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Application of the Selected Countermeasures for Animal Products to a Dynamic Food Chain Model in a Nuclear Emergency

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Abstract

The methodology for the application of the principles of radiation protection on the selected countermeasures in linking with a dynamic food chain model DYNACON was studied using the cost and benefit analysis and its application results were analyzed in terms of net benefit. The considerations focus on the simple and easy countermeasures to carry out in the first harvest after the deposition for animal products, such as the ban of food consumption and the substitution of clean fodder. The net benefit of the selected countermeasures depended on a variety of factors such as foodstuffs, radionuclides, starting time and performing duration of countermeasures. The methodology used in this study may serve as a basis for the planning and preparedness of long-term countermeasures as well as the rapid decision of countermeasures against the contamination of agricultural ecosystems in a nuclear emergency.

1. INTRODUCTION

Radioactive materials released into the environment due to a nuclear accident lead to the contamination of agricultural ecosystems, thereby resulting in economic and social damages as well as health risks by the consumption of contaminated foodstuffs. The competent authorities responsible for radiation protection should be prepared with systematic methods based on the principles for mitigating radiological consequences to the public. The basic principles of radiation protection being recommended by international organizations are summaried as justification of action and optimization of protection[1,2].

The contamination level of radionuclides in foodstuffs is essential information for implementing countermeasures. It is strongly dependent on the date (or season) on which deposition of radioactive materials occurs due to a different growth stage of the plant species. Therefore, different countermeasures may be applied according to the date of deposition. The contamination level of radionuclides in foodstuffs can be determined through the prediction of a model from radioactivity on the ground as well as direct measurements of radioactivity in foodstuffs. In view of the rapid control of foodstuffs, the implementation of countermeasures based on a prior prediction will probably be more effective, especially in the control of animal products produced continuously like milk and beef. A dynamic food chain model DYNACON[3], which is a module for assessing ingestion dose in Korean real-time dose assessment system FADAS[4], has been developed to predict time-dependent radioactivity in foodstuffs from the radioactivity on the ground considering Korean agricultural conditions.

In this study, the methodology for the application of the principles of radiation protection on the selected countermeasures in linking with DYNACON was studied, and its application results were discussed. Using the cost and benefit analysis, the net benefit of the selected countermeasures was quantitatively estimated in terms of avertable doses and monetary costs. Among the important attributes concerning the final decision of countermeasures, the some intangible attributes such as social and political factors were not considered. The considerations focus on the simple and easy countermeasures to carry out in the first harvest after the deposition for animal products, such as the ban of food consumption and the substitution of clean fodder.

2. MATERIAL AND METHODS

In a nuclear emergency, decision-aiding techniques may be used to assist in justifying the action and optimizing the protection. The oldest and perhaps the most straightforward tool of decision analysis in radiation protection is the cost and benefit analysis where net benefit, ΔB , is quantified in terms of avertable dose and monetary costs by implementing countermeasures.

$$\Delta B = \Delta Y - X \qquad (1)$$

where

ΔY = cost equivalent of the avertable dose by implementing the countermeasure,

X = monetary cost of implementing the countermeasure.

The cost equivalent of the avertable dose by implementing the countermeasure, ΔY, is given by :

$$\Delta Y = \alpha \cdot \Delta H \qquad (2)$$

where

α = monetary cost assigned to unit avertable dose,

ΔH = avertable dose by implementing the countermeasure.

The α value based on a human capital approach is approximately proportional to the country's average annual GNP (Gross National Product) per head[1]. In this study, the α value of 10,000 US \$ Sv^{-1} was used on the basis of annual GNP per head in 1996.

The time-dependent radioactivity in foodstuffs after unit deposition (Bq kg^{-1} per Bq m^{-2}) was predicted using DYNACON for long-lived radionuclides ^{137}Cs ($T_{1/2}$ = 30 years) and ^{90}Sr ($T_{1/2}$ = 29 years), which are critical radionuclides associated with ingestion pathways in the accidents of nuclear power plants. It was assumed that the deposition occurs on August 15 when pasture is in fully developed stage. In 1996 consumer prices, it was ssumed that the cost per mass of foodstuffs is 1.0\$ L^{-1} and 12.0\$ kg^{-1} for milk and beef, respectively[5]. The cost of fodder is approximately 0.2 \$ kg^{-1} and the replaceable (pasture) weight as clean fodder is 10 kg d^{-1} and 5.2 kg d^{-1} for dairy cow and beef cow, respectively[5,6]. The production rate of milk and the mass of meat per animal were assumed to be 10 L d^{-1} and 300 kg, respectively[1].

3. RESULTS AND DISCUSSION

In DYNACON, the radioactivity in animal products is modelled by considering the variation of radioactivity in pasture and soil ingested by animals. After the substitution of clean fodder, the variation of radioactivity in animal products, $C(t)$ (Bq kg^{-1}), can be simply expressed by :

$$C(t) \;=\; C^{*}\, e^{-(\lambda_b+\lambda_d)t} \tag{3}$$

where

C^{*} = radioactivity in animal products at starting time of substitution (Bq kg^{-1}),

λ_b = biological excretion of animal products ($=\ln 2/T_{1/2,b}$) (d^{-1}),

λ_d = radioactive decay constant (d^{-1}).

For milk, the net benefit of countermeasures was estimated on the basis of the dose resulting from the consumption of milk produced from one animal over one year after the deposition. The net benefit from the substitution of clean fodder (ΔB_s) and the ban (ΔB_b) can be estimated by :

$$\Delta B_s \;=\; \alpha \cdot H_M \cdot (1-f) \;-\; V_f \cdot b_f \cdot \Delta T \tag{4}$$

$$\Delta B_b \;=\; \alpha \cdot H \cdot (1-f) \;-\; P \cdot b \cdot \Delta T \tag{5}$$

where

H_M = integrated dose resulting from the consumption of milk produced from one dairy cow over one year without the countermeasures $\left(= P \cdot e(50) \cdot \int_0^{1yr} C(t)\; dt,\;\; \text{Sv animal}^{-1}\right)$,

V_f = intake rate of replaceable clean fodder (kg (animal · d)$^{-1}$),

b_f = cost of clean fodder (US \$ kg^{-1}),

P = production rate of milk (kg (animal · d)$^{-1}$),

f = relative ingestion dose (ratio of dose with the countermeasure to that without the countermeasure, dimensionless),

ΔT = performing duration of the countermeasure (d).

Table 1 shows the net benefit of the countermeasures for milk as a function of the substituting or banning duration with 10 d delay after the deposition of 100 kBq m^{-2}. Although the integrated radioactivity over one year after the deposition and the relative dose reduction after the countermeasures are similar for both radionuclides, the net benefit for ^{90}Sr was distinctly higher than that for ^{137}Cs due to a higher dose factor. It means that the introduction of countermeasures for milk in case of ^{90}Sr deposition may be more easily justified than that in the case of ^{137}Cs deposition. The net benefit of substitution was greater than that of the ban. For ^{137}Cs, the substituting duration representing maximum net benefit, *i.e.*, $d(\Delta B)/dt=0$, was approximately 30 d. It is so called the optimized substituting duration. The substitution for more than 30 d made the net benefit decrease gradually because of the increasing cost of substituting clean fodder. The ban was not justified in all cases for ^{137}Cs. For ^{90}Sr, the substitution was required for a long duration as compared with ^{137}Cs. The substitution may be required for more than 100 d to produce maximum net benefit. The justifiable banning duration was approximately 50 d, and the banning duration to produce maximum net benefit was approximately 20 d.

For beef, it was assumed that clean fodder is substituted until slaughter time. Also, it was assumed that the benefit achieved by an increase of meat mass from the deposition to slaughter time is cancelled with the cost of non-replaceable fodder imposed during the same duration. The net benefit from the substitution of clean fodder can be estimated by :

$$\Delta B_s = \alpha \cdot H_B^* \cdot (1-f) - V_f \cdot b_f \cdot \Delta T \qquad (6)$$

where

H_B^* = dose resulting from the consumption of one beef at starting time of substitution ($= M \cdot e(50) \cdot C^*$, Sv animal^{-1}),

M = the mass of meat per animal (kg animal^{-1}).

Table 2 shows the net benefit for beef as a function of substituting duration of clean fodder with 10 d delay after the deposition of 100 kBq m^{-2}. The net benefit for ^{137}Cs was much greater than that of ^{90}Sr due to high radioactivity in two orders of magnitude and short half-life as compared with ^{90}Sr. Therefore, the introduction of countermeasures for beef in the case of ^{137}Cs deposition may be much easily justified than that in the case of ^{90}Sr deposition. For ^{137}Cs deposition, the substitution was required for a long duration, if practicable. For ^{90}Sr deposition, the justifiable substitution duration was approximately 60 d, and the optimized substitution duration was approximately 30 d.

4. CONCLUSIONS

In the present study, the methodology for the application of the principles of radiation protection on the selected countermeasures for animal products in linking with DYNACON was studied, and its application results were analyzed. The net benefit of the selected countermeasures for animal products, which are simple and easy to carry out in the first harvest, was qualitatively estimated using the cost and benefit analysis for the deposition on August 15 when pasture is in fully developed stage. It depended on a variety of factors such as radionuclides, foodstuffs, ground, starting time and performing duration of the countermeasures. The substitution of clean fodder was an effective countermeasure. It was obvious that a fast reaction after the deposition is more important than performing duration of the selected countermeasures. The introduction of countermeasures for milk in the case of ^{90}Sr deposition was more easily justified than that in the case of ^{137}Cs deposition, while it is opposite for beef.

Since these conclusions are situation-specific, they should not be construed as applying generically. Also, one has to be aware that these results are based on model calculations. In the case of a real accident, model calculations have to be compensated through the comparison with measured radioactivity in foodstuffs for the planning and preparedness of reliable long-term countermeasures. The methodology used in this study may serve as a basis for the rapid decision of countermeasures against the contamination of agricultural ecosystems in a nuclear emergency.

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Table 1. Net benefit for milk as a function of substituting or banning duration with 10 d delay after the deposition of 100 kBq m^{-2} (US $).

Substituting or banning duration (d)	^{137}Cs		^{90}Sr	
	Substitution (ΔB_s)	Ban (ΔB_p)	Substitution (ΔB_s)	Ban (ΔB_p)
10	62.6	-4.8	170.6	130.8
20	89.5	-50.7	254.3	170.8
30	95.5	-120.0	290.0	148.6
40	91.1	-201.8	301.1	92.6
50	85.0	-287.9	308.4	22.5
60	78.2	-374.7	314.3	-50.3
70	71.5	-461.4	321.5	-124.4
80	65.4	-546.9	327.5	-197.2
90	58.6	-634.9	334.7	-271.3
100	51.3	-722.8	340.6	-344.0

Table 2. Net benefit for beef as a function of substituting duration of clean fodder with 10 d delay after the deposition of 100 kBq m^{-2} (US $).

Substituting duration (d)	^{137}Cs	^{90}Sr
10	1,118.7	3.0
20	2,082.2	4.5
30	2,933.7	4.9
40	3,587.0	3.7
50	4,197.2	2.6
60	4,738.4	0.1
70	5,227.9	-3.2
80	5,648.4	-6.4
90	6,025.9	-11.3
100	6,291.3	-15.5