Target system materials and engineering problems

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1 INTRODUCTION

As a model for our discussion we consider a spallation source which is fed by a high power proton beam of the order of one Megawatt (pulsed or continuous). Such a source will have roughly the following flux performance:

i) pulsed $\phi_{max} \geq 10^{16} n/cm^2s$

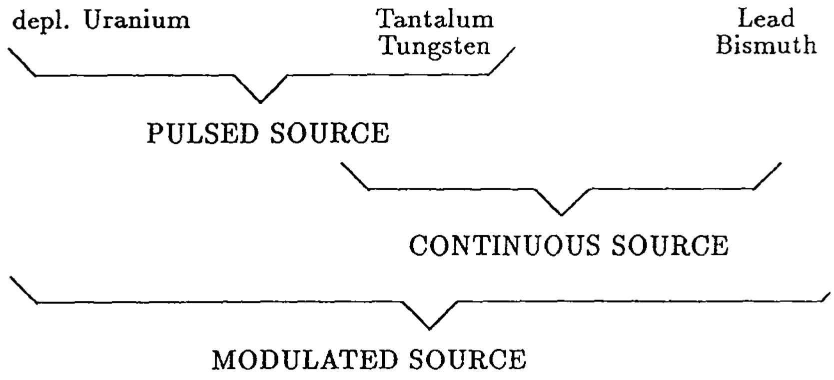
ii) continuous $\bar{\phi} \geq 10^{14} n/cm^2s$

The materials used for the target stations and particularly for the spallation target itself depend on the source concept we are aiming for — that is, whether the source is built for

- pulsed
- modulated
- or continuous operation

The difference of the materials used is mainly determined by the neutronics considerations. Depending on the choice of the materials for the target systems, the characters of materials problems met, are of somewhat different nature.

For spallation sources realized or planned up to now, the following choices for the target materials have been taken (or considered).



In this paper we refrain from considering the booster-target concept.

The typical materials problems for the engineering of the various spallation targets can be summarized as follows:

Depl. Uranium	- Heat density, Thermal stress - Phase transitions (temperature range) - Disturbance of material properties by radiation - Micro- and Macro-Cyclic Stress - Cladding
Tantalum Tungsten	- Heat density, Thermal Stresses - Disturbance of material properties by radiation - Micro- and Macro-Cyclic Stress - Cladding ?

Lead
Bismuth — Liquid target — Heat density

We assume that for the case of a liquid target a target window is needed in any case – even e.g. if the proton beam is injected from above. Outgassing of volatile spallation products at higher target temperature can not be avoided. Hence a seperation between target material, beam line – and accelerator – vacuum is necessary.
The material problems for this target version become therefore the problems for the

target window —	Heat density, Thermal stress Disturbance of material properties by radiation Compatibility between liquid and solid metal Macro-Cyclic Stress

We recognize that for each target version quite specific difficulties have to be overcome. On the other hand there is a whole set of problems which is common to all the target versions.

These are:

i) heat load in the region of proton beam interaction

ii) Thermal stress and cycling

iii) Radiation Damage

2 POWER DENSITY IN TARGETS

For the discussion of the heat load of the target we use the following semiempirical data:

i) parameters of the proton beam
The proton beam is characterized by the two parameters – total beam current (I_p) and a parameter for the beam width. For gaussian profiles we write

$$\frac{dI}{df} = \frac{I_p}{\pi\sigma^2} e^{-r^2/\sigma^2}$$

If a parabolic profile is assumed we use

$$\frac{dI}{df} = \frac{2I_p}{\pi r_0^2}\left[1 - \frac{r^2}{r_0^2}\right]$$

The maximal current density for the first case is given by

$$j_{max} = \frac{I_p}{\pi\sigma^2}$$

The same maximal current density is obtained for the second case if we put

$$r_0 = \sqrt{2} \cdot \sigma$$

ii) power density in the material
For the power density we use

$$h(z) = \alpha \cdot \frac{\Sigma E \cdot j_p}{1 - exp(-\Sigma R(E))} \cdot e^{-\Sigma z}$$

$\Sigma = \frac{\rho}{A} \cdot 6 \cdot 10^{23} \cdot \sigma_{tot}[cm^{-1}]$	total macroscopie cross section of protons with kinetic energy E in a material of density ρ and atomic number A

$$R(E) = 233 \cdot \rho^{-1}\, Z^{0.23}\, (E[GeV] - 0.032)^{1.4}$$

This is the range of protons in this target material. The parameter α depends on the target geometry. $(1-\alpha)$ expresses essentially that part of the energy which escapes the target as kinetic energy of secondary particles. From Monte Carlo investigations of the cascade processe we know that $\alpha = 0.6 - 0.8$; here we assume $\alpha = \frac{2}{3}$.

iii) Neutron yield (non fissile)

$$Y = 0.1(A + 20)\, (E[GeV] - 0.12)$$

The contribution of fast fission in uranium targets depends rather strongly on the material distribution and the size of the target. We do not need it here.

As a typical example we consider tungsten as target material (Z = 74, A = 184) and a proton beam energy of 1 GeV.
The range of the protons is

$$R(\rho) = \frac{600}{\rho}[cm]$$

ρ is here the effective density of the target material including the cooling medium.
The yield is $Y = 18\frac{n}{p}$
For a beam current density of $20\frac{\mu A}{cm^2}$ (typical) the maximal heat load in a target plate becomes

$$h_{max} = 1.42\frac{kW}{cm^3}$$

These are the typical values which have to be considered.

A comparison of the heat load with a beam-tube reactor

The thermal flux in the reflector of a research reactor has the following property

$$\phi \sim \frac{P}{A} \sim \frac{P}{V^{2/3}} \sim P^{1/3}\left(\frac{P}{V}\right)^{2/3} \sim P^{1/3} \cdot p^{2/3}$$

P is the total core power, A and V the core-surface and -volume resp. and p the power density in the reactor core.

The corresponding relationship for a spallation-source is very roughly

$$\phi \sim \frac{P_p}{r^{1/2}}$$

P_p is the power of the proton beam and r the radius of the target. For pulsed sources ϕ depends strongly on details of the geometry and materials used for the moderator. We have also to keep in mind that ϕ is not the only figure of merit for a pulsed source.

From these relations we conclude that

i) the reactor design aims rather for high power density, then for high total power

ii) For a spallation source we essentially aim for high beam power. Decreasing the target size would increase the power density on a window like $p_w \sim \frac{P_p}{r^2}$

The Problem of Power Density

As general orientation we give here some data for a few prominent neutron sources (operational or planned)

	P[MW]	V(active)[l]	$\bar{p}[\frac{MW}{l}]$	$\phi_{th}[\frac{n}{cm^2 s}]$	$\frac{n}{cm^2 s}$ per MW
ILL	57	35	1.6	$1.5 \cdot 10^{15}$	$2.6 \cdot 10^{13}$
Oak Ridge	270	35	8.6	10^{16}	$3.7 \cdot 10^{13}$
SINQ	1	~ 3	0.33	$1.5 \cdot 10^{14}$	$1.5 \cdot 10^{14}$

From these numbers it is evident that SINQ has a very high "neutronic efficiency". In an attempt to push this type of source towards higher flux the average power density will not be the main problem. This favorite situation is caused by:

i) the low power deposition per neutron produced by the spallation reaction – 55 $\frac{MeV}{n}$ as compared to 140 $\frac{MeV}{n}$ in a fission reactor

ii) the compact target

iii) virtual absence of flux depression

However, if we want to achieve a flux of e.g. $5 \cdot 10^{15} \frac{n}{cm^2 s}$ we have to feed a SINQ-type source with a beam current of $J_p \simeq 30\ mA$, leading to a current density of $400 \frac{\mu A}{cm^2}$ from the proton beam. The power density in a stationary target-window or-plate becomes larger then $20 \frac{MW}{l}$. Hence a moving target including target-window seems to be unavoidable.

We admit that for a pulsed source the peak flux ϕ_{max} is for a large class of experiments equivalent to the continuous flux ϕ of a steady source. The IPNS II proposal [1] considers a pulsed proton beam (60 Hz) with a current of $I_p = 500\ \mu$A at an energy of 800 MeV. With an uranium target the system could provide a peak flux of $10^{16} \frac{n}{cm^2 s}$ with a time average of $1.8 \cdot 10^{13} \frac{n}{cm^2 s}$.

The power density in the first target plate would be $p_{max} \simeq 2 \frac{kW}{cm^3} (2^{MWatt} l)$. This is comparable to the power density in the ILL-reactor and therefore does not seem to be unfeasible. However, in view of the thermal cycling problems and the radiation damage due to the high energy proton beam, we may have some doubt concerning a sufficiently long lifetime of this target.

3 RADIATION DAMAGE

Radiation damage is certainly one of the main causes limiting the lifetime of a target and the structure material in its vicinity. Although the damage produced by the radiation field escaping the target has to be considered the most severe effect is produced by the proton beam in the material exposed to it. While the heat load relative to the neutron source strength in a spallation environment is lower than in a fission reactor, radiation damage effects might be more severe in a spallation neutron source due to the presence of high energy particles.

An estimate for the number of displacements in the materials is given by

$$S \left[\frac{dpa}{s} \right] = \eta \frac{< \sigma E_D >}{2 E_d} \cdot \phi \cdot 10^{-21}$$

E_D and E_d are the damage and displacement energies, $\eta = 0.8$ is the collision efficiency factor and ϕ the particle flux $[cm^{-2} \cdot s^{-1}]$. For the damage rate due to the proton beam we can write accordingly

$$S \left[\frac{dpa}{s} \right] = \frac{3.26 \cdot 10^{6} < \sigma E_D > \cdot I(mA)}{E_d \cdot D^2}$$

where D is the beam diameter.

An idea about the gas production – for our case He and H have the main significance – can be obtained by

$$P = \sigma \cdot \phi \cdot 10^{18} = \frac{7.95 \cdot 10^{-3} \cdot \sigma \cdot I(mA)}{D^2}$$

The relevant parameters for a proton energy of 800 MeV for a few materials are given in the following table

	$(\sigma E_D)[b \cdot keV]$	$E_d[eV]$	$\sigma_{He}[b]$	$\sigma_H[b]$
Al	63	40	0.21	0.86
Steel	300	40	0.32	2.52
Cu	330	30	0.40	2.58
Mo	900	58	0.58	4.00
W	1430	65	0.58	5.13

Let us now estimate the expected damage in a window or a first target plate after a running time of 6000 hours. We assume a maximal current density in the proton beam of $20\frac{\mu A}{cm^2}$. This corresponds to the operation conditions of one year at SINQ.

	Material	dpa	He(appm)	H(appm)
Window:	steel	8	820	6500
	tungsten	24	1500	13200

For material in the immediate vicinity of the spallation-target, exposed to the secondary radiation field but not to the proton beam, we obtain:

Material	dpa	He(appm)	H(appm)
steel	0.9	6	31
aluminium	0.2	4	11

The numbers of this table have been extracted from actual measurements of the He-gas production in test samples in the TRIUMF-neutron station [2] and from Monte-Carlo calculations [3].

We are now confronted with the everlasting question: What do these numbers tell us about the actual macroscopie properties of the material?

The only statement we can make at this place is the following (optimistic version): If the window lasts safely for one operational year, the structure material in the vicinity should have a lifetime of more then ten years.

In order to obtain quantitative information about the behaviour of the irradiated material experimental tests of the macroscopic material properties are needed. There is no other choice today. Such an attempt is shown in the following.

This data was taken at LANL for a window-material test for the SINQ-target [4]. The irradiation was made at samples which were in contact with molten Pb/Bi – the SINQ target material – in order to search for corrosion effects. The samples were irradiated by the proton beam up to estimated damage parameters:

$$S = 1.7 \text{ dpa} \quad P_{He} = 173 \text{ appm} \quad P_H = 1360 \text{ appm}$$

The performance of Fe, Ta and the steels Fe - 2.25 Cr - 1 Mo, Fe - 12 Cr - 1 Mo (HT9) are shown in Fig. 1 – 3. As rather expected, the pure metals lose their ductility, while the steel samples perform well. These type of steel is therefore a genuine candidate for the target-window and -container material. Further testes, up to higher radiation damage are however in preparation.

Investigation about swelling of irradiated materials has mainly be done in reactors. This radiation environment leads mainly to dpa-dominated swelling. Its onset starts for steels between 20 – 30 dpa. Due to the presence of high energy particles in the radiation field of spallation targets, material test with high $\frac{He}{dpa}$-ratio are more relevant. Useful data is still rather rare.

Much information about the damage problems of uranium targets could be gathered from the operational experience of the ISIS-target. Two targets have been used up to end of life and subsequently analysed. These matters are discussed elsewhere at this conference [5]– we hence restrain from any further discussion.

4 THERMAL STRESSES

As a reference case for our discussion we assume a plate irradiated by a proton beam whose power deposition is given as discussed in chapter 2. The cooling medium is assumed to cover either

i) the front- and back side of the plate (possibly also the periphery) as a model for a target plate – or

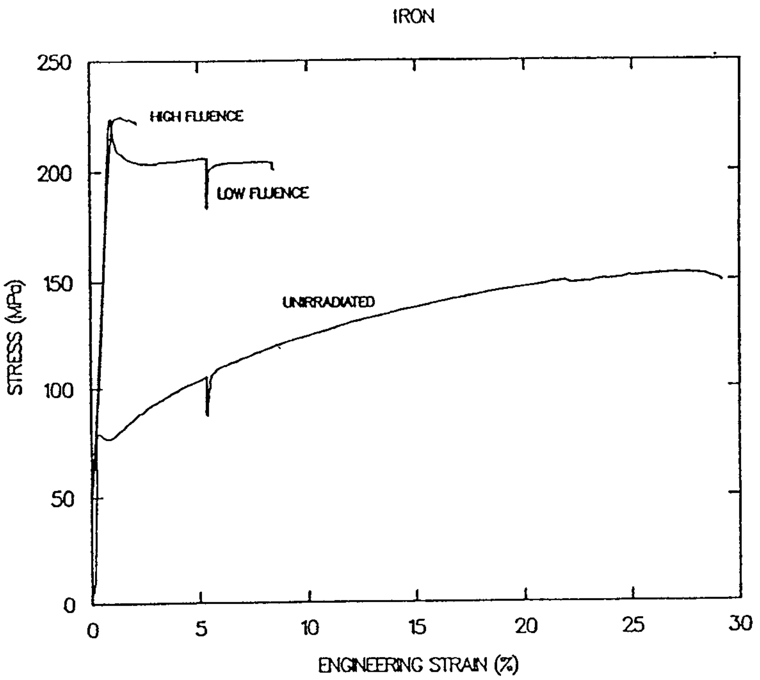


Fig. 1 Stress-strain behavior of pure iron after irradiation with 800-MeV protons. Low fluence: 4.8 x 10^{19} p/cm^2; High fluence: 5.4 x 10^{20} p/cm^2; Sample temperature was 400°C.

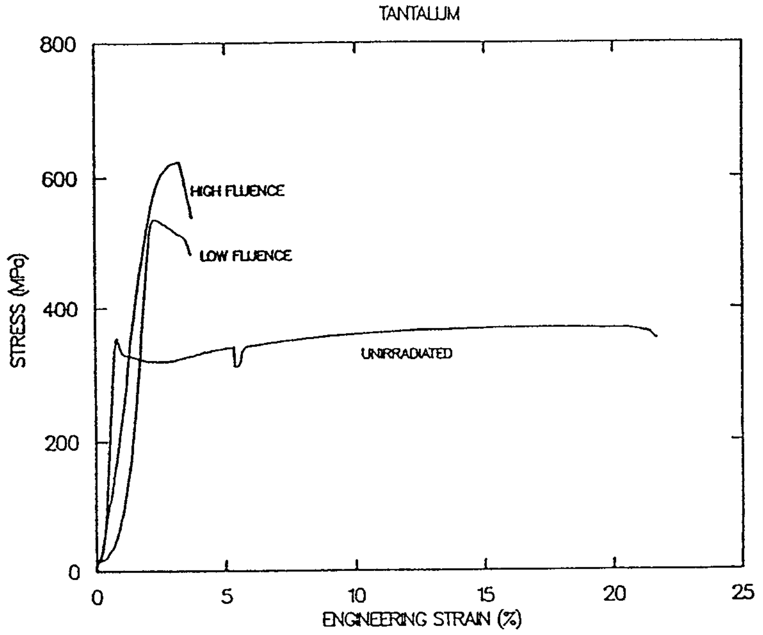


Fig. 2 Same as Fig. 1. Material: tantalum.

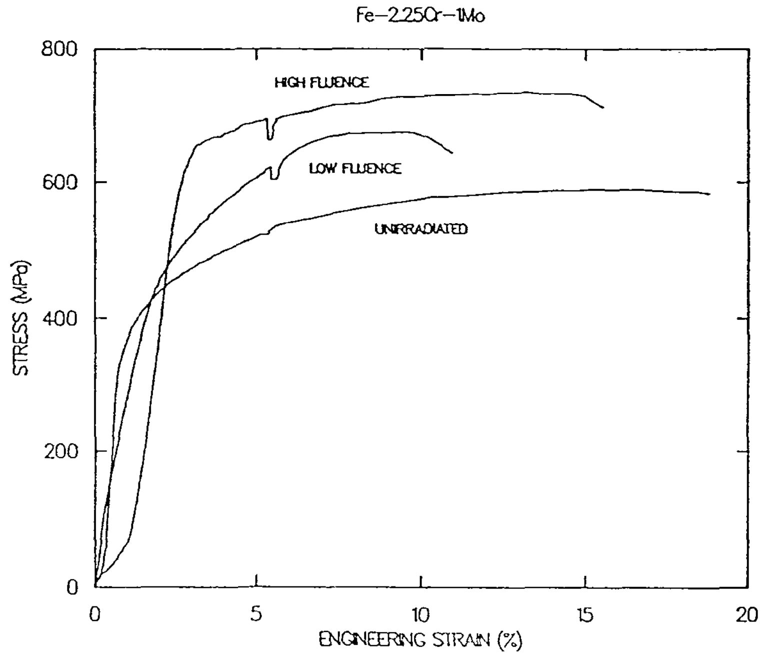


Fig. 3 Same as Fig. 1. Material: Fe - 12 Cr - 1 Mo steel.

ii) the back-side only as a model for a target window

Depending on the plate thickness, the temperature of the cooling medium and the heat-transfer from the plate to the cooling medium, we obtain temperature gradients in the plate, which may lead to considerable thermal stresses.

Furthermore, for a pulsed source the thermal stresses are not stationary – they follow "micro-cycles" corresponding to the pulse-sequences of the proton beam. An other source for non stationary loads is the "macro-cycling" due to instabilities in the operation of the accelerator. As a consequence the target material deteriorates due to thermal cycling growth. This effect is particularly strong in materials which go through phase transitions within the temperature range covered during a cycle (e.g. uranium). Synergetic effects with swelling due to gaseous fission – and spallation-products as well as He-gas production have to be taken into consideration also.

In principle the thermal stress is determined by

- symmetry properties and kinematics
- Hook's law

- equilibrium conditions

if the temperature distribution in the material is known. For a cylindrical plate we obtain

$$\sigma_r = \frac{\beta E}{1-\nu} \int_{o'}^{R} \frac{dr'}{r'^3} \left[\int_o^{r'} \rho^2 \frac{dT}{d\rho} d\rho \right] = \sigma_\phi$$

$$\sigma_z = E\beta \left[T - \frac{2}{R^2} \int_o^R T r dr \right] + \nu \left[(\sigma_r + \sigma_\phi) - \frac{2}{R^2} \int_o^R (\sigma_r + \sigma_\phi) r dr \right].$$

E is Young's modulus, ν the Poisson contraction ratio and β the parameter for thermal expansion. R is the radius of the plate.

The problem can be solved either by
the powerful method of finite elements for more complicated geometries or under certain circumstances even analytically; e.g. in the present case the transversal problem, layer by layer in z-dimension. The T(r) - distribution is then given by a Fourier-Bessel serie [6]. If T(r) is not too narrow, that is the proton beam is sufficiently broad, one to two terms are sufficient for a 1 % precision.

As typical examples we show here data from the

- LANCE II, W-target [7]
- SINQ, window [6]
- IPNS II, U-target [1]

LANCE II, Fig. 4 - 6
beam power 1 MWatt
target plate: diameter 10 cm, thickness 1 cm
heat transfer to cooling medium is 1.4 $\frac{Watt}{cm^2}$ °C.

The maximal temperature in the center of the target plate is 900°C. The stress distribution contains components reaching values up to 5500 $\frac{kg}{cm^2}$ (550 MPa). These correspond to 70 % of the tensile yields of the material.

SINQ Fig. 7 - 8
beam power 0.9 MWatt
target plate: diameter 16 cm, thickness 0.6 cm
heat transfer to the cooling medium on one side of the plate (window) is assumed to be 3.9 $\frac{Watt}{cm^2 {}^oC}$ [8]. This performance is based on model measurements.

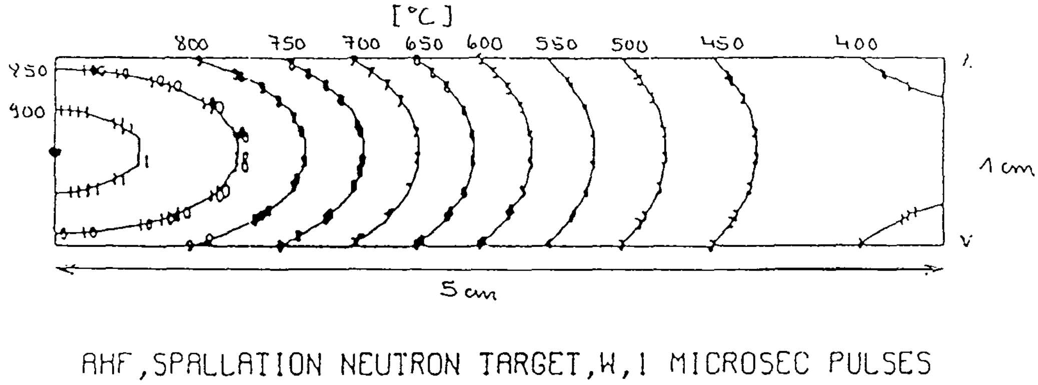


Fig. 4 Temperature distribution in a tungsten target plate for a beam power of 1 MWatt. Cooling is on both plate sides with 1.4 W/cm^2 °C.

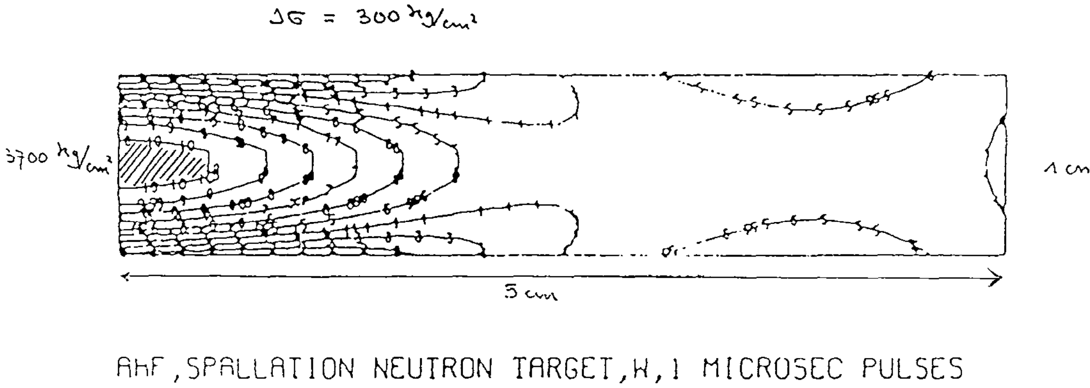
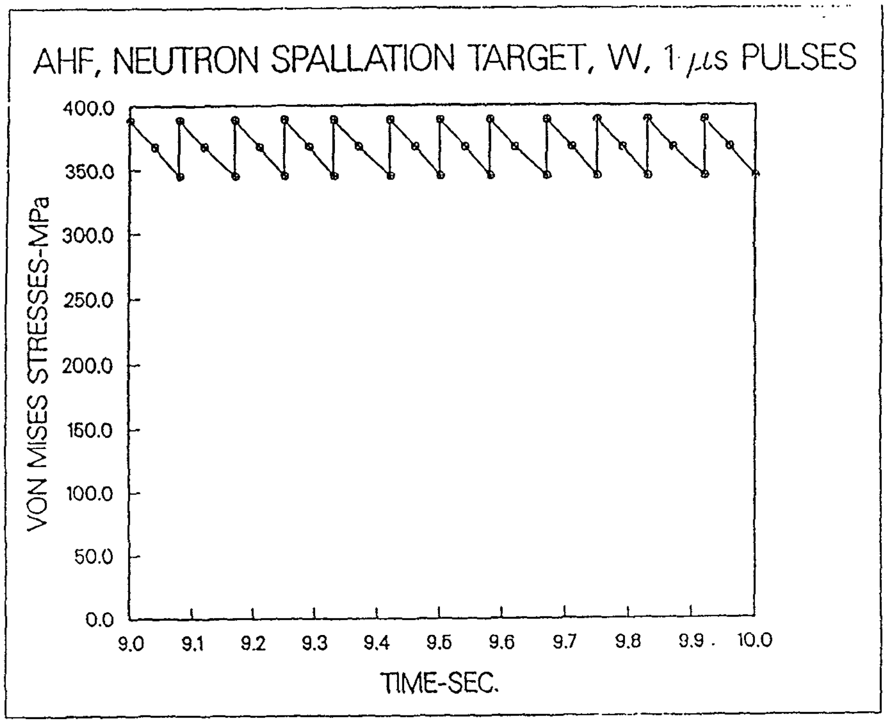


Fig. 5 Stress distribution for the same target plate as Fig. 4.



500 kg/cm²

Fig. 6 Thermal cycling of the maximal von Mises-stress (a measure for yielding) due to the pulsed proton beam.

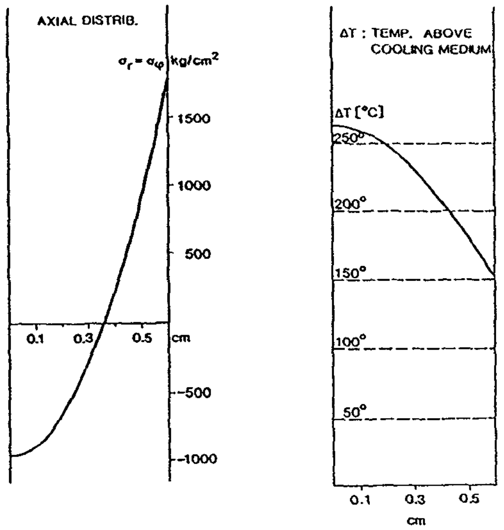


Fig. 7 Longitudinal temperature--and stress-distribution in a tungsten plate cooled at one side only. Heating is with a proton beam of 600-MeV energy and a current of 1.5 mA. Heat transition at the cooled surface is 3.9 W/cm² °C.

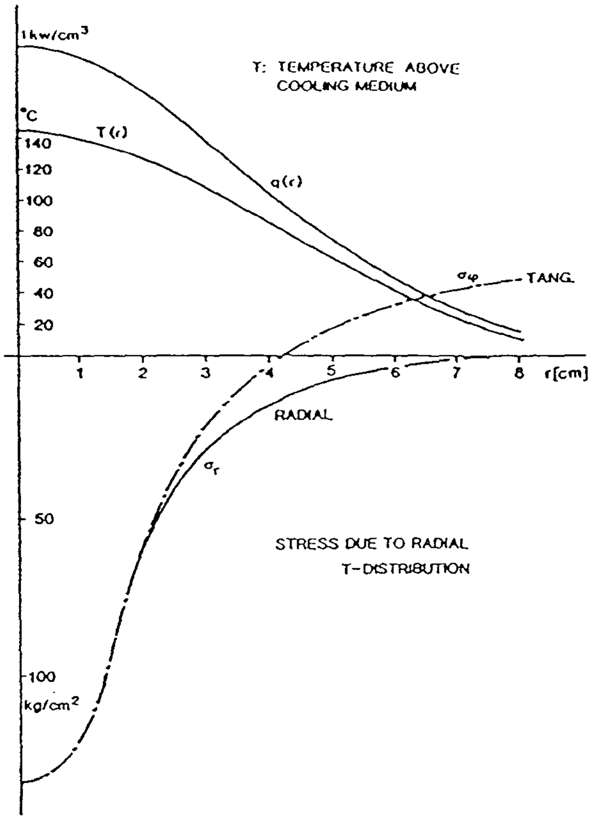


Fig. 8 Radial temperature--and stress distribution at the cooled back side of the tungsten plate due to a proton beam of 600-MeV energy and a current of 1.5 mA. The radial beam profile is a Gaussian with σ = 5 cm.

Due to the relatively large beam diameter (10 cm) the maximal current-density on the plate is 20 $\frac{\mu A}{cm^2}$. The corresponding maximal temperature becomes 380 °C. The stress distribution reaches -1100 $\frac{kg}{cm^2}$ (radial and tangential compression) at the front of the plate and 1630 $\frac{kg}{cm^2}$ at the back (tensile)

IPNS II Fig. 9 – 11
beam power 400 kWatt
parabolic beam profile, truncated at 3 cm radius
The performance of the plate cooling has to be such,
to keep the maximal temperature of the (U - 10 % W)
plate below 400 °C.

$$k\partial_x T = h(T_{Mat} - T_{cool}) \qquad h = 15.25\frac{W}{cm^{2o}C}$$

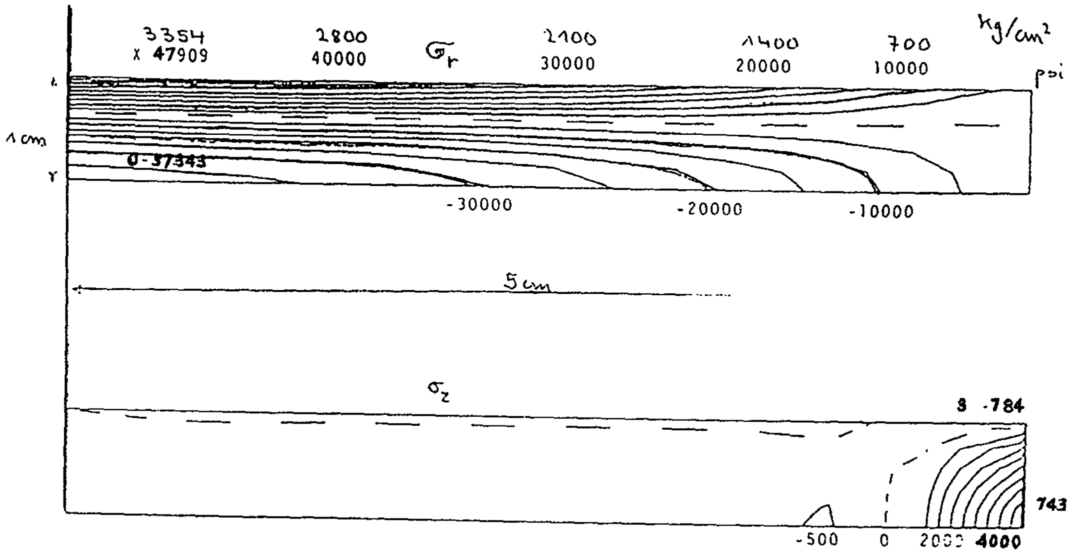


Fig. 9 Isostress lines for the radial and longitudinal stress distribution in a uranium-molybdenum disk. Beam power is 0.4 MWatt.

The cooling medium would be Na - K.

The result is a maximal temperature of 360 °C. The stress distribution contains radial and tangential compression of -2800 $\frac{kg}{cm^2}$ in the center and a tensile stress of +2800 $\frac{kg}{cm^2}$ at the back- and frontside of the plate.

While these stresses are well within the yield of the U - 10 % W-target material, they exceed at r $\simeq$ 0 cm the yield of the Zirkaloy cladding. In view of the experience with the ISIS-target concerning swelling due to thermal cycling, this case seems to us at the ultimate limit of feasibility.

5 CONCLUSIONS

We tried to discuss the common problems of target design.

- power load
- radiation damage
- thermal stress

While each of these problems may find a more or less simple solution, the challenge for the engineers starts with the attempt to solve these problems simultanuously. The following kind of dialectics has then to be considered.

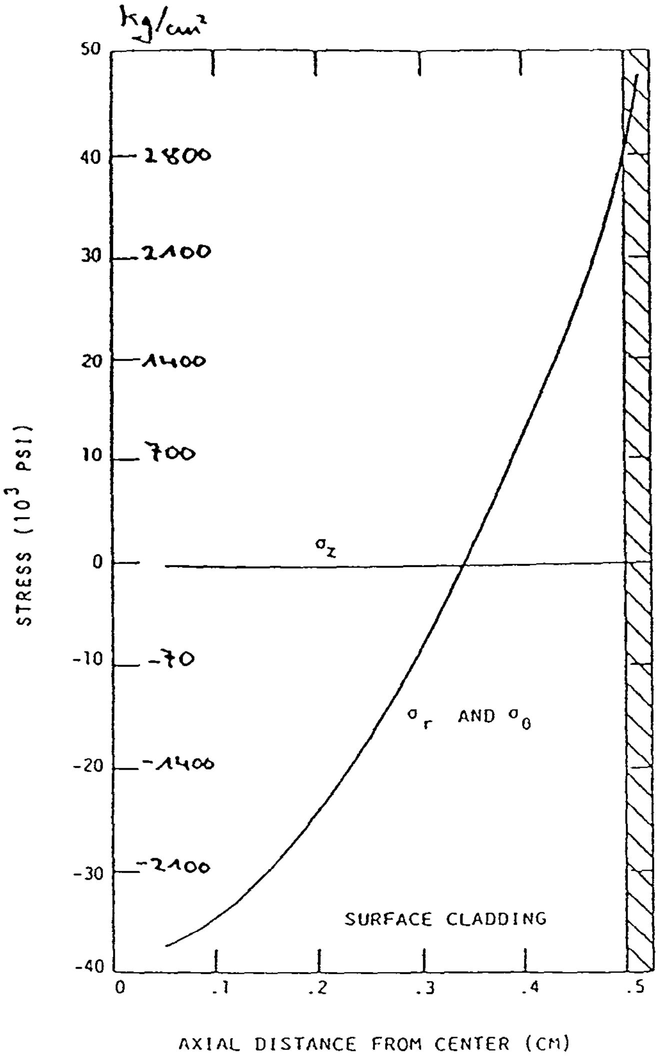


Fig. 10 Thermal stress along axial elements of Zirkaloy-clad uranium-molybdenum disk.

- Temperature limits can always be taken into consideration but
- Strong dilution of the heavy target material by cooling media has to be avoided

or

- Uranium is concerning the neutronics a favorite material, but
- Uranium leads to high heat load and has to be operated at very low

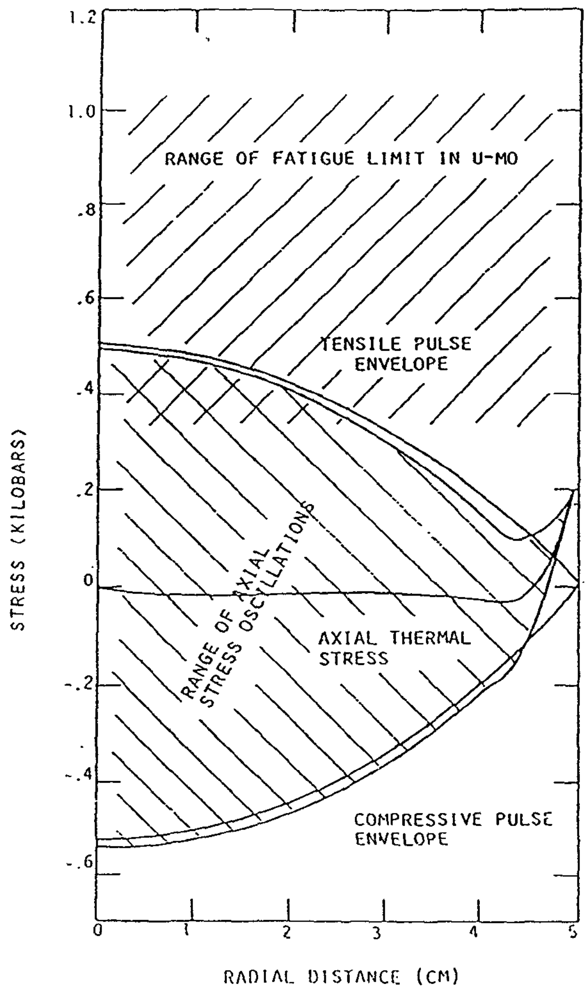


Fig. 11 Oscillation range of the axial thermal stress due to pulsation of the proton beam in the uranium-molybdenum target plate. In the center of the plate the fatigue limit is exceeded in the tensile phase of the pulse.

termperature (< 400 °C) since it has the most miserable material properties of all given candidates

or

- (Nearly) all problems can be avoided with the choice of the concept of a liquid metal target, but
- A beam entrance window is needed

This dialectic becomes even more nasty, when considering radiation damage as well. Even if a solution has been found, the next question which comes up is: How long does it last?

The material properties change with operation time due to the influence of radiation damage. How does it?

This depends strongly on the solution chosen to solve the problems concerning power load and thermal stress.

We have shown that solutions to the whole package of problems up to a beam power of 0 (1 MWatt) have been found. But what next?
e.g. 0 (10 MWatt)

The whole effort concentrates onto the region of the first few centimeters of beam penetration into the target. Two solutions have been proposed:

i) Keep the power of the proton beam limited and produce the neutrons elsewhere in the target. This is probably the only argument for a (high intensity) booster.

ii) Dilute the power by moving mechanically the target and the window. This proposal has been worked out in considerable detail for the late SNQ-project. If higher power sources turn out to be the way to go, this version should ultimatly be taken up again.

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