Engineering and Environmental Aspects of Fusion Reactors

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FUSION TECHNOLOGY INSTITUTE

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In trying to assess the engineering and environmental problems with fusion reactors one might think that the problem will strongly depend on the chosen fuel cycle. With some exceptions this is not the case at all. It turns out that any fusion system employing deuterium will have similar neutron currents and the choice therefore falls back on which system is easiest from the plasma physics point of view.

Figure 1 shows the different fuel cycles generally considered for fusion and with each reaction is listed the minimum temperature at which the reactor can operate as well as the minimum product of the density and confinement time required to produce sufficient energy to just keep the system going. These numbers reflect some assumptions about the total energy released in the reaction and the efficiency of converting kinetic energy of reaction products and heat to electricity, but the numbers clearly indicate that the D-T fuel cycle is by far the easiest to achieve. Therefore, in this discussion we assume operation on the D-T cycle but ultimately the other cycles may be possible and highly desirable.

As we investigate the details of this cycle we see that while it poses the simplest problem for the plasma physicist it may be the most difficult for the reactor engineer. This stems from the fact that in this system 80% of the energy is released in the form of a fast (14.1 MeV) neutron and that tritium is not a naturally occurring isotope of hydrogen. The former problem is not unlike that found in a fission reactor except for the higher neutron energy and the latter problem is solved somewhat like the fast breeder reactor in that we can produce tritium by the fission capture of a neutron in lithium as shown in the bottom two reactions One might therefore say that the fuel for these fusion reactors is deuterium and lithium.

This then forms the basis for our engineering and environmental problems and we seek to explore the details of this as far as possible. We will be dealing with a system that produces 3·10^7 neutrons per second for each megawatt of thermal power and this is about a factor of 4 higher than that in a fission reactor. The system must produce tritium essentially as fast as it is consumed or about 0.2 gram per megawatt day. This compares to the fuel consumption in a LMFBR of about 9 g per megawatt day, or a fusion reactor consumes about 50 times less fuel by weight per day.

To handle the neutron and breeding problems of a fusion reactor, a blanket like that shown in Fig. 4 is envisioned to surround the reacting plasma. In this blanket the neutron must be thermalized to remove its energy, captured in lithium to produce tritium and additional energy, and finally stopped in the shield to isolate the outside world and especially the superconductors from neutron leakage. The blanket must somehow be supported and cooled and this requires structural materials as well as a flowing coolant. Because of the neutron flux, the high temperature and the corrosive nature of lithium, the materials will have to be something quite special. Further complications occur because the reactor requires a strong magnetic induction for plasma confinement. Since superconductors are the only economic way to make large static magnetic fields, and keeping them cold generally requires that they be located outside the blanket. This suggests that the whole blanket region will be immersed in the strong induction. This will complicate our cooling problem because lithium is a good conductor and its motion in the magnetic field will set up Lorentz forces. Therefore, one may not be able to take advantage of its good heat transfer properties due to the pumping power loss in moving it across the magnetic field. It may be desirable to bring in lower conductivity coolants such as gasses or fused lithium salts as the heat transfer fluid.

In terms of the problem of slowing down and capturing the neutron in the blanket, let us look at some details of a so-called standard blanket similar to that shown in Fig. 2. This model is depicted in Fig. 3 and envisions a cylindrical system with a plasma radius of 150 cm, a vacuum wall radius of 200 cm, a thin 0.5 cm first wall, a 3 cm first wall coolant, another 0.5 cm wall, a large breeding region, a graphite reflector, some more lithium and finally a shield. Notice that the coolant region has 94% Li and 6% structure in a homogenized form. The two specified walls are merely to look at neutronic details within a metallic structure. For calculational purposes we assume a slab geometry and that the reactor produces 200 MW(th) per meter length which results in a neutron wall loading of 10 MW/m^2 or a neutron current of $4.4 \cdot 10^{14}$ $neutrons/cm^2 sec$. For reasons which will be discussed later, we use niobium as the structural material and natural lithium which contains 7.4% Li^6 as the coolant. Figure 4 shows the absolute neutron flux for the 100 cm thick blanket as well as the energy deposited per unit volume by the neutron and resulting gammas as it undergoes elastic and inelastic collisions. Notice that the first wall operates in the highest flux range (about $3 \cdot 10^{15}$ n/cm^{2}sec) and highest energy deposition per unit volume (about 120 watts/cm^3). These details suggest the first wall is going to be an especially important problem area to investigate. It is somewhat like the cladding of a fission reactor fuel element.

A blanket like this has not been optimized but for discussion, it produces 1.2 tritons per incident neutron, giving a breeding ratio comparable to fast breeder reactors. It also has a leakage of .07 neutrons per incident neutron and the average energy of these neutrons is about 100 keV suggesting a very effective shield must occupy the region beyond the breeding blanket. This is required not only for biological safety but because this heat load into the surrounding superconductors would be intolerable. Shields for such reactor blankets are being designed and appear to offer no insurmountable problems.

Since breeding ratios over 1.6 have been calculated in some blanket configurations. The large breeding ratio may become a problem because tritium thus far appears as the worst radiation hazard for fusion. Equations 1-4 are simple rate equations developed by Vogelsang of Wisconsin which describe the fuel doubling time in a reactor. Here I_B is the inventory of tritium in the blanket, I_o the initial external inventory, $\lambda = 1/\tau_R$ where τ_R is the mean residence time of tritium in the blanket, τ is the half life due to radioactive decay and we use I_x as the stored inventory of tritum external to the blanket which is ready for fueling or start-up of other plants. The rate of production and consumption of tritium are $\dot{N}^+$ and $\dot{N}^-$ respectively, while their ratio $\dot{N}^+/\dot{N}^-$ is the breeding ratio T. The minimum external inventory is I_{xm} and the equilibrium inventory of tritium in the blanket is I_{BSat}. Writing

$$\frac{dI_B}{dt} = \dot{N}^+ - \lambda I_B - \frac{1}{\tau} I_B = \dot{N}^+ - I_B(\lambda + \frac{1}{\tau}) \qquad (1)$$

$$\frac{dI_x}{dt} = \lambda I_B - \dot{N}^- - \frac{I_x}{\tau} . \qquad (2)$$

Solving (1) and (2) we find

$$I_o = I_{xm} + \frac{\dot{N}^+}{\lambda} \left[1 - (T-1) \ln \frac{T}{T-1} \right] \qquad (3)$$

and

$$\tau_D = \frac{I_{xm} + I_{BSat}}{\dot{N}^- (T-1)} . \qquad (4)$$

For a 5000 MW(th) plant we find that about 0.8 kg of tritium is consumed per day. Figure 5 is the doubling time of fuel in a fusion system as a function of the breeding ratio with the recovery time and (I_{xm}) as a parameter. From this we see that the doubling time is more sensitive to the residence time

($\lambda = 1/\tau_R$) than the breeding ratio (T) so long as the initial inventory is low and $\lambda < 1$/day. If rapid recovery is possible ($\lambda > 1$/day), low blanket inventories will be attainable and the breeding ratio can be significantly reduced.

A way to reduce the residence time in the blanket is to use a breeding and cooling material that has a low solubility for tritium such as $2LiF\text{-}BeF_2$. Using this in a blanket configuration similar to that previously examined and not optimized gives a breeding ratio of about 1.1. If this reduction is coupled to the further reduction that will occur when we add access holes through the blanket, a net breeding ratio even closer to 1.0 will be found. From the figure we see that for a breeding ratio of only 1.05, if the residence time is around 0.1 day and the external minimum inventory is 6 kg or less, a doubling time of less than 160 days is found. This is quite good and is to be compared with over 7 years for a LMFBR. A further beneficial feature about the fusion system is that fuel reprocessing or recovery can be accomplished at the plant site with rather simple chemical or diffusional separation techniques.

Moving on to other aspects of these neutron rich plants it is well to remember that the flux is comparable to a LMFBR but the spectrum is harder. Therefore, let us next look at what appears to be the most formidable technological problem in fusion power--that of materials radiation damage. We know that the wall and structural materials must be safe from chemical corrosion by lithium or its salts and that they also must have good physical properties at the higher operating temperatures envisioned in these devices. For this and other reasons the refractory metal niobium was thought to have the most desirable properties and many calculations were performed with it as a standard. We will see later that there may be reasons to sacrifice the higher temperature qualities of niobium for better neutronic qualities at the high fluence predicted.

Because of the large neutron flux, elastic or inelastic collisions of neutrons with wall material atoms will result. After 20 years of operation transmutation collisions due to (n,2n), (n,p) and (n,α) reactions have been calculated by Martin to produce some 0.5, 0.28, 0.6 and 10 atomic percentages of H, He, Y and Zr respectively, in the niobium structure. The H will diffuse out, the yttrium is marginally soluble and the zirconium is quite soluble in niobium so that these may be minor problems. However, the helium will become of considerable importance because of bubble formation and growth which will degrade the physical properties of the material and enhance swelling since the helium does not diffuse out.

Elastic collisions are also extremely important in the structural materials because the energy transferred to a lattice atom or primary knock-on can do considerable damage as it cascades down in energy. It has been estimated that due to the high fluence and energy in fusion systems, every niobium lattice atom will undergo a displacement every day. Such a high displacement rate gives rise to enhanced void production and this will lead to increased swelling. While swelling in reactor materials is flux dependent it is also temperature dependent and Kulcinski gives us Fig. 6 to show the general trends. At low temperatures, only isolated defects survive but as the temperature is increased, interstitials become immobile and then tend to precipitate into platelets while the vacancies are still isolated. Raising the temperature somewhat further allows the vacancies to become mobile and precipitate into loops or three dimensional voids. Further increases cause the swelling to be reduced as the mobility is increased and self-annihilation of displacements and vacancies takes place. Above about 0.3 T_m (where T_m is the melting point) swelling again increases and then finally drops to zero at about 0.5 T_m. In fusion reactors it may be possible to operate at 0.3 T_m or above 0.5 T_m to reduce this problem but as yet it is unclear what the situation will be in alloys that may be used.

In general, radiation damage of metals increases their yield strength but severely degrades their elasticity until they become like glass and can fracture under strain. Neutron radiation damage is not the only problem with reactor materials. Steiner of ORNL has calculated the induced radioactivity in possible niobium structural materials of fusion reactors using the reactions previously indicated as well as (n,n') and (n,γ) reactions. While good cross section data are not yet available in the high energy range, the induced activity shown in Fig. 7 is obtained as a function of the irradiation lifetime of a plant. From this we see that ^{95}Nb and the isomeric states of ^{94}Nb and ^{95}Nb are the major contributors to the activity and consequently they form the major source of reactor after-heat and radiation waste that must be considered. Steiner has applied these calculations to a system that looks like the referenced blanket we saw in Fig. 2 and the resulting after-heat is shown in Fig. 8. The 1% we see here is about a factor of 7 less than that found in present and planned fission plants.

Considerations such as this form another engineering and environmental problem for fusion reactors and again there are ways around it. As we have mentioned, niobium was a first choice material to be investigated and because of that we know quite a bit about its neutronic properties. This has occurred even though there are definite uncertainties about the details of inelastic cross sections at high neutron energies. Vanadium is also a refractory metal that has good high temperature physical properties but one that has no long lived radioactive isotopes. Steiner has estimated that by using vanadium, the induced activity and after-heat are reduced by between 10^3-10^4 compared to that of niobium, but there are other problems with vanadium.

We therefore see that radioactive structural materials may be present or produced in fusion reactors and this represents an environmental burden. However, the waste is of solid form and of reasonably short half-life which makes its handling and/or disposal a significantly simplified problem. Uncertainties remain in this area and designs are being investigated where this radiation is reduced even further; however, the insult to the environment from niobium systems still looks better than anything currently available in the energy production area by over four orders of magnitude.

Moving on to other engineering and environmental problems, we concern ourselves with the waste heat of a potential fusion reactor. This problem is coupled to the fact that the blanket must be cooled because it is ultimately the heat source for the system. Since we are trying to convert heat energy to electrical energy we are tied to Carnot cycle efficiencies. Present day plants use Rankine cycle turbines and of course this must be the first consideration for fusion reactors. As most of you know, the cycle efficiency for such systems is determined by the maximum operating temperature. At present, steam turbines are limited to inlet temperatures around 1050°F and this has generally limited modern coal fired power plants to thermodynamic efficiencies (η) of less than 42%. Because of a number of factors, present fission plants have trouble meeting this value and consequently they reject slightly more heat. This can be seen because the reject heat is equal to $(1-\eta)/\eta$ times the power out. A plant producing 1000 MWe operating with $\eta = 0.42$ rejects about 15% less heat than a plant operating with $\eta = 0.38$.

Fusion plants should be able to operate at higher temperatures because of their potential ability to take dimensional changes due to thermal expansions. To take advantage of this, Fraas of ORNL has adapted a potassium topping cycle to a fusion plant. This binary vapor cycle is shown in Fig. 9 and his calculations indicate that efficiencies of around 54% should be possible and this sounds very attractive.

The problem of moving a conducting liquid metal coolant out of the magnetic field region will present some problems but again there are several alternatives. One that looks especially attractive to me is to use gas cooling of the blanket. Several groups have looked at this and D'Hospital and Hopkins of GGA conclude that helium gas cooling coupled to Brayton cycle turbines could operate with $\eta = .49$ and if these turbines are coupled to dry cooling towers the environmental impact as far as waste heat is concerned would be extremely small. Unfortunately large Brayton cycle turbines do not yet exist but as the need becomes clear they will be developed and could be available by the time fusion is here.

In the longer term, or for systems where it is especially suited, cycles such as D-D or D-H_e^3 can be used for the direct extraction of charged particle kinetic energy and conversion to electricity may be possible with efficiencies near 85%. Since electrostatic direct conversion only is applicable to charged particles, it is of little consequence for D-T systems where 80% of the energy is in the neutron.

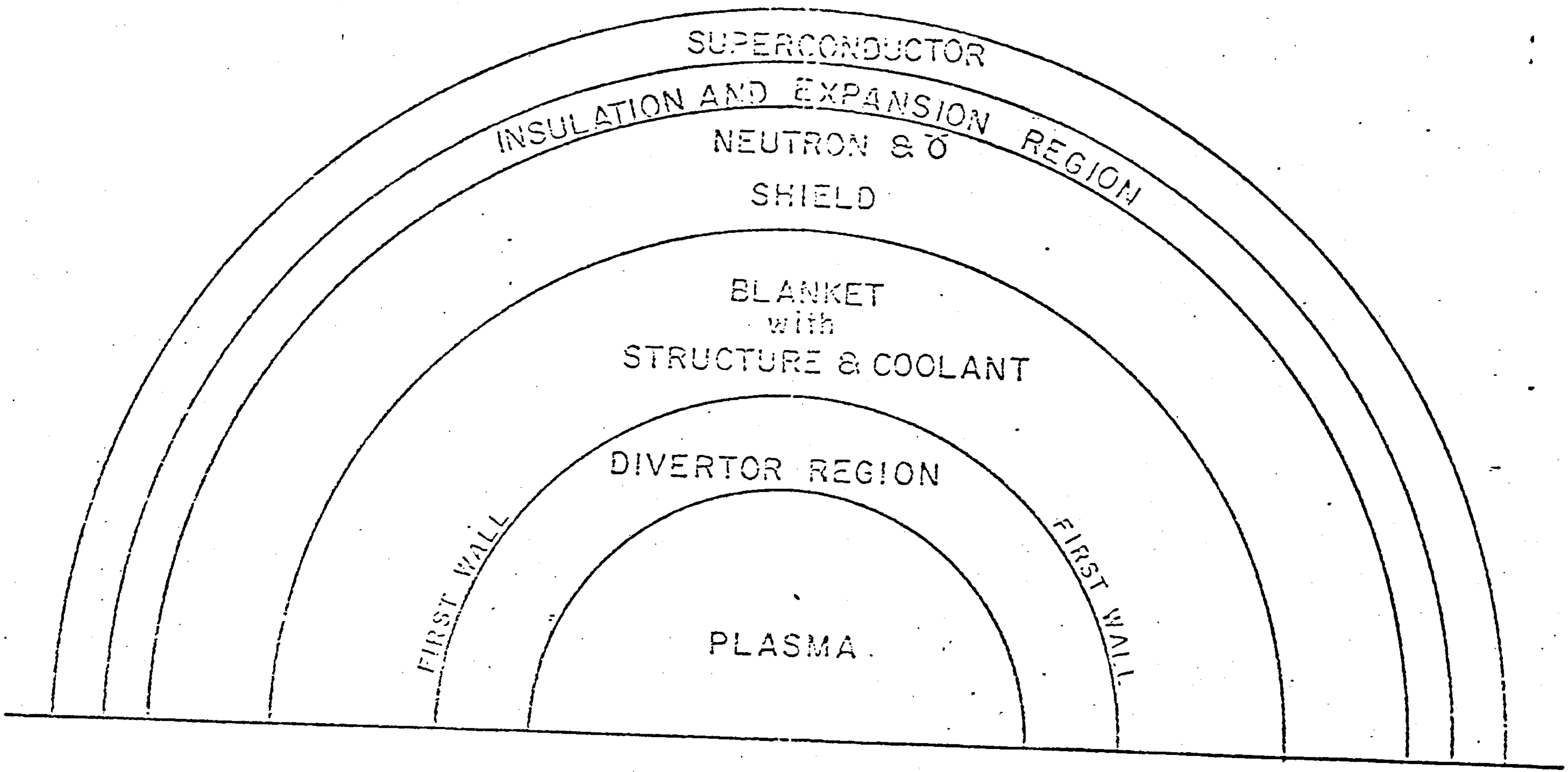
One final area of engineering that I would like to cover has to do with fueling and heating of reactor systems. Initially a fusion reactor has to have enormous quantities of energy supplied to the plasma to heat it to the point where reactions are taking place at a sufficient rate that one might hope to keep it going. The way to envision this is that hot fuel is injected into or created in the reacting volume but it is always leaking out. As D-T reactions take place, neutrons leave this region but the other reaction product, the 3.5 MeV helium ion or alpha particle, is charged and therefore trapped in the reaction volume. It will give up its energy to the background plasma through Coulomb collisions and provide the needed heat to the fuel. In the ideal case, one would only have to inject cold D&T fuel into the reaction volume to keep the system going. Such an ideal situation will be modified by our inability to confine the plasma and hot α particles beyond a certain period. As the fuel leaks out of the magnetic container it must be cooled, collected and recirculated. The recirculation will either be done at high energy or as cold fuel depending on the system and the need to control the reactor burning rate. At present it appears that fuel will have to pass through the reacting volume on the average of some twenty times before it is burned. This general leakiness and the need to always supply fuel from the outside, either energetically or not, is both a blessing and a problem for fusion systems. It is a blessing because it guarantees the inherent safety of a reactor and its inability to undergo a nuclear excursion. However, it is a problem because small amounts of radioactive tritium, about 1 kg per day, must be handled many times exceedingly well to prevent minute losses outside the plant.

In conclusion then this has been an outline of some engineering problems in fusion reactors that will have direct interaction on and implications for their environmental impact. Of course eventually reactors may be different than they are presently envisioned, however, unless the designs change considerably they appear to offer a significant environmental advantage over anything presently available. When this advantage is coupled to the long term availability of fuels for fusion, it suggests that the sooner fusion power becomes available in a realistic sense, the better we will be able to meet the need for clean, safe, eccnmic electric power.

Special thanks is extended to my colleagues for their permission to use slides and data from their works.

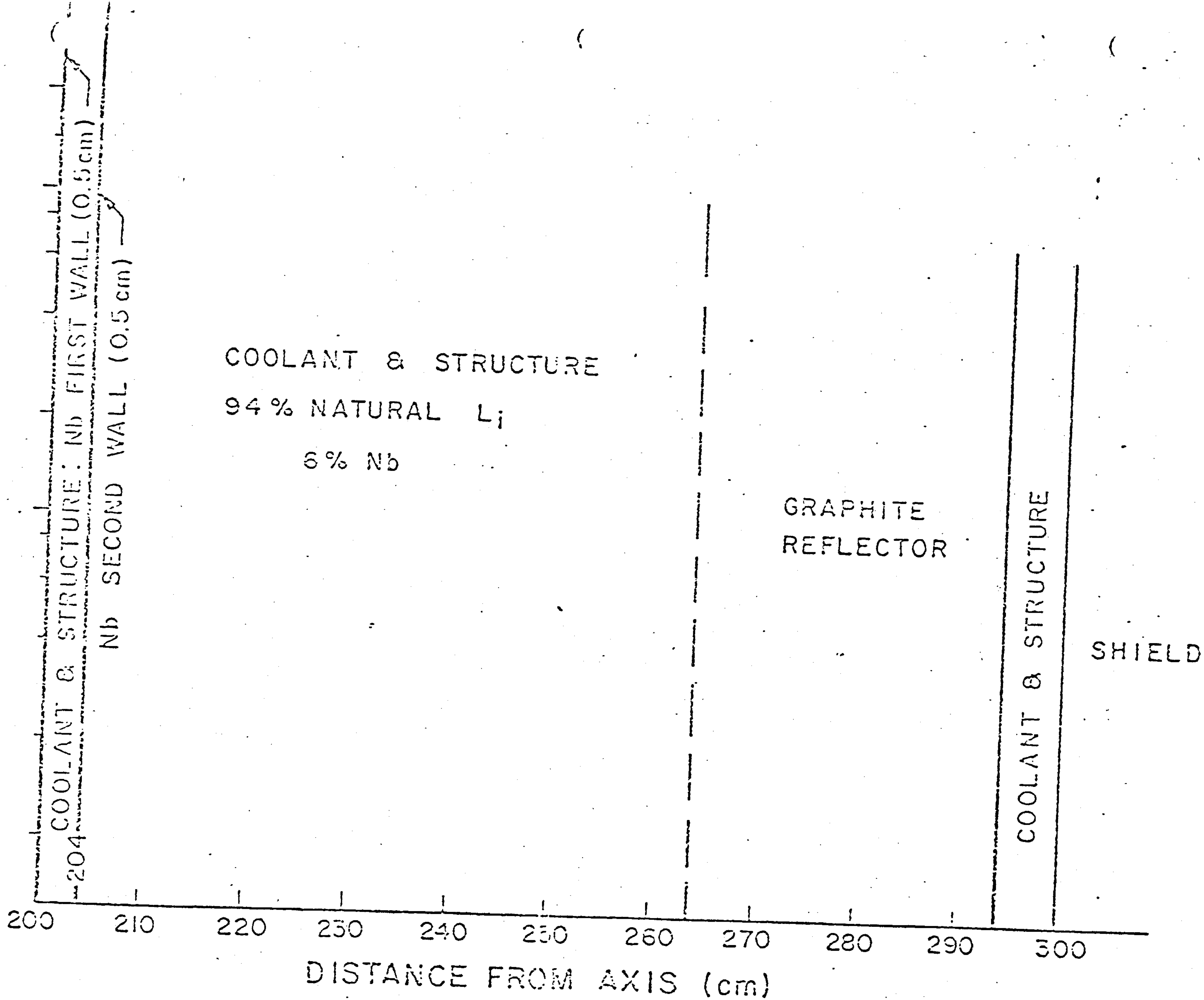
REACTION	IGNITION TEMPERATURE	$n\tau$
$D + T \rightarrow He^4\ (3.5) + n\ (14.1)$	4.5 keV	$5 \cdot 10^{13}\ cm^{-3} sec$
$D + D \rightarrow He^3\ (0.8) + n\ (2.6)$ $D + D \rightarrow T\ (1.0) + p\ (3.0)$	28 keV	$10^{15}\ cm^{-3} sec$
$D + He^3 \rightarrow He^4\ (3.7) + p\ (14.7)$	22 keV	$7 \cdot 10^{14}\ cm^{-3} sec$
$n + Li^6 \rightarrow He^4\ (2.1) + T\ (2.7)$	—	—
$n + Li^7 \rightarrow n + He^4 + T - (2.5)$	—	—

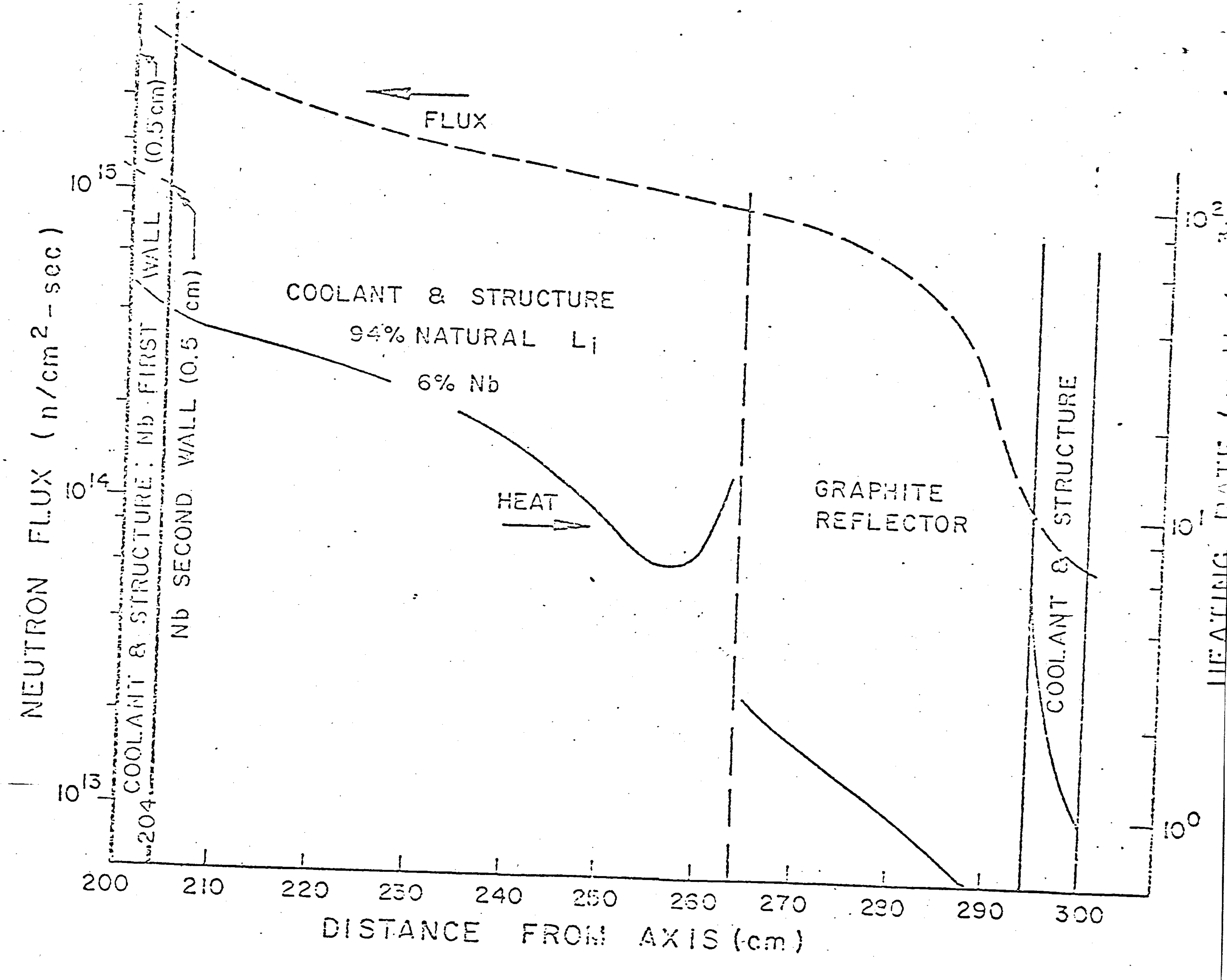
FIGURE 1

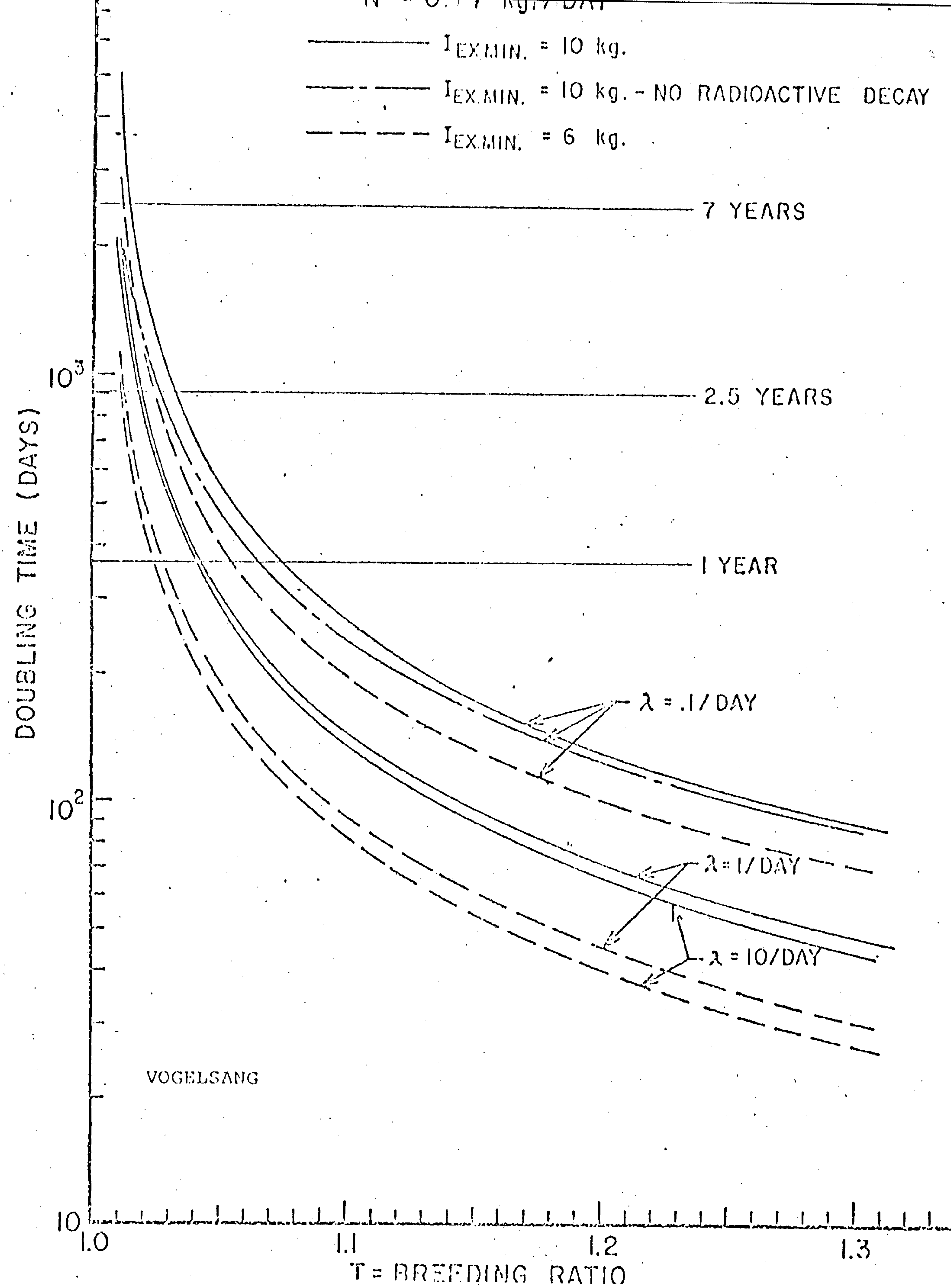


FUSION REACTOR CROSS SECTION

FIGURE 2


COOLANT & STRUCTURE : Nb FIRST WALL (0.5 cm)
Nb SECOND WALL (0.5 cm)
204
COOLANT & STRUCTURE
94 % NATURAL Li
6 % Nb
GRAPHITE
REFLECTOR
COOLANT & STRUCTURE
SHIELD
200
210
220
230
240
250
260
270
280
290
300
DISTANCE FROM AXIS (cm)


FLUX
COOLANT & STRUCTURE
94% NATURAL Li
6% Nb
HEAT
GRAPHITE
REFLECTOR
COOLANT & STRUCTURE
COOLANT & STRUCTURE : Nb FIRST WALL (0.5 cm)
Nb SECOND WALL (0.5 cm)
204
NEUTRON FLUX (n/cm2 - sec)
10 15
10 14
10 13
10 2
10 1
10 0
200
210
220
230
240
250
260
270
280
290
300
DISTANCE FROM AXIS (cm)


I EX.MIN. = 10 kg.
I EX.MIN. = 10 kg. - NO RADIOACTIVE DECAY
I EX.MIN. = 6 kg.
7 YEARS
2.5 YEARS
1 YEAR
λ = .1/DAY
λ = 1/DAY
λ = 10/DAY
DOUBLING TIME (DAYS)
10³
10²
10
1.0
1.1
1.2
1.3
T = BREEDING RATIO
VOGELSANG

SWELLING IN MOLYBDENUM

Kulcinski - PNL

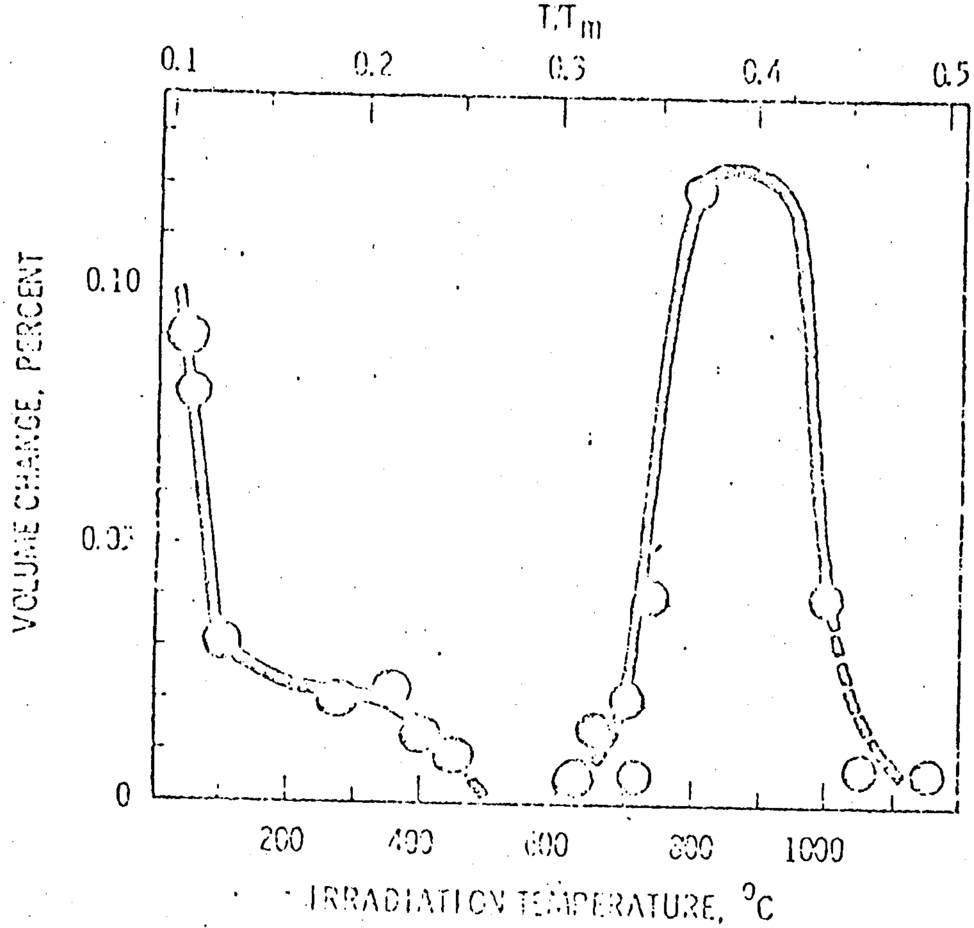
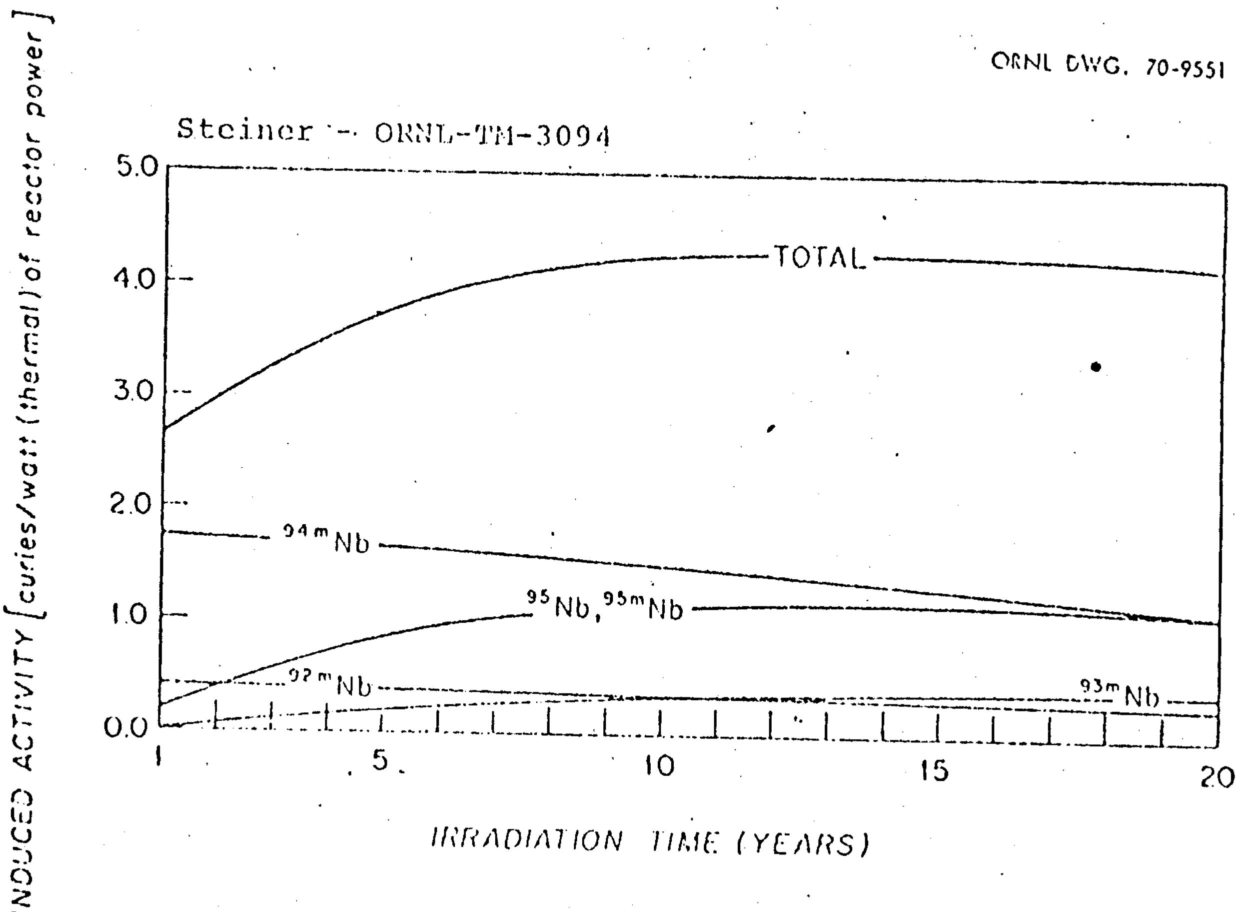


FIGURE 6



ORNL DWG. 70-9551
Steiner -- ORNL-TM-3094
INDUCED ACTIVITY [curies/watt (thermal) of reactor power]
5.0
4.0
3.0
2.0
1.0
0.0
TOTAL
94m Nb
95 Nb, 95m Nb
92m Nb
93m Nb
1
5
10
15
20
IRRADIATION TIME (YEARS)

FIGURE 7

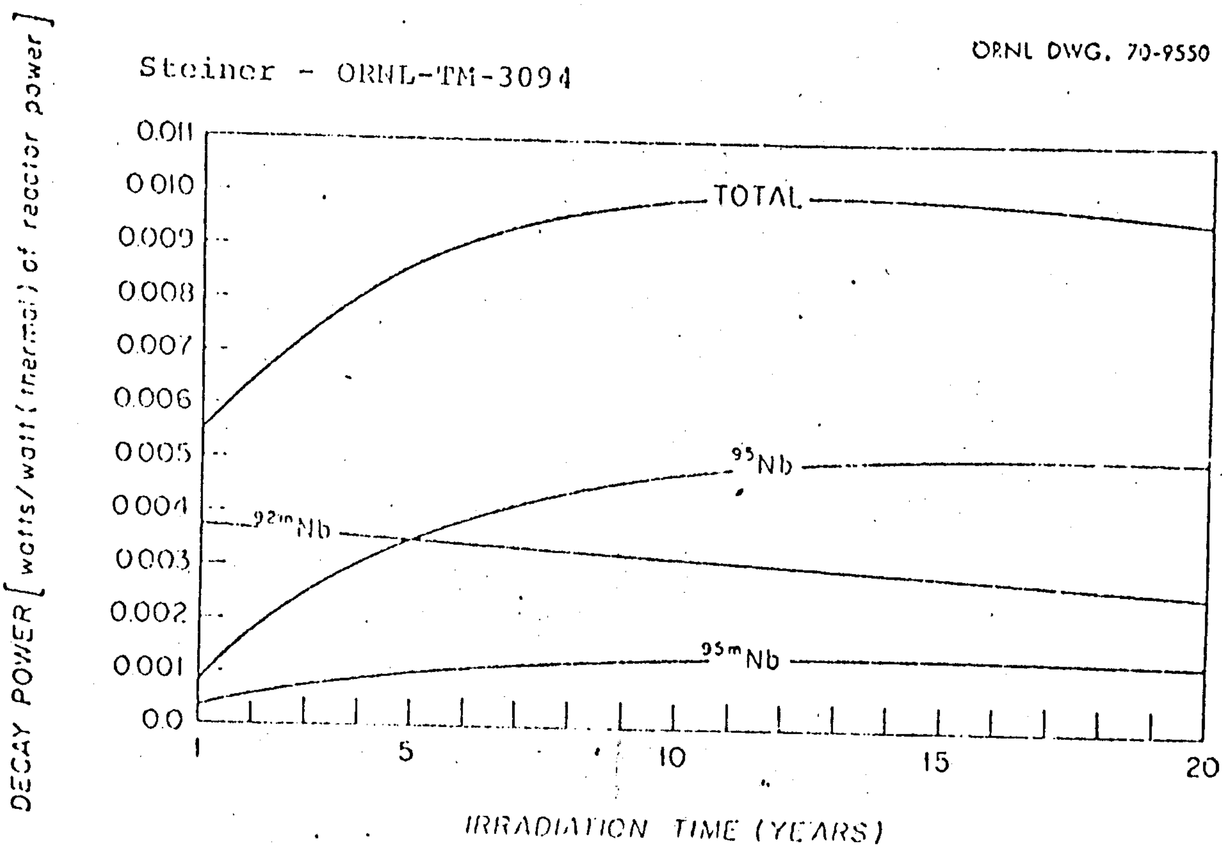

Steiner - ORNL-TM-3094
ORNL DWG. 70-9550
DECAY POWER [watts/watt (thermal) of reactor power]
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.0
TOTAL
95Nb
92mNb
95mNb
1
5
10
15
20
IRRADIATION TIME (YEARS)

FIGURE 8

Fraas - ORNL-TM-2358