fuel assembly
Cooling time in days after the irradiation
maximum emissivity hexagonal tube = 0,525 ; heat transfer coeff for turbulent flow motion (VDI)
nominal emissivity hexagonal tube = 0,35 ; heat transfer coeff for undistorted laminar motion (VDI)
Temperature
[°C]
Diagr. : 1


MAXIMUM TEMPERATURE OF THE ALUMINIUM FILLING MATERIAL AT THE CENTER OF THE FUEL ASSEMBLY TYPE Na 1 AS A FUNCTION OF THE HEAT POWER PRODUCTION AND THE COOLING TIME AFTER THE IRRADIATION
Melting point of Al ~ 680 °C
Cooling conditions
Assembly in vertical position
Natural convection in stagnant air atmosphere at 20°C
Radiant heat transmission ε = 0,35 to 0,53 for SS 304 L
* With contact between filling material and hexagonal tube.
Maximum temperature of Al filling material with gasgap of about 1,6 mm after solidification of the Al
ε SS 304 L = 0,35
ε Al = 0,15
(a)
(b)
(c)
(VDI)
maximum emissivity hexagonal tube = 0,525 ; heat transfer coeff. for turbulent flow motion
nominal emissivity hexagonal tube = 0,35 ; heat transfer coeff. for undistorted laminar motion
Molten zone of Al.
Maximum heat power evacuation over the length of the fuel assembly
Mean heat power production over the length of zone 1 of the fuel assembly
Cooling time in days after the irradiation
[W/cm]
[W/kg (UO2 PuO2)]
[days]
Temperature
[°C]
Diagr. : 2


MAXIMUM TEMPERATURE OF THE COPPER FILLING MATERIAL AT THE CENTER OF THE FUEL ASSEMBLY TYPE Na 1 AS A FUNCTION OF THE HEAT POWER PRODUCTION AND THE COOLING TIME AFTER THE IRRADIATION
Melting point of Cu ~ 1083 °C
Cooling conditions
Assembly in vertical position
Natural convection in stagnant air atmosphere at 20°C
Radiant heat transmission ε = 0 35 to 0 53 for SS 304 L
* With contact between filling material and hexagonal tube
Maximum temperature of Cu filling material with gasgap of about 1 mm after solidification of the Cu
ε SS 304 L = 0,75
ε Cu = 0,15
(a)
(b)
(c)
heat transfer coeff for turbulent flow motion (VDI)
heat transfer coeff. for undisturbed laminar motion (VDI)
maximum emissivity hexagonal tube = 0,525
nominal emissivity hexagonal tube = 0,35
Maximum heat power evacuation over the length of the fuel assembly
Mean heat power production over the length of zone 1 of the fuel assembly
Cooling time in days after the irradiation
[W/cm]
[W/kg (UO2 PuO2)]
[days]
Temperature
[°C]
Diagr. : 3


MAXIMUM RADIAL TEMPERATURE DISTRIBUTION IN THE FUEL ASSEMBLY TYPE Na 1 AS A FUNCTION OF THE COOLING TIME AFTER IRRADIATION
Assembly cooled in vertical position by natural convection and radiant heat transmission in stagnant argon at 1atm. and 20°C (emissivity of SS 304 L = ε = 0,35)
Melting point of Al ~ 660 °C
Melting point of Cu ~ 1083 °C
Maximum heat power evacuation over the length of the fuel assembly
Mean heat power production over the length of zone of the fuel assembly
Cooling time after irradiation
Maximum temperature of Cu filling material with gasgap of about 0,6 mm after solidification of the Cu (ε = 0,15)
Maximum temperature of Al filling material with gasgap of about 1,5 mm. after solidification of the Al (ε = 0,15)
Melting zone of Al.
(c)Cu
(c)Al
* With contact between filling material and hexagonal tube.
Maximum temperature at the outside surface of the hexagonal tube with heat transfer coefficient (V.D.I.) for turbulent motion.
Maximum temperature at the outside surface of the hexagonal tube with heat transfer coefficient (V.D.I) for undistorded laminair motion
Maximum temperature of copper filling material at the center of the assembly *
Maximum temperature of aluminium filling material at the center of the assembly. *
Temperature in °C
Diagr. : 4

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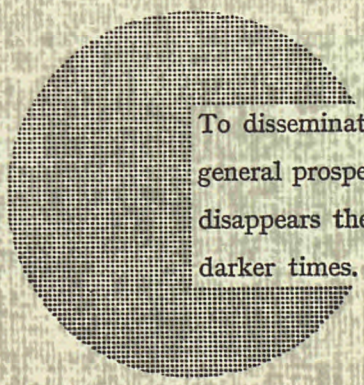

To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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