Hazards for pregnant women and nursing mothers working in nuclear fusion laboratories

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Objective: Investigating some biological side effects of radiations resulted from fusion reaction experiments in DAMAVAD Tokamak.
Materials and Methods: The absorbed dose of the personnel in DAMAVAND Tokamak was measured using LIF dosimeters and analyzed.
Results: In DAMAVAND in areas near the forbidden zone around this device the level of the received dose is very high (more than 6 mSv for each 100 shots) and in regions around the control panel and shielding room that personnel usually attend the level of the effective absorbed dose is about 1.16 mSv for each 100 shots. In each working period in DAMAVAND Tokamak about 100 shots are being done weekly. Hence, each of the personnel will absorb about 5×1.16= 5.8 mSv that is very high for a short period (5 days).
Conclusion: managers of the fusion laboratories must govern personnel's duties properly and arrange female working conditions in critical situations of their lives.
Therefore, it is recommended that the contribution of the pregnant women must not be more than 60 shots per month and it is better to be decreased to 55, because they absorb some extra doses from the experiments with other device while attending to the building of laboratory.

Introduction

It is known that the conventional energy sources (fossil, nuclear fission, hydroelectric &wood) are limited in amount and can not cover the increasing demand of the world for energy. Nuclear fusion offers good solutions in this regard. In the fusion reactions, the nuclei of light atoms like Hydrogen combine with each other and make heavier atoms like Helium. Proper fuels for fusion are the isotopes of Hydrogen and other light atoms such as Lithium and Boron (1–5). This method has not the difficulties such as limitation of the sources, environmental problems, nuclear wastes and so on. Also the possibility of the implosion or notable accident in a fusion reactor is almost zero. Despite of the noted benefits for nuclear fusion, its commercial use is not practical yet. From the total experimental and theoretical investigations, it is concluded that the Deutrium–Tritium compound is the best fuel for fusion, but because the Tritium is radioactive and is not found in nature, in little research laboratories (specially for developing countries) and universities the pure deuterium has been used as fuel. The Deuterium–Tritium and Deuterium–Deuterium reactions are (1, 2, 6):

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$$D^2 + T^2 \rightarrow n\ (14.07\ MeV) + He^4\ (3.52\ MeV)$$
$$D^2 + D^2 \rightarrow n\ (2.45\ MeV) + He^4\ (0.82\ MeV)$$
$$D^2 + D^2 \rightarrow p\ (3.02\ MeV) + T^4\ (1.01\ MeV)$$

For self–contained fusion reactions in D–T mixture, it must be heated to temperatures higher than 100 million Kelvin degrees. In such temperatures the fuel will be on plasma form (the forth state of the matter) (1, 2,5,6). For pure Deuterium self–contained fusion needs higher temperatures.

In the past six decades several devices such as θ–Pinch, Z–Pinch, Plasma Focus, Laser Fusion, and Tokamak have been designed and constructed for reaching to a commercial fusion reactor. Tokamak is the most important one in latter series (1, 2).

In D–D & D–T fusion reactions in addition to high energy neutrons, large amounts of hard and soft x–rays will be generated because of synchrotron and bremmschtralung radiations, which all may cause important health dangers for operators (1–3, 6–9). By proper designation of a shield around the radiation source, it is possible to reduce the received dose by personnel to negligible levels. The principal parts of the shields are: water for slowing the fast neutrons, Boron or polyetilen for absorption of slow neutrons and lead for absorption of x–rays. The total necessary thickness of shield is about 1 meter and the major part of it is water (8, 10, 11).

Usual radiations received by human include:

1) *Natural radiations, such as cosmic rays and the rays that originate from the radioactive materials of the outer layer of the earth, building materials and ex-isting radiating particles in water and air.*
2) *Radiations from man–made sources like x–rays used for therapies, and other industries that use ionizing rays, radiations from wastes of nuclear reactors and so on.*

The existing rays in nature are separated into 2 groups of ionizing & non–ionizing (11, 12). The International Commission on Radiological Protection (or ICRP) separated the ionizing rays into 2 groups (11, 12):

1) *Direct ionizing rays including charged particles such as alpha, beta, proton and heavy ions.*
2) *Indirect ionizing rays including x–rays, gamma and neutron.*

The energy of photons of non–ionizing rays is not enough for doing ionization in the biological tissues. Absorption of non–ionizing electromagnetic waves by organic tissues makes them warm as the most important biological effect of these rays. Some other effects of them results from the chemical reactions and the mechanism of the others are not still identified (12). Radiochemical effect causes the variations in chemical components of the cells. As water makes the major weight and volume part of the cells, the main part of this effect is related to interactions between rays and water molecules generating new molecules due to interactions of the ions and resulted free radicals. One of the most important resulting toxic materials is H_2O_2 (11–13).

Considering different types of the non–ionizing rays it is observed that visible light, ultraviolet, infrared and laser have not direct effects on fetus. The effects of the ultrasonic waves & very low frequency electromagnetic waves on human body are very small. For microwave and radio frequency waves the biological effects are very tortuous.

Especially at frequencies from about 100 MHz to 3 GHz they have high influences on the internal organs because the major part of the energy is absorbed by internal organs. Their penetration depth in the human body is more than light rays and their effects specially in lower frequencies is not restricted to skin and eye (11, 12).

Nuclear fusion laboratories like DAMAVAND & ALVAND Tokamaks in Tehran face with strong magnetic fields.

The effects of rays on biological tissues can be categorized as below (11,12):

1) ***Certain effects:*** *When the amount of the received dose is high enough, the certain effects will appear and cause the damaging of a lot of cells. There is always a threshold level and at levels higher than threshold, intensity of certain effects will increase with the amount of received radiation. Maintaining the dose under the threshold level is the way of protection against certain effects such as skin inflammation, blood cell count alterations and cataract.*
2) ***Possible effects:*** *These effects may or may not happen on any dose level, but in the case of occurrence it is dependent to the dose level. The most important side effects are different types of cancer that generally maybe recognized several years after the first radiation absorption or even occur in next generation. The incidence of this type of effects is*

very low in general population and seems to be negligible in comparison to other risk factors in daily life such as smoking.

The International Commission on Radiological Protection (ICRP) determined the maximum permissible effective dose to be 2 mSv per year for general population and 20mSv per year for personnel working with rays and this dose must not be received abruptly(11). However, it is the maximum limit and in practice the principle of ALARA (As Low As Reasonably Achievable) must be observed, it means that radiation exposure (individual radiation exposure as well as collective dose equivalent) must be kept as low as reasonably achieved. This principle has been legislated with respect to the possible effects. For this purpose 3 tasks must be carried out: Decreasing the time of receiving radiation to minimum, increasing the distance from the radiation source to maximum and shielding around the radiation source (11,12). Based on the new principles received dose of the pregnant women from the beginning to full term pregnancy must not exceeds 4 mSv and not to be received in the critical months of pregnancy (the first 3 months).

Therefore, the maximum permissible dose for each month excluding the critical months & the last month of pregnancy is about 0.8 mSv. It must be noted that although ICRP determined this maximum permissible dose, but in experience absorb doses should be as less as possible with special attention to the points in below:

1) *Pregnant women do not receive this maximum permissible dose abruptly in order to avoid critical effects of the radiation.*
2) *They must not attend at critical months & the last month of pregnancy in the experiments.*
3) *During lactation, the same permissible dose is defined for mothers.*

Regarding the principles of the radiation protecttion, specially for decreasing the dangers that relate to pregnant personnel such as radiation absorption by the fetus or absorbed radiation in the milk, female personnel must inform the event of pregnancy in order to change their working condition, if necessary. The pregnancy is not a reason for desertion the job and can be compensated through readjustment of working conditions in order to restrict the absorbed radiation by the fetus to the levels below the permissible limit (12).

The effects of radiation on fetus are more prominent in higher doses and/or younger fetus. These effects are especially considerable in the first 4 weeks of fetal growth. Regarding the sensitivity to radiation fetal period is divided into 3 sequences (12,13):

1) ***Very sensitive period:*** *In the first two weeks of pregnancy the most important effect is spontaneous abortion. Considering the results from patients under radiotherapy, fortunately the probability of this matter generally is 100% or nothing i.e. either abortion happens because of radiation or the embryo continues to grow uneventfully.*
2) ***Sensitive period:*** *Organogenesis happens in the first three months of pregnancy. In this period ionizing radiations may cause urinary tract malformation, mental retardation, abortion, dental disorder, dwarfism and other skeletal disorders. Abortion may be the result of hormonal imbalance due to radiation.*
3) ***Fetal period:*** *After the third month of pregnancy the fetus is moderately resistant to radiation. Although high dose radiation may cause unsolicited effects such as: microcephaly, dwarfism, sterility, leukemia and some other types of malignancy.*

Similar to some other chemical and physical factors, radiation can destroy base arrangement of DNA molecules conducting to incongruity in germinal cells including single and double chain fractures resulting in gene mutations.

In this paper the results of measuring the average value of absorbed dose by personnel in DAMAVAND Tokamak is reported and some recommendations is given for safety of the pregnant women working in this laboratory.

Experiments and Method

In the Plasma Physics & Nuclear Fusion Research School of the Nuclear Science & Technology Research Institute of "Atomic Energy Organization of Iran" two small size Tokamak devices (ALVAND & DAMAVAND) and one medium size Plasma Focus Facility (DENA) are in operation. In order to investigate some biological side effects of them, the absorbed dose of the personnel in DAMAVAND Tokamak was measured and analyzed. In experiments with our Tokamaks, we used Hydrogen instead of Deuterium for generating plasma because Deuterium is expensive and in these little devices, notable fusion reactions do not happen. Therefore, it is better to generate hot plasmas by using Hydrogen as working gas for the study of physics and properties of plasmas. It must be noted that the estimations based on the experimental results of "Dena" Plasma Focus Device have shown that the absorbed dose by personnel is so much lower than the maximum permissible effective dose and can be neglected. Also, ALVAND is a little Tokamak and the emitted radiation from it is very small in comparison to DAMAVAND. Therefore, our research activities are concentrated on DAMAVAND.

In the experiments of the DAMAVAND, the thermoluminescence crystal dosimeters (TLD's) have been used to measure the equivalent absorbed dose of the personnel. These devices include: TLD–100, TLD–400 & TLD–700 and their material is LiF. The reason of selecting this crystal is its effective atomic number (8.1) which is close to the effective atomic number of soft tissue (7.4) (14). Therefore, these dosimeters are considered to be equivalent with the soft tissue and the equivalent absorbed dose in soft tissue is estimated directly by them. Another advantage of this type of dosimeters is their high resistance against the environmental parameters such as temperature and moisture. Because of their small sizes it is possible to install them in different points of the body and get the equivalent effective dose of a specific organ (11, 14).

Results

Unfortunately during November and December 2005 inattention to protection principles resulted in some undesirable bio effects in two expert technicians working in DAMAVAND laboratory. They made about 5000 shots in two subsequent months without sufficeent protection. The first complications of the radiation absorption such as vertigo and nausea appeared in the first month. After one month i.e. about the first 3000 shots, some more obvious complications appeared in the form of skin eruptions. Other manifestations included alopecia and thyroid function disorders.

At the end of second month the film badges showed the absorbed dose resulting from about 5000 shots to be more than 27 mSv that was more than maximum permissible effective dose (20 mSv).

The case of alopecia was documented to be the result of an immune disorder. Dermatologic symptoms resolved completely in one year while taking cyclophosphamide as an immunosuppressor. The thyroid function disorder included hyper and hypothyroidism in the same person resembling immune disorder of thyroid gland and lasted for at least four years and the patient was symptom free in recent three months.

Discussion

Averaging the experimental results in DAMAVAND shows that in areas near the forbidden zone around this device the level of received dose is very high (more than 6mSv for each 100 shots). Fortunately, laboratory personnel mostly do not attend this region. With increasing the distance from device the radiation absorption dose decreases and in regions around the control panel and shielding room that personnel usually attend the level of the effective absorbed dose is about 1.16 mSv for each 100 shots (14). Considering the ICRP recommended maximum permissible dose of 20 mSv/year (12,15) it is estimated that each of personnel can attend these regions during about 1700 shots per year (140 shots/month). Also, as mentioned before, 20 mSv is the maximum limit. In practice the absorbed dose must be much less than it. In each working period (3–5 days) in DAMAVAND Tokamak about 100 shots are being done. Hence, each of the personnel will absorb about 1.16 mSv. According to health physics references the level of the permissible dose for pregnant women is 4 mSv from beginning until full term pregnancy (13) and specially in the critical months (the first 3 months) of pregnancy their received dose must be as low as possible. Therefore, it is recommended that they only attend in experiments from 4^{th} until 8^{th} month of pregnancy. It means that they can receive the permissible dose in 5 months and the average value of this permissible dose is 4/5=0.8 Sv per month that is equal to the absorbed dose in 60 shots. It is better that their contribution be a little less than this value (for example, 50 shots) because they absorb some extra doses from the experiments with DAMAVAND Tokamak and DENA Plasma Focus device while attending the building of laboratory.

The number of shots per year in DAMAVAND Tokamak is more than permissible threshold (more than 2000). As in DAMAVAND and our other laboratories transportation of the peripheral components such as power supplies and control systems to further distances from the main devices seems not to be cost effective, the level of the absorbed dose of the personnel must be decreased in other ways such as:

1) *Decrement of the time of absorption by lowering the number of attended shots for each person and serializing the personnel (especially when someone reaches dangerous internal regions during the main-problems of laboratory experiments including: difficulties in some parts of the magnetron system,*

turning on and off the feedback circuit, testing the capacitor bank during the discharge and so on).

2) *Proper shielding.*

It must be mentioned that ALVAND and DAMAVAND are small Tokamaks and Dena is a medium size Plasma Focus device. Therefore, the value of emitted radiation from them is very small in comparison to large devices. For example, the maximum reported number for generated neutrons in carried experiments on Dena is about 10^9 neutrons/shot, whereas in large size devices values up to 10^{13} neutrons/shot have been measured, just similar to the measured values of the emission for other rays (x–rays, electron beams, ion beams, and so on) (16) .

Accordingly, absorbed dose of the personnel will increase similarly and it must be tried to decrease it by using the 3 principles of the radiation protection. But the time duration for attendance of personnel can not be less than a lower limit. When there are large number of personnel that replace each other in different experiments, it will not be proper from the economical view. Also, it will amaze the personnel and overlap their duties. Therefore, the best solution for this problem is to increase the distance from the devices as more as possible & blocking the radiation by designing proper shields.

Conclusions

Considering the hazards of radiation for women specially radiation absorption by fetus and lactating ladies, managers of the fusion laboratories must govern personnel's duties properly and arrange working conditions of female personnel in critical situations of their lives according to the principles of radiation protection.

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