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HFR Report No. 89: CONSEQUENCES OF THE EMBRITTLEMENT OF CHANNELS FOLLOWING NEUTRON IRRADIATION IN A HIGH FLUX REACTOR

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1. *INTRODUCTION*

The channels of a High Flux Reactor (HFR) make it possible to remove neutron beams from the reactor for scientific purposes. At the same time, they constitute one of the material barriers between the heavy water in the primary circuit and the experimental areas located in the reactor building.

One of the ends of the channels is placed in the high neutron flux areas that provoke transformations involving the chemical composition and mechanical properties of the material.

Tests performed on material irradiated in the HFR reveal that these transformations lead to an embrittlement of the material resulting specifically in a reduction of plastic yield prior to breaking during tensile tests.

The purpose of this study is to examine the consequences of this embrittlement for the operation and safety of the reactor.

2. REVIEW

In the following chapter, the channel design, the safety devices related to the channels and the possible defect modes of the channels are reviewed.

2.1. Channel Design

Figure 1 shows a schematic example of a horizontal channel in the reactor. The reflecting can, filled with heavy water and containing the fuel element is submersed in a light water pool, itself limited on the outside by walls with a concrete center core covered with stainless steel lining. The can has extrusions, connected to collars that assure containment of the heavy water in relation to the pool and in relation to the experimental areas of the reactor building. The channels penetrate the reflector can through the collars, with the heavy water being contained between the collar and the channel.

The channels are either filled with helium or kept under vacuum. A closing device which is a part of the rear flanging delimits the interior volume of the channel and assures part of the radiological protection of the experimental zones.

In this design, the reflector can is extended to the rear flanging by interposed collars.

The channel represents the walls of a cavity placed within it.

The various straps in the rear flanging are bolted to each other and fixed to the center core. Consequently, the rear part of the channel is embedded in the rear flanging, and the front part, exposed to radiation, is overhanging. Support bosses placed in the extrusions keep the channel from vibrating, while still allowing it to expand.

The HFR has 12 horizontal channels, 4 inclined channels and one so-called vertical channel (actually slightly inclined to the vertical). Three other vertical channels are currently disassembled and have been replaced by plugs.

Figure 2 shows the location of the various types of channels with respect to the reflector can, the fuel element and the natural convection shutters that assure cooling of the fuel element after reactor shutdown.

It can be seen that the rear flanging of the inclined channels and the vertical channels is at a higher than level than that of the natural convection shutters ($\Delta H > 0$) making drainage of the convection shutters and the fuel element in case of channel rupture impossible.

On the other hand, the level of the rear flanging of the horizontal channels is lower than the shutter level ($\Delta H < 0$) and at the upper edge of the fuel element ($\Delta H^* < 0$). Specific equipment in these channels should, therefore, prevent draining in case the channels are destroyed.

2.2. Horizontal Channel Equipment

Most of the channels are designed for used with an exiting beam. The beam of neutrons that exits via the channel is directed toward a target placed outside the channel in the experimental zones. In this case, the channel equipment is static, given the fact that the material containment formed by the channel itself and its plugging device is never broken while the reactor is operating.

A small number of channels used for nuclear physics experiments is designed for introduction of targets in the channel and their recovery while the reactor is in operation. Consequently, the equipment in these "inside use" channels is different from that of the exiting beam channels, even though the basic design of these two types is the same.

2.2.1. Exiting Beam Channels

Figure 3 shows the basic equipment of an exiting beam channel. Inside the channel, whose diameter decreases from the strap to the thin bottom, is placed a plug equipped with a collimator with an entry window. The plug is set in the thick parts of the channel using locking shims. The housing extending towards the safety valve to the exit window is set hermetically in the channel strap. The low point of the housing is equipped with water detection sparking plugs.

The space between the safety valve and the exit window is provided with a connector with an isolation valve that makes it possible to create a vacuum in the channel or to add helium.

While the reactor is operating, the safety valve is always open. However, the space delimited by the channel remains contained by the channel itself, the housing and the exit window. In case the channel breaks, the presence of heavy water is detected by the sparking plugs placed in the housing and they cause the safety valve to close.

2.2.2. Inside Use Channels

In order to show the equipment of an inside use channel compared to an external beam channel, Figure 4 shows both of them for the purpose of comparison.

From the design standpoint, the channel itself, the plug, the housing and the safety valve (channel containment A) as well as the experimental containment B, delimited by the exit window and the isolation/safety valve are the same. The only difference is constituted by space C placed between the two of them, consisting of the source changer containment which allows introduction of targets by an airlock system and handling devices. Space C is equipped with a remotely controlled cart that allows the target to be carried towards the channel interior. In the "irradiation" position of the target, the cart is completely engaged in the channel and locked mechanically, freeing the safety valve which can be activated like that of an external beam channel. In "change" position of the target, the cart is between the safety valve and the isolation valve, which also allows normal operation of the safety valve.

During transfer of the cart from A to C and from C to A, the presence of the cart in the passage way plane of the inner capsule prohibits the safety valve from closing. In order to compare the designs of the two types of channels, space C can be considered as a part of space A. In fact, the walls of the source changer containment and the isolation valve have the same pressure resistance as the housing, thus forming a unit with a homogeneous design.

2.3. Channels Proper

The channels are made of AG3 NET aluminum alloy containing approximately 3% magnesium and fabricated from cylindrical ferrules connected to each other by conical reductions (see Fig. 5). The rear parts are common to all of the horizontal channels (with the exception of H1/H2 and H7), the shape of the front part is specific to each group of channels (cylindrical/conical/rectangular). For reasons of neutron transparency, the bottom of the front part is as thin as possible and still remain compatible with the operating conditions.

As an indication, Figure 5 shows the support plane in the reflector can extrusions (see Fig. 1) as well as the plane for cutting during channel disassembly.

With normal reactor operation, the channels are subjected to an external heavy water pressure of 4 bars that can reach approximately 4.7 bars in transient phases. When the reflector can is drained, the external pressure approaches atmospheric pressure; during planned drying operations, several millibars will be reached.

The channels are either filled with 1.6 bars max. of helium or kept under vacuum. Since the front parts are overhanging up to the support plane, the bouyancy, with the can filled with heavy water is reflected by a upward bending moment; the weight proper, with the can empty, by a downward bending moment. However, it should be noted that the stresses due to these bending moments are maximum in the support plane and decrease to zero at the channel nose.

The stresses in the material due to these operating conditions are compatible with the maximum allowable stresses that account for the safety coefficients usually selected. In fact, the pressure that most of the channels could withstand is approximately 9 bars because of the risk of buckling of the parts located outside the flux. The only parts accepting lesser pressures are constituted by the front plate of the H1/H2 unit located outside the flux and the concave window of the glove finger IH1 aimed at the cold source. In these cases, the allowable pressures are about 5 bars, accounting for the usual safety coefficients.

With the exception of the concave bottoms H3, H4, H8, H2, IH1 and IH3, all of the parts subjected to radiation withstand compression stresses. Consequently, it is the buckling that limits the maximum allowable pressure. The only characteristic related to the material used in the theoretical calculations is the modulus of elasticity, given that fact that a stability problem is involved. During normal reactor operation, the concave bottoms of the channels mentioned above are subjected to tensile stresses much lower than the elastic limit of AG3 NET. Rupture of these concave bottoms would require a very high heavy water pressure. In the case of a new channel, rupture would be preceded by considerable plastic deformation.

The front parts of the channels are placed in the high neutron flux zones from $1.27 \cdot 10^{15}$ n_{th}/cm^2s ($1.5 \cdot 10^{15}$ n_{th}/cm^2s undistrubed) for the vertical channel V4 to approximately $3 \cdot 10^{13}$ n_{th}/cm^2s) at the level of the cylindrical wall of the reflector can. The other channels are exposed to neutron fluxes as a function of their level in comparison to the center plane of the fuel element and of their distance from the axis of the reflector can. This flux distribution essentially causes the ends of the channels to be strongly irradiated, while the rear parts are practically located outside the flux.

Figure 6 shows the reflector can schematically with the fuel element (EC) in the middle and the hot (SC) and cold (SF) sources. The horizontal and inclined channels are shown by straight lines whose ends indicate the position of the channel nose.

In order to provide a notion of the irradiation of the channels as a function of exposure time, constant integration lines of $8 \cdot 10^{15}$ n_{th}/cm^2 have been added, calculated from the undisturbed fluxes in the center plane of the fuel element and accounting for an operation of 6 x 44 days = 264 days per year at nominal power. Consequently, the constant integration lines do not show the real irradiation of a channel. However, they show the general evolution.

The dose of 8 • 10^{22} n_{th}/cm^2 was selected as the dose that causes considerable embrittlement of the material, based on the results presented below.

We see that the channel noses placed in the median plane and exposed to an undisturbed flux reach dose integrations of 8 • 10^{22} n_{th}/cm^2 after approximately three years of operation. After ~5 years of exposure, almost all of the channels have reached this limit, with the lengths irradiated to higher doses being approximately 20 to 40 cm for most of the channels. In the 5 subsequent years, the limit of 8 • 10^{22} retreats approximately 25 cm on the average towards the cylindrical walls of the reflector can. The exposure time required for an additional retreat of 25 cm from the limit is another 10 years.

Figure 6 shows that the front ends of the channels quickly reach high doses and that the very irradiated zones extend increasingly slowly towards the reflector can.

3. CHANNEL FAILURE MODES

Failure of a channel or the simultaneous failure of several channels can take place either following an event of a sudden nature (1) (explosion in the reflector can accompanied by destruction of the channel) or after a loss of seal (2) (provoked by cracking, corrosion, etc...); or after incidents during maintenance operations when the reactor is shut down (3) (mechanical blows).

The reactor design takes into account a channel failure and devices designed for this purpose will make it possible to limit the consequences of such incidents.

3.1. Events of a Sudden Abrupt Nature

An explosion in the reflector can leads to such high pressures in the heavy water that even new channels are totally or partially destroyed with loss of seal and the presence of heavy water in the channels. It is the safety valves, open while the reactor is operating, that close after a sufficient pause to allow any shock wave to pass through and they restore containment of the heavy water, thus preventing the accidental draining of the reflector can.

The risk of explosion comes from equipment other than the channels. Consequently, the condition of the channel does not influence the probability of such an incident. Given the fact that even new channels are not designed to withstand very high pressure, events of a sudden nature do not need to be taken into consideration during evaluation of the consequences related to an embrittlement of the channels.

3.2. Loss of Seal

Loss of seal can be caused by effects of corrosion, particularly by pitting corrosion, by cracking due to application of mechanical loads or thermal gradients, as well as by the effects of mechanical fatigue related to vibrations.

The risk of corrosion is determined by the chemical compatibility of the material with the medium in which it is found. Consequently, modifications of the mechanical properties during irradiation have no direct effect on the risk of corrosion.

Mechanical loads and thermal gradients applied to the channels in established and transient regimes of the reactor do not, in any case, lead to plastic deformations of the material. This means that any modification of the material properties that does not cause the moduli of elasticity or limits of elasticity to drop below values related to non-irradiated materials does not need to be taken into consideration.

Zones that may be subjected to effects of mechanical fatigue by vibration are generally located near the support plane of the channels in the extrusions. Since the neutron fluxes are very low at this level, the problem of vibration can be considered independent of an evolution under flux.

3.3. Handling at Reactor Shutdown

Incidents during maintenance operations can provoke blows to the material the require absorption of the energy of these blows by elastic deformation and, if necessary, plastic deformation of the material. An embrittlement of the material therefore increases the risk of damage in case of blows. However, it should be noted that this risk only arises when the reactor is shut down, after discharge of the irradiated fuel element.

4. MODIFICATIONS OF THE CHARACTERISTICS OF AG3 NET UNDER THE EFFECT OF NEUTRON IRRADIATION

The experimental HFR-AG3 NET program makes it possible to follow the evolution of the characteristics of the aluminum alloy under the effect of a neutron irradiation in the HFR. The results of the second part of the program involving specimens irradiated up to $12.8 \cdot 10^{22}$ n_{th}/cm^2 can be summarized as follows:

Embrittlement, noted at the end of the first part of the program, continues, and is reflected by ellongations to the breaking point that are very low (<0.6 %) or even non-existent starting with a flux of approximately $8 \cdot 10^{22} n_{th}/cm^2$. The yield point has a tendency to stabilize at values around 700 MPa for the maximum flux of $12.8 \cdot 10^{22}$ n_{th}/cm^2.

The swelling that takes place during irradiation is low, generally below 0.3%. The results of hardness measurements reveal almost a tripling of the value of MHV 25 (Vickers method) compared to a non-irradiated material, with stabilization between $8 \cdot 10^{22} n_{th}/cm^2$ and $12.8 \cdot 10^{22} n_{th}/cm^2$.

The mode of rupture changes from ductile (non-irradiated material) to a mixed mode with a preponderance of non-ductile elements. However, it should be noted that the appearance of the three sets of very irradiated specimens ($7.5 \cdot 10^{22}$ to $12.8 \cdot 10^{22} n_{th}/cm^2$ is practically the same.

5. CONCLUSIONS

Channel failure is an incident that the reactor design takes into account and whose consequences have been studied and accepted during the safety analysis of the facililties. The study of the failure modes (Chapter 3) has shows that the embrittlement of the material due to neutron irradiation does not constitute a fact that could fundamentally change the probability of failure compared to a new reactor.

The mechanical properties of the irradiated material in elastic regime are not below the values of the new material.

In this respect, the second part of the AG3 NET - HFR test program, whose results are available, does not raise concerns, given the very high mechanical properties of the irradiated material. Consequently, no preventive provisions have to be made, since the irradiated material is compatible with its use as structural material for the channels.

The study of the failure modes also demonstrated that mechanical blows applied to irradiated material could lead to destruction because of the reduced plastic deformability. However, this risk only arises when the reactor is shut down during maintenance operations that require access to equipment placed inside the channels.

The conditions under which these operations take place are as follows:

- the operators handling this equipment are members of the Pile-Unit group of the Reactor Department,
- the irradiated fuel element is discharged,
- the primary heavy water circuit is shut down,
- the reflector can is drained, at least partially. The channel is question is dry during the entire work phase requiring opening of the containment of the rear flanging and the plugging device,
- a seal test is performed prior to raising the level of heavy water in the reflector can.

However, it should be noted, that corrosion, particularly corrosion by pitting, which is independent of embrittlement properly speaking, but whose speed of developement could be related to neutron irradiation, constitutes a fact that increases the probability of failure compared to new material.

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Figures

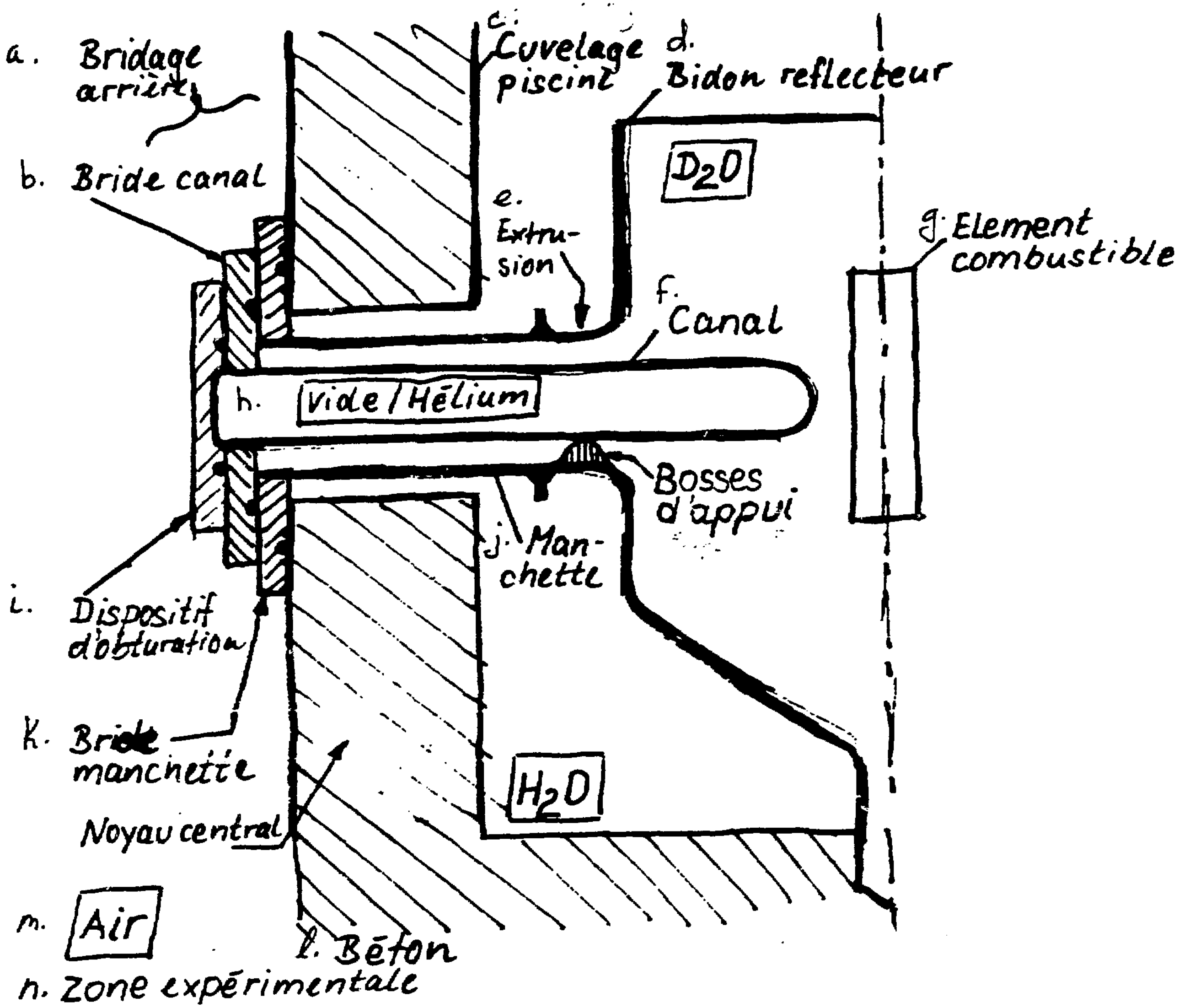

Fig. 1 : Schematic of a horizontal channel in the reactor

Key:

a.	Rear flanging	h.	Vacuum/helium
b.	Channel strap	i.	Plugging device
c.	Pool Lining	j.	Collar
d.	Reflector Can	k.	Collar strap
e.	Extrusion	l.	Concrete
f.	Channel	m.	Air
g.	Fuel Element	n.	Experimental zone

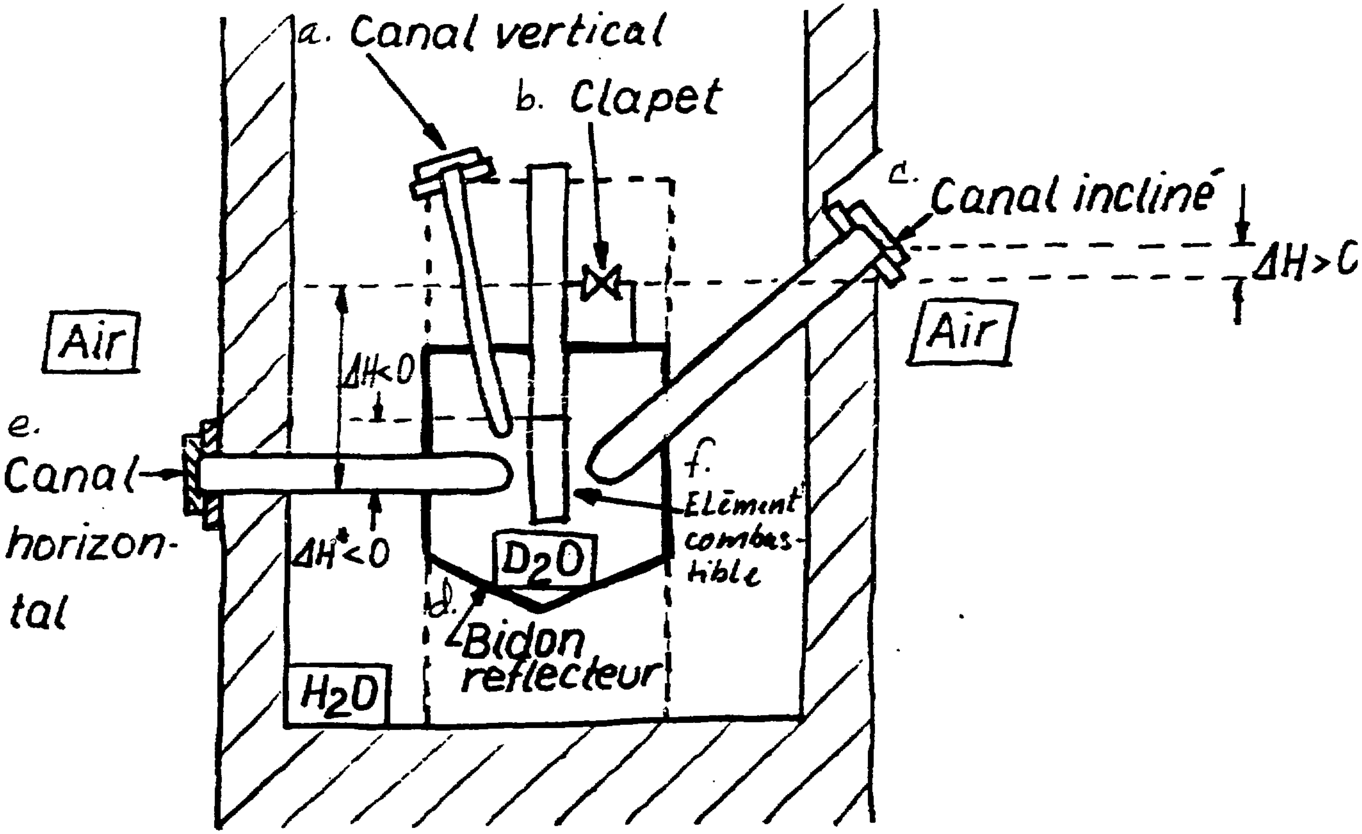

Fig. 2: Channel Location

Key:

a.	Vertical channel	d.	Reflector can
b.	Shutter	e.	Horizontal channel
c.	Inclined Channel	f.	Fuel element

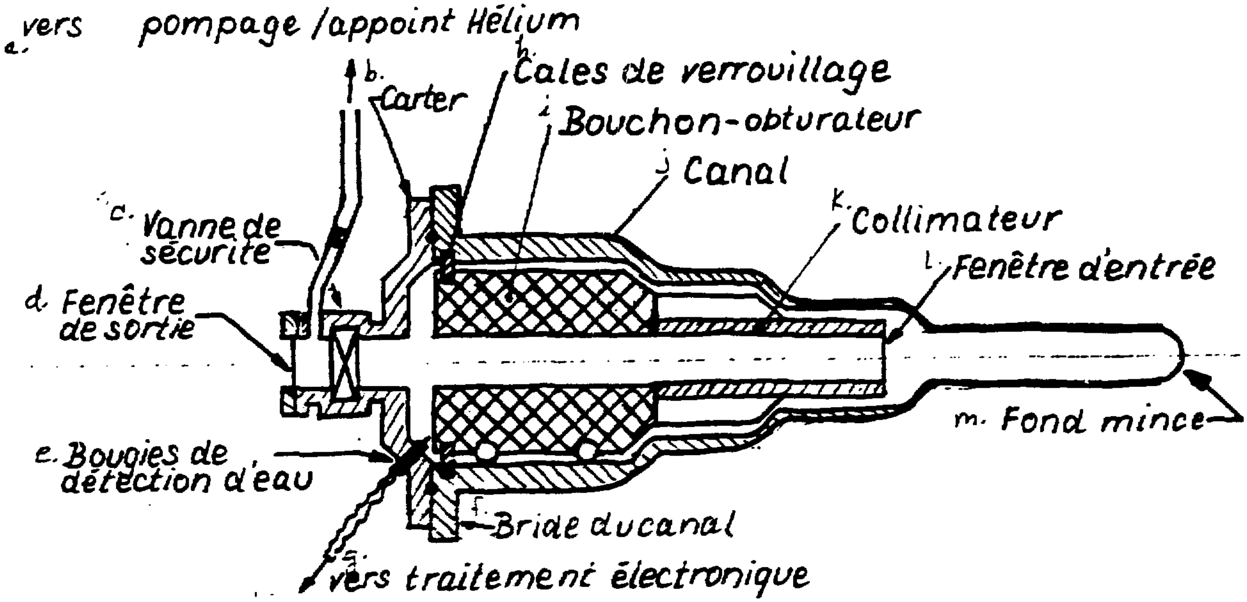

Fig. 3: Equipment of an "Exiting Beam" Channel

a. To pumping/helium fill
b. housing
c. Safety Valve
d. Exit window
e. Water detectors
f. Channel strip
g. To electronic processing
h. Locking shims
i. Plug
j. Channel
k. Collimator
l. Entry window
m. Thin bottom

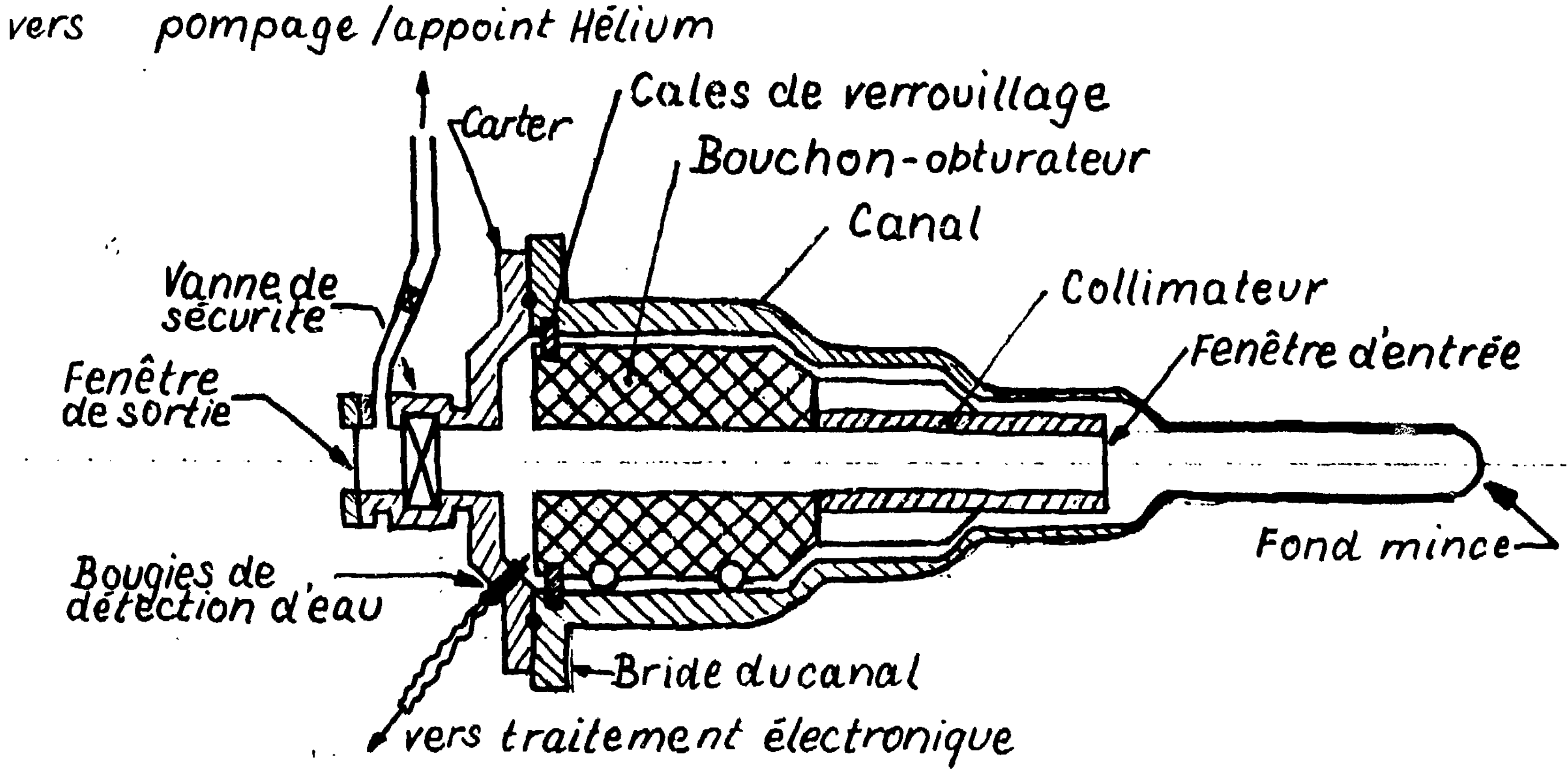

Fig. 3 Equipement d'un canal "à faisceau sortant"

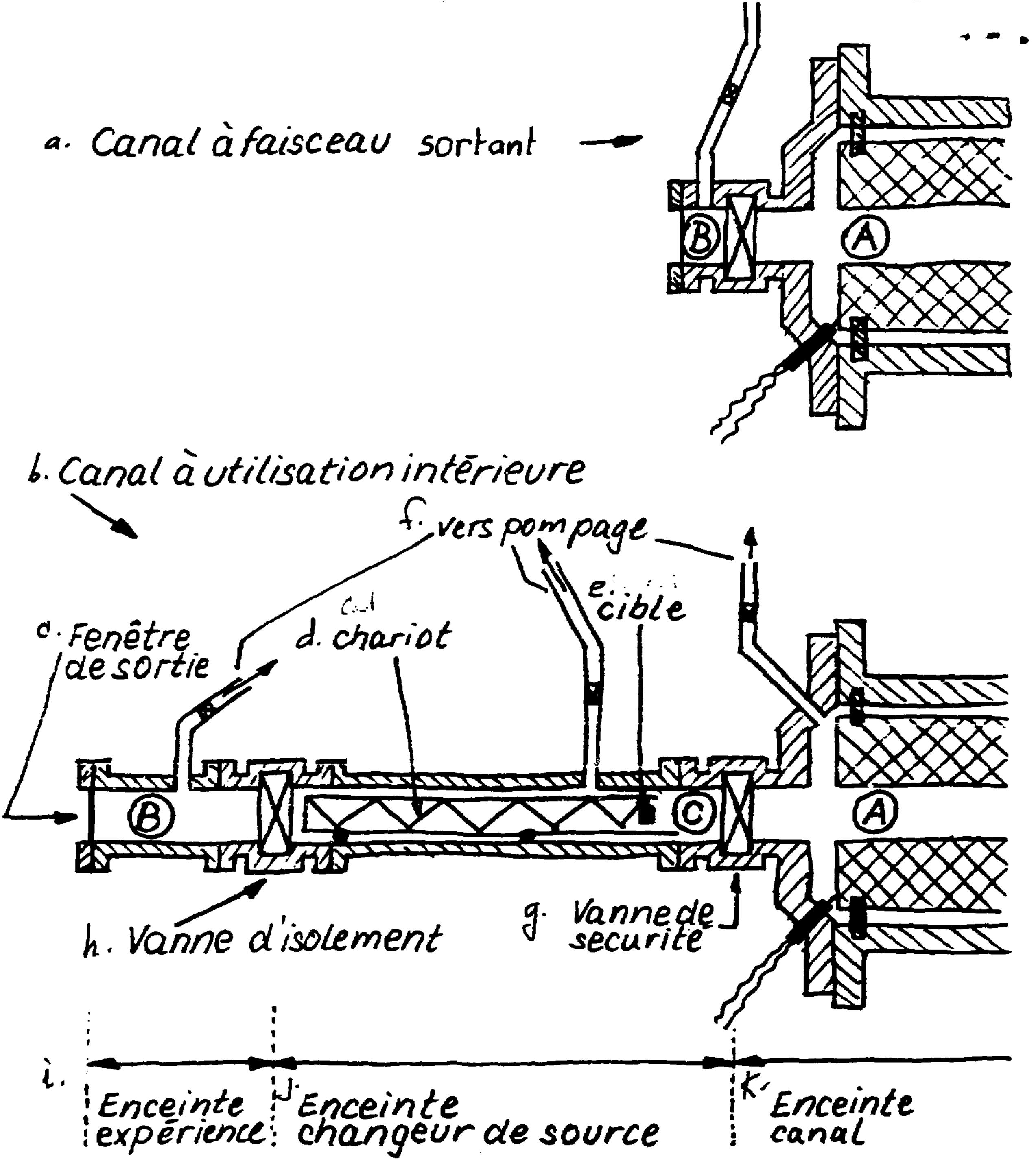

Fig. 4: Equipment of an Inside Use Channel

a. Exiting beam channel
b. Inside use channel
c. Exit window
d. Cart
e. Target
f. Towards Pumping
g. Safety Valve
h. Isolation Valve
i. Experimental Enclosure
j. Source Changer Enclosure
k. Channel Enclosure

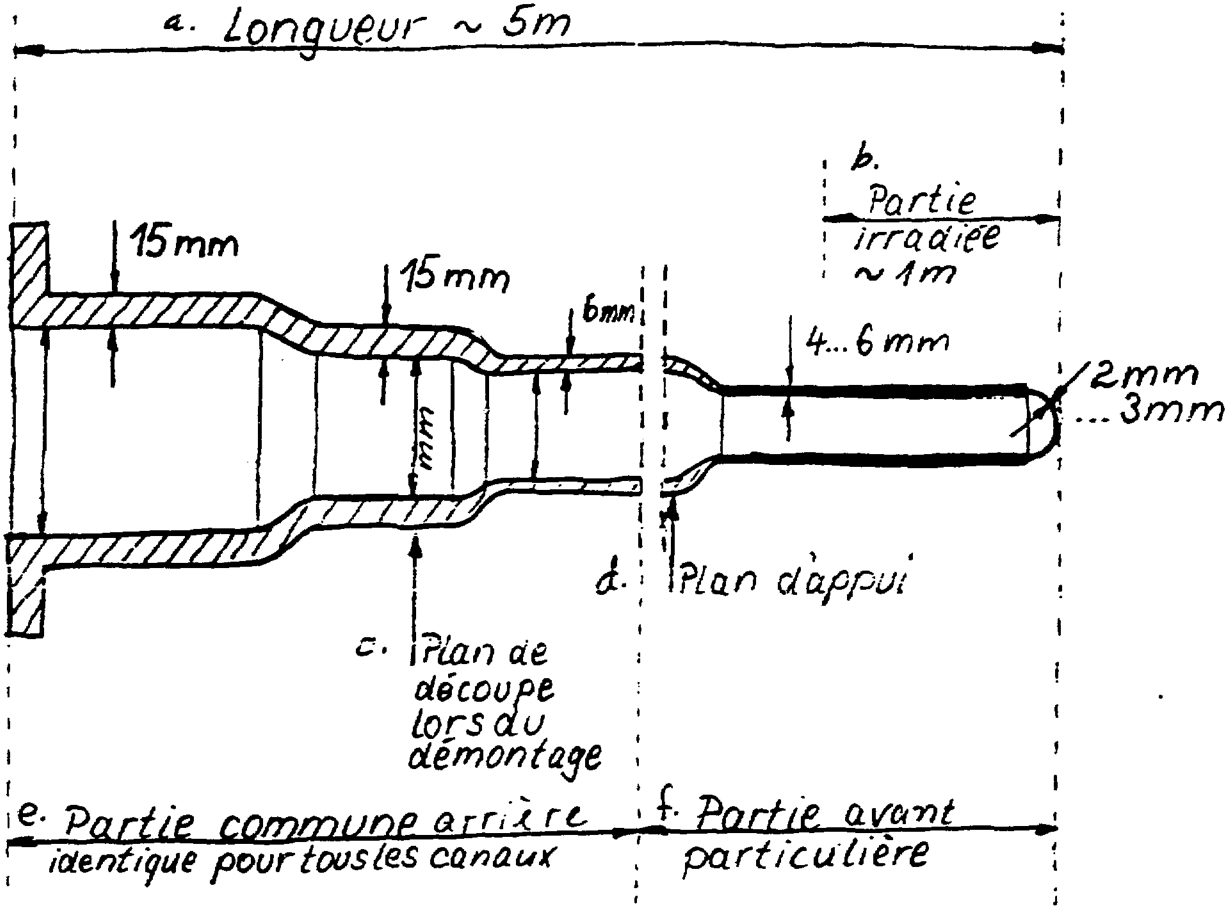

Fig. 5: Channel Details

Key:

a. Length approx. 5 cm
b. Irradiated portion, approx. 1 m
c. Cutting plane during disassembly
d. Support Plane
e. Rear common part, identical for all channela
f. Front Part, specific

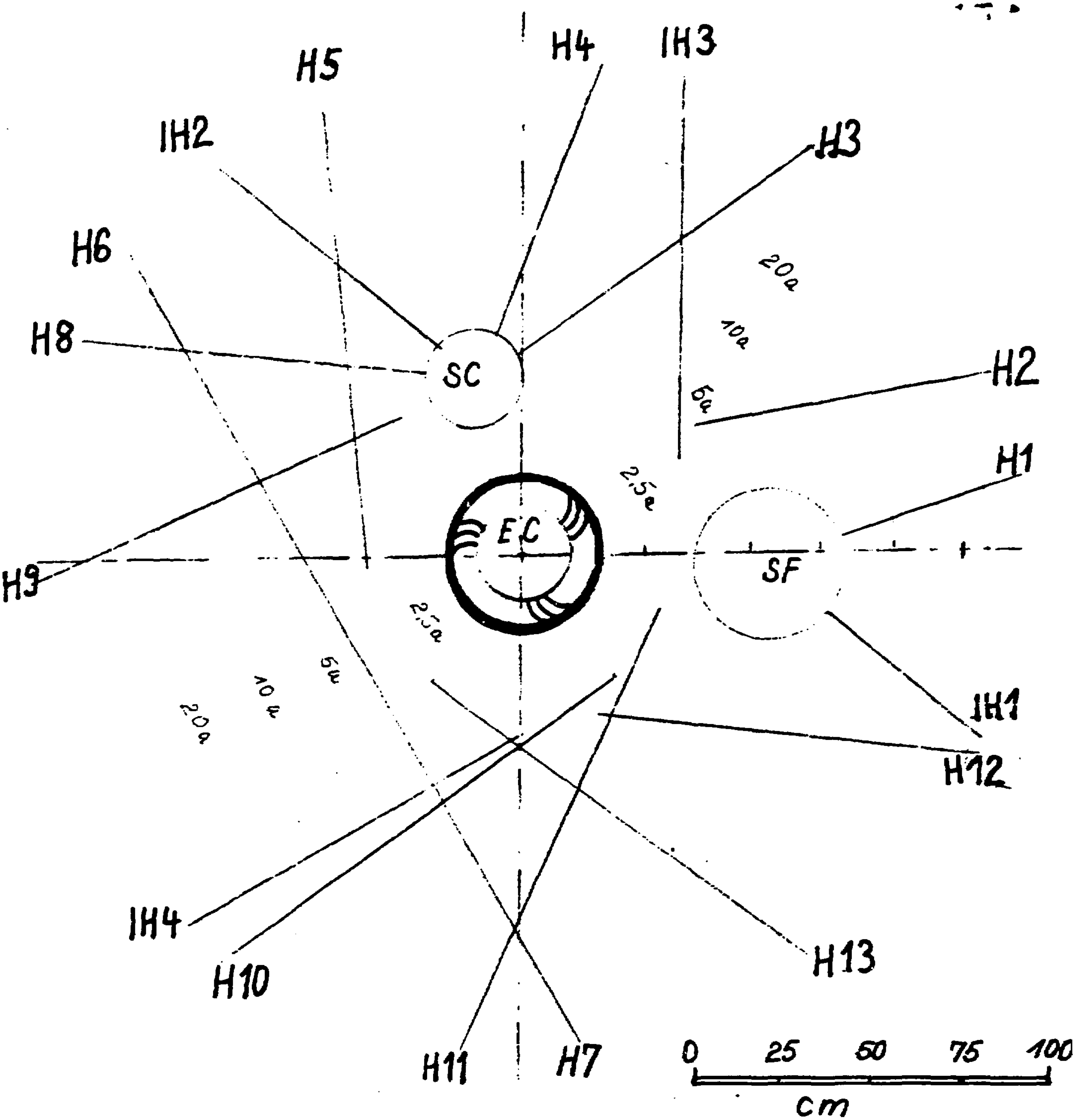

Fig. 6: Constant integration lines ($8 \cdot 10^{22} n_{th}/cm^2$) as a function of exposure time (undisturbed flux, 6 cycles of 44 days at nominal power).