FBR ITALIAN POSITION
THE PEC REACTOR AND ITS CONTROL RODS SYSTEM

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1. INTRODUCTION

The greatest effort in Italy concerning Fast Breeder Reactors is concentrated on the PEC project. This project represents in fact the sole Italian work on the FBR option. Furthermore the Italian Parliament has stated that the FBR project must remain at the research level while more knowledge is acquired on the economic and safety aspects of this mode of exploitation of nuclear fuel.

The PEC (Fuel Element Testing) reactor is a 120 MW_{th} fast reactor, sodium-cooled, fed by $(U+Pu)\,O_2$ fuel with about 30% of Pu and U enriched up to 8%. Its purpose is not energy production (the energy will be lost to the air), but is testing new design fuel elements and/or reaching high figures of burn-up. These goals are achieved though a separate cooling system that allows a test element (up to 3 MW) to be inserted in the reactor centre, in a neutron flux of about $\emptyset_{max} = 4 \cdot 10^{15}$ $n/cm^2 \cdot sec$. This possibility makes the plant important to not only Italy, but also to other countries with present or future LMFBR programmes.

The PEC programme is one of ENEA's (National Committee for Research and Development of Nuclear and Alternative Energy Sources) research projects.

The core and fuel design are carried out by ENEA itself with cooperation from CEA and Novatome (France). The rest of the project work is given by ENEA to a number of contractors, among these the principal is NIRA (Italy) which takes care of the design (except core and fuel) and construction work of all the plant. In support of ENEA's design work there are the following ENEA research centres.

a) Brasimone (near Bologna) Area Laboratories. These laboratories are built inside the PEC reactor area. Among the facilities present at Brasimone, in this paper we mention the Espresso and CEDI sodium loops for tests of endurance and thermal shock of elements (fuel, control rod, reflector, etc), both single and in bundles of seven.
b) Casaccia (near Rome) Area Laboratories. Among their many facilities we mention here the IPM experimental plant, where the behaviour in sodium of the PEC control rod with its driving mechanism is tested.

Seismic tests are carried out by NIRA in the ISMES plant (near Milan), specialized in testing of large structures under forced vibration conditions.

Up to now the state of progress of the PEC project is as follows:

- Design work on reactor components and related systems: 80%
- Civil engineering work : 45%
- Components construction : 18%

It has recently been stated that construction of the plant must be finished by 1987.

2. PEC REACTOR CONTROL ROD SYSTEM DESCRIPTION

The PEC Reactor has 11 control rods (C.R.)(fig. 1). Their layout is peripheral, in two rings, close together, between fuel and reflector zones. Their positioning in this way is in order to avoid any mechanical interaction between the C.R. drivers and the test assembly loop, because of the small size of the fuel zone (equivalent radius of fuel zone ≃41.6 cm).

All C.R.s have exactly the same design and function in the reactor. They all work at the same level of insertion for compensating the burn up as well as for shut-down or scram. This mode of working allows a more homogeneous use of the fuel and of the C.R.s themselves. Only one C.R., called the regulating one, can, for a limited time, move up or down a short distance relative to the common level to obtain a small variation in reactivity (e.g. compensating the burn up) as well as a fast variation in reactivity (e.g. change in power output). Each C.R. is the central assembly of a bundle of seven (since all fuel elements and C.R.s and some reflector elements are assembled in bundles of seven).

The C.R. system must under ordinary con-ditions allow:

a) compensation for the burn up, which causes a reactivity loss of about 1400 pcm for a cycle of 60 full days (Full Power Equivalent Day);
b) power variation, to simulate the real operations of power reactors.

In every situation the C.R. system and the modes of operation laid down must insure a reserve of antireactivity of at least 3000 pcm, by insertion of only 2 sets of C.R.s out of 3 with the rod with the must worth jammed. (In PEC we have 1 \$=390 pcm and a power coefficient of $\Delta k/\Delta p \simeq 3 \div 6$ pcm/MW).

The precepts laid down (deriving directly or indirectly from the Autorization Decree) require that the mechanical design be such as to ensure:

a) insertion of all the 11 C.R.s during a 1/2 TSS(+) earthquake with the possibility of restarting the reactor, provided the necessary substitutions are made;
b) insertion of at least 4 C.R.s out of 11 during a TSS earthquake or a local fuel melting accident with fuel-sodium reaction.

The PEC C.R. is made of a guide-element, externally shaped in a hexagonal prism, with an inner coaxial cylindrical hole in which the absorber element can slide. The absorber element contains seven absorber pins, for a greater absorbing power and a better cooling (fig. 2), each constituted of a number of cylindrical pellets with a cladding. Pellets are made of B_4C with boron enriched up to 90% in B10 and sinterized at a density of 0,955 theoretical density. The absorber pin cladding has a porous plug that allows the gas produced to escape. The sodium leaks through the plug and fills the gap between pellets and cladding.

Each absorber element is driven by a motor, connected to it by a shaft, with speeds of 2 and 6 mm/sec (extraction and insertion speeds); for the regulating rod there is a motor giving a speed from 0 to 12 mm/sec. Scram happens when the current in the electromagnets clasping the absorber element is cut off; the whole insertion then takes a time of about 0,5 sec. The fall of the absorber element is braked at its end hydraulically with an acceleration of a=-10g. In case of

(+) TSS = Sure Shut-down Earthquake. The 1/2 TSS earthquake is the strongest possible one by historical and geological studies of the site and has a ground acceleration figure of a=0.15 g.

malfunction of the damper, the absorber element comes to a standstill with an acceleration of a=-40g; in this hypothesis the element can destroy itself, nevertheless its presence is requirod to mantain the antireactivity figure.

Thermohydraulic data for C.R.s are as follows:

- sodium inlet temperature = 400°C
- sodium outlet temperature = 550°C
- B_4C hot spot temperature (both in nominal working and in accidental situations, with probability p=0.999) $\leq T_f = 2450$°C
- Δp at the top and bottom extremities of the C.R.=0.1 Kg/cm^2

Thermomechanical quoted figures are as follows:

- for scram events:
  - minimum number of allowable drops with a=-10 g = 27
  - minimum number of allowable drops with a=-40 g = 1 (maintaining its absorbing power)
- for refueling operations:
  - maximum axial force from load-unload machine during extraction = 300 Kg; during insertion = 100 Kg
  - maximum lateral force by load-unload machine (against the head of the guide-element) = 15 Kg
  - static force between elements of a bundle (against the pads) = (5+1) Kg

The construction of the C.R.s, both real and dummy, is carried out by AGN (Italy); the supply of B_4C is carried out by Quartz and Silica Company (France). At the present time a number of dummy C.R.s have already been constructed for mechanical and hydraulic tests.

3. GUIDE-LINES OF THE PEC C.R.'s DESIGN

3.1. Methodology

The C.R. design, like the rest of the core, is the competence of ENEA with, as previously stated, cooperation from CEA and Novatome (France). The design is carried out by two work-groups which look after respectively the neutronic aspect and the thermomechanical and thermohydraulic aspects. The principal features of the design work are:

a) analytic calculations and checks (reactivity, generated power, temperatures, mechanical stresses, deformations, etc.);

b) experimental verifications for setting calibration and for problems in which analysis is not reliable (endurance, seizure, etc.);

c) analogies with similar components that have been used in Rapsodie and Phenix and have been observed and studied after unloading.

3.2. Neutronic Design

In designing C.R.s four levels of insertion are considered:

- OUT and IN for C.R. worth calculations;
- FUNZ (insertion of 10,8 cm) representing an average insertion during the cycle;
- MICORE (insertion of 32,5 cm, as far as the core central line) for calculations related to worst possible situations.

For the first time of use an irradiation time is foreseen as long as the time in core of the surrounding fuel elements, i.e. 360 full days.

Nevertheless the design is based on a working time of 480 full days for a future more efficient use of the C.R.s. Neutronic calculations have generally been carried out in XY geometry, with a discretization of 4 meshes per element (cross section of the element surface = 64,05 cm^2), with a homogenized composition for each core zone, cross section libraries of 6 and 25 energy groups (derived from the ENDF B/4 data file) and using the diffusion code CITATION. To normalize the results, some evaluations have been made to take into account the approximations of two-dimensional geometry and of a finite number of meshes. Also some verifications concerning spatial heterogeneity (using 12 meshes per cross section of C.R.) and the diffusion approximation have been carried out using the transport code DOT 3.5. These normalizing effects on C.R. antireactivity, to be applied to the standard XY results, have been found to be as follows:

- spatial heterogeneity effect : - 16%
- diffusion-transport plus infinite discretization effect:
  - for inner ring of C.R.s : + 3%
  - for outer ring of C.R.s : + 7%

The electrical supply to the motors driving the absorber elements is divided into 3 circuits in order to obtain 3 independent sets of C.R.s:

a) the first set is made up of the 5 C.R.s of the outer ring;

b) the second set is made up of 3 alternate C.R.s of the inner ring;

c) the third set is made up of the remaining 3 C.R.s of the inner ring.

The calculated antireactivity worths are as follows:

a) average worth of one inner C.R.	: 815 pcm
b) average worth of one outer C.R.	: 470 pcm
c) the C.R.s all together	: 6870 pcm
d) 1st set of C.R.s	: 2400 pcm
e) 2nd and 3rd sets of C.R.s	: 2570 pcm each
f) minimum worth of 2 sets out 3 of C.R.s (with the most worth C.R. in OUT position)	: 3900 pcm

The mutual interaction effects on the C.R.'s antireactivity in PEC is always of a few percents. To obtain the best figures for the C.R. worths, an analysis of the PECORE experiment (carried out on the MASURCA facility, Cadarache-France, in 1976) is currently underway. If necessary a new "ad hoc" experiment might be proposed.

The main neutronic results of interest for thermohydraulic and thermomechanics designs are listed below:

a) maximum neutron flux in C.R.s	$2.7 \cdot 10^{15}$ n/$cm^2 \cdot$sec
b) maximum absorption intensity (MICORE position)	$4 \cdot 10^{14}$ cap/cm^3 $B_4C \cdot$sec
c) maximum burn up (480 full days)	$8 \cdot 10^{21}$ cap/cm^3 B_4C
d) maximum atomic displacement intensity (TRN standard)	$7 \cdot 10^{7}$ DPA/sec
e) maximum power in a C.R. (MICORE position) ((n,α) reaction, scattering, γ-heating)	100 KW (of which 75 KW are in the absorber element)
f) maximum linear power in the B_4C pin	330 W/cm

3.3. Thermomechanics Design

The analytic calculations are carried out using the French codes CEA SEMT and are focussed on the following points.

a) Elastic analysis is made according to the RAMSES standards for materials out of the neutron flux (damage < 3 DPA TRN Standard); materials in the neutron flux are dealt with using more severe criteria, as suggested by the CEA.
In cases where elastic analysis is insufficient, plastic analysis is used and "ad hoc" experiments are made.
Among these, some experiments of seismic simulation on the core are programmed for this year (ISMES facility).
The goal is the determination of forces against the C.R. arising from the earthquake, in order to verify experimentally the behaviour of the foot and contact areas of the C.R. (AGN).
The C.R.s are in a zone characterized by a high grad Ø and grad P (fuel-reflector interface). For these reasons the C.R.'s bowing, due to differential swelling as well as that due to the temperature gradient, is very important. Both these effects work in the same direction. To reduce the bowing the reflector assemblies surrounding C.R.s are under cooled, obtaining a temperature field through the C.R. as flat as possible. Displacements of the head of a C.R. have been calculated to be as follows:
   - maximum figure due to temperature gradient 4,5 mm
   - maximum figure due to differential swelling:
      - for 360 full days of work 3,2 mm
      - for 480 full days of work 6,7 mm

b) Materials used. The stainless steels used in C.R.s are:
   - for the guide-element: AISI 316 cold worked up to 20%
   - for the cladding of the absorber element: AISI 316 cold worked up to 20% (the foot is covered by stellite)
   - for the cladding of the pin: AISI 316 Ti annealed (this allows a low level of swelling and a good compatibility with B_4C).

Swelling figures used are supplied by CEA. These figures, like the figures related to insert materials, have been updated by the studies on the assemblies used on Phénix.

c) Structural control calculations are carried out for:
   - stress states and deformations arising from thermal gradients and swellings;
   - stress states and deformations arising from dropping the C.R. and the C.R. coming to a standstill with a = -10 g and a = -40 g;
   - stress states arising from misalignments;
   - stress states arising from seismic forces.

Of course the calculations are carried out for the most critical sections and with different loads simultaneously superimposed. So for example, the absorber element foot is verified in the stress state due as well as to the seismic load, to the thermal transient arising from a drop of an irradiated C.R.

d) Analytic calculations concerning the functioning. The clearance between pellet and cladding has been controlled to be enough to avoid any mechanical interaction due to swelling.
This gap, filled by static sodium, allows a pellet swelling of about 11%. The maximum misali-gnment between the collet axis of the load-unload machine and the axis of the guide-element's head (due to deformations and construction clearances) has been controlled to be less than 17 mm, as laid down.

3.4. Thermohydraulic Design.

Having singled out the most critical C.R. from the point of view of power developped both in the guide element and in the absorber element (situated in the inner ring, of course) and the most unfavorable level of insertion (MICORE), the following calculations have been made.

a) Definition of the flow rate in order to verify the thermohydraulic criteria.

b) Definition of the apertures to obtain the required flow rate, definition of the loss of pressure and related experimental tests.

c) Calculations of the radial and axial variation of the temperature, for different levels of insertion of the absorber element (e.g. fig. 3).

The codes employed are "ad hoc" ones, written by ENEA and used together with the THECA codes system (EURATOM) for the fuel.

3.5. Experimental Features

3.5.1. Mechanical Tests

a) All the normal operations of the C.R. and its driving mechanism have been tested in sodium in the IPM facility. Insertion, extraction and scram tests with the C.R. have been successfully performed with the maximum disalignment foreseen both for the thermal gradient and for the swelling.

b) Thermal shock tests have been performed in the CEDI facility on a bundle of seven elements. This bundle is composed of a C.R. surrounded by 2 fuel elements and 4 reflector elements. The heating has been applied in such a way so as to reproduce the real maximum thermal gradients (in every direction).

c) On the IPM facility tests have been carried out in order to verify the behaviour at the contact between the absorber element and the guide element (covered by stellite inserts in the contact area), during the sliding of one relative to the other. These tests are done to avoid any possible jamming of the absorber element.

d) Tests have been carried out by FIAT on the clasping and release of the C.R. in water.

e) The following tests are foreseen to be made in the near future.

- Control of the functioning of the C.R. and its driving mechanism in sodium whilst withstanding an earthquake (on IPM facility).

  This test is a quasi-static test, meaning that seismic conditions are simulated by a static disalignment.

- Verification of the functioning of the C.R. in dynamic conditions arising from a TSS earthquake (on ISMES facility).

  In this test the seismic conditions are simulated applying the necessary vibrations to different points on the C.R.

- Verification that a local fuel melting event with fuel-sodium reaction is an accident contained within an assembly (ISPRA).

  This is in order to insure the functioning of at least 4 C.R.s out of 11, as is required.

3.5.2. Thermohydraulic tests

The C.R. has been hydraulically characterized in water in the Brutus loop (Cadarache, France) and in the CEF loop (Brasimone).

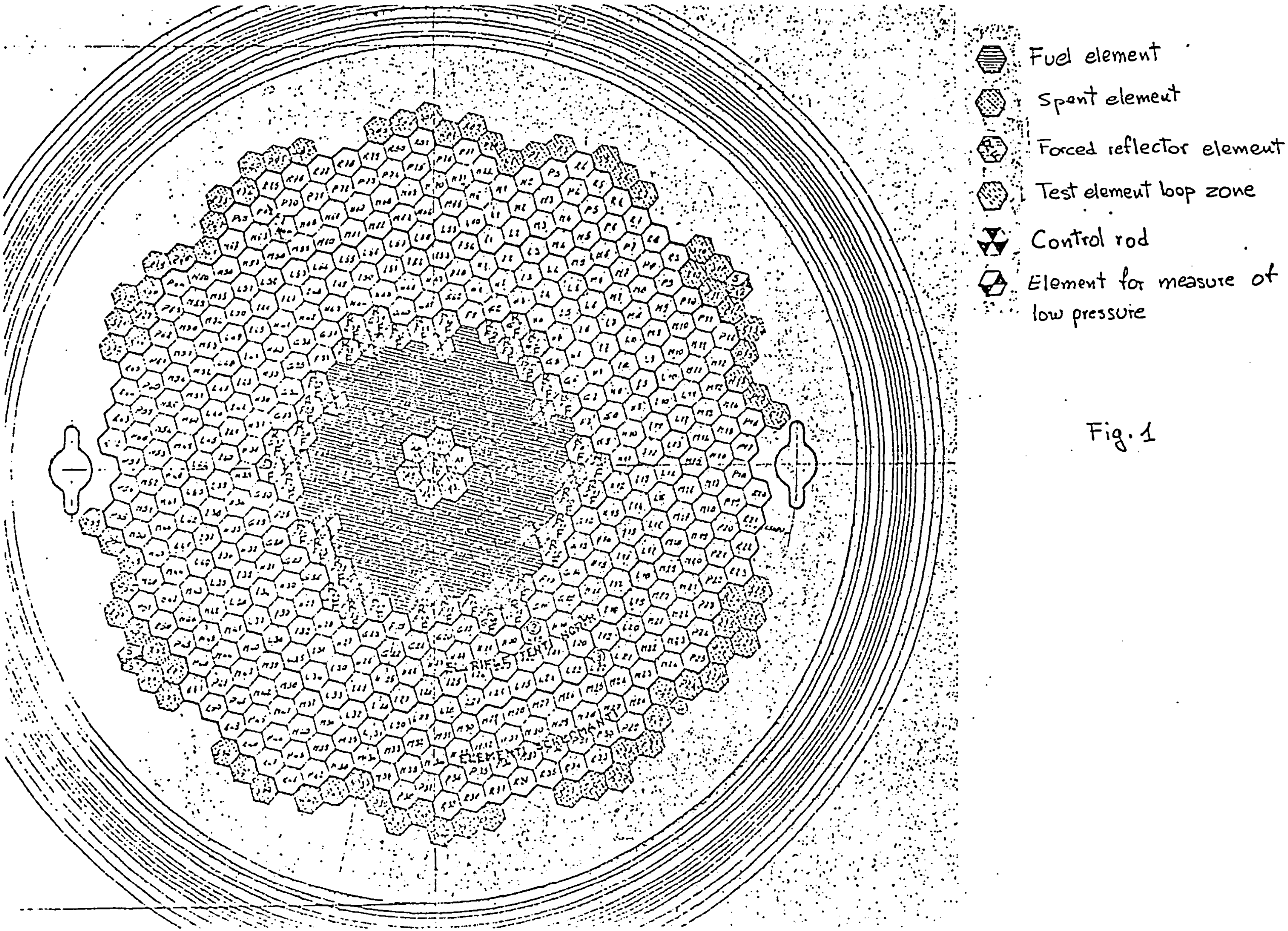

Fuel element
Spent element
Forced reflector element
Test element loop zone
Control rod
Element for measure of low pressure

Fig. 1

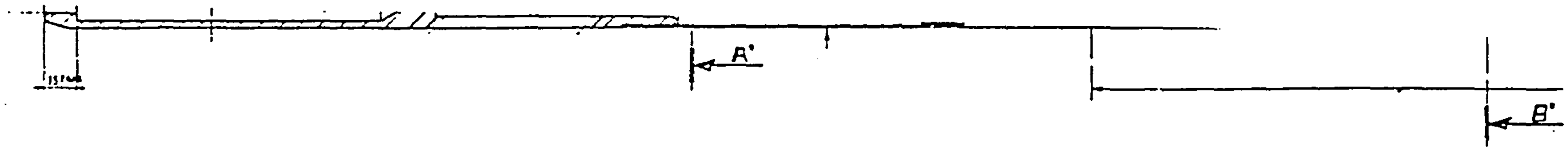
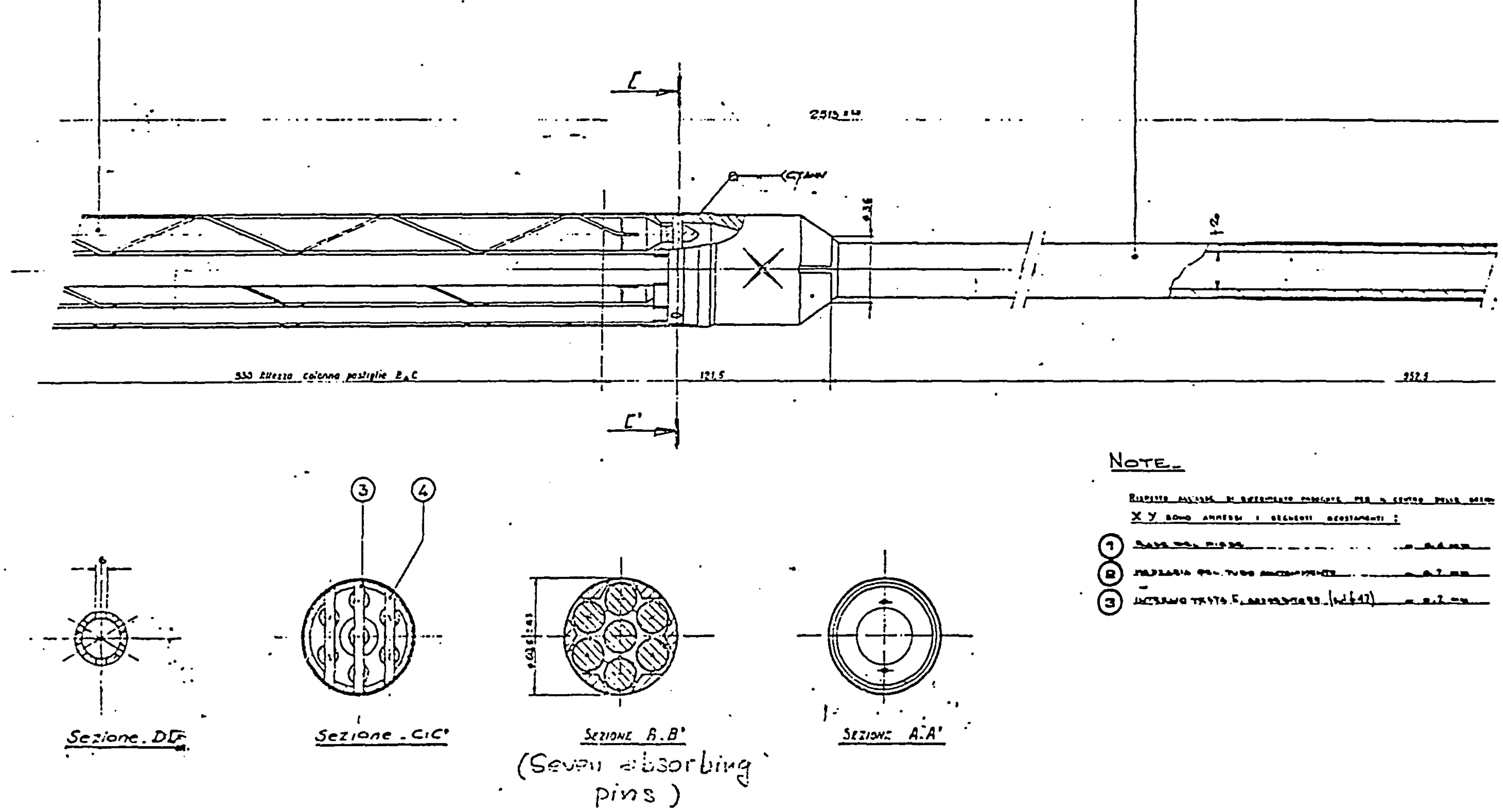


Fig. 2

Detail of the absorber element



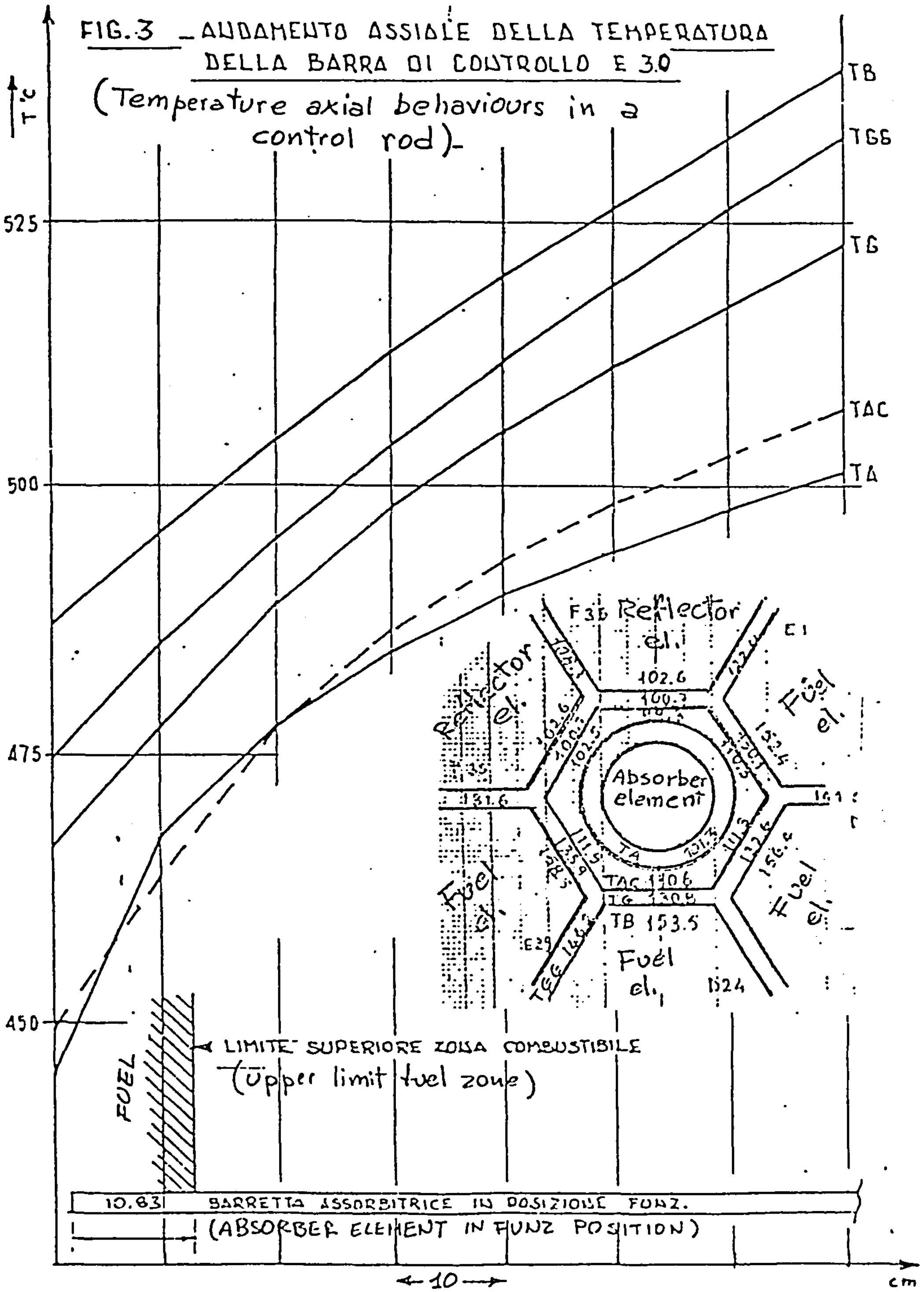


FIG.3 – ANDAMENTO ASSIALE DELLA TEMPERATURA DELLA BARRA DI CONTROLLO E 3.0
(Temperature axial behaviours in a control rod).

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