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EFFECTS OF COBALT-60 EXPOSURE ON HEALTH OF TAIWAN RESIDENTS SUGGEST NEW APPROACH NEEDED IN RADIATION PROTECTION

W.L. Chen □ National Yang-Ming University, 155 Li-Nong Street, Sec. 2, Pei-tou, 112 Taipei, Taiwan

Y.C. Luan, M.C. Shieh, S.T. Chen, H.T. Kung, K.L Soong, Y.C. Yeh □ Nuclear Science & Technology Association, 8F, No. 182, Sec. 2, Beisin Road, Sindian City, Taiwan

T.S. Chou, S.H. Mong, J.T. Wu, C.P. Sun □ Nuclear, Biological and Chemical Protection Society, 11F-5, 110 Cheng-Tu Road, Taipei ,Taiwan

W.P. Deng □ Institute of Biological Materials, Taipei Medical University, 250 Wu-Hsing Street, Taipei, Taiwan

M.F. Wu, M.L. Shen □ National Taiwan University, Taipei, Taiwan 10764

□ The conventional approach for radiation protection is based on the ICRP's linear, no threshold (LNT) model of radiation carcinogenesis, which implies that ionizing radiation is always harmful, no matter how small the dose. But a different approach can be derived from the observed health effects of the serendipitous contamination of 1700 apartments in Taiwan with cobalt-60 ($T_{1/2}$ = 5.3 y). This experience indicates that chronic exposure of the whole body to low-dose-rate radiation, even accumulated to a high annual dose, may be beneficial to human health. Approximately 10,000 people occupied these buildings and received an average radiation dose of 0.4 Sv, unknowingly, during a 9-20 year period. They did not suffer a higher incidence of cancer mortality, as the LNT theory would predict. On the contrary, the incidence of cancer deaths in this population was greatly reduced—to about 3 per cent of the incidence of spontaneous cancer death in the general Taiwan public. In addition, the incidence of congenital malformations was also reduced—to about 7 per cent of the incidence in the general public. These observations appear to be compatible with the radiation hormesis model. Information about this Taiwan experience should be communicated to the public worldwide to help allay its fear of radiation and create a positive impression about important radiation applications. Expenditures of many billions of dollars in nuclear reactor operation could be saved and expansion of nuclear electricity generation could be facilitated. In addition, this knowledge would encourage further investigation and implementation of very important applications of total-body, low-dose irradiation to treat and cure many illnesses, including cancer. The findings of this study are such a departure from expectations, based on ICRP criteria, that we believe that they ought to be carefully reviewed by other, independent organizations and that population data not available to the authors be provided, so that a fully qualified epidemiologically-valid analysis can be made. Many of the confounding factors that limit other studies used to date, such as the A-bomb survivors, the Mayak workers and the Chernobyl evacuees, are not present in this population exposure. It should be one of the most important events on which to base radiation protection standards.

Address correspondence to Y.C. Luan, Nuclear Science & Technology Association, 8F, No. 182, Sec. 2, Beisin Road, Sindian City, Taiwan. E-mail: nbcsoc@hotmail.com

I. INTRODUCTION

An extraordinary incident occurred 22 years ago in Taiwan. Recycled steel, accidentally contaminated with discarded cobalt-60 sources ($T_{1/2}$ = 5.3 y), was formed into construction steel for more than 180 buildings containing about 1700 apartments, and also public and private schools and small businesses, in Taipei City and nearby counties. About ten thousand people occupied these buildings for 9 to 22 years. While this construction occurred during 1982-84, most of the buildings were completed in 1983.[1, 2] In this preliminary assessment, we consider 1983 to be the first year of the incident. The radioactive state of the buildings was gradually discovered, beginning on July 31, 1992.[2] Less than 100 contaminated apartments were identified in 1992. The number increased to more than 200 in 1993; then to a total of 896 in 1995, 1206 in 1996, and 1277 in 1997. An intensive research program was conducted in 1998, and more than 1600 apartments were finally documented by the Atomic Energy Council (AEC) of Taiwan. After approximately four cobalt-60 half-lives, most of the apartments now have relatively low levels of radiation, less than 5 mSv (500 mrem) per year, and are still in use today. Half of the residents in apartments with high radiation levels have been evacuated, starting in 1996. They all lived in these buildings for at least nine years, with some staying as long as 22 years.

II. MEASUREMENT OF APARTMENT DOSE RATES

Dose-rates were measured with very accurate GM survey meters calibrated in dose-equivalent units, μSv/hr. Doses were carefully determined using an AEC procedure specifically designed for this project. For evaluating the average dose to the residents, their average occupancy time was conservatively taken as 12 hours in living rooms, 8 hours in bedrooms, and 4 hours at other locations (i.e., half of the residents assumed to be outside 8 hours/day).[1] The dose evaluations were used to classify the apartment dwellers into three cohorts, based on contamination level (average dose rate), for government remedial measures and care:[3]

• High contamination cohort (~11%):	> 15 mSv/y
• Moderate contamination (~9%):	5-15
• Low contamination cohort (~80%):	1-5

III. NUMBER OF PEOPLE AFFECTED

More than 1600, who lived in apartments that were highly and moderately radioactive (dose rate > 5 mSv/y), were registered, and more than 2400, in the apartments with low radioactivity (1 to 5 mSv/y).

AEC studies, beginning in 1992, indicated that the average dose rate in 20% of the apartments was more than 5 mSv/y. Assuming the remaining 80% of the apartments had the same occupancy rate, the number in those apartments was estimated to be $1600 \times 0.8/0.2 = 6400$, giving a total of approximately 8000 residents.

A kindergarten child, who had occupied a radioactive classroom, died of leukemia in 1996, and another pupil died of leukemia in 2000. As a result, about two thousand students were registered as affected. In international symposia in Taiwan and Japan, specialists recommended increasing the number of affected people to approximately 10,000. Therefore, we used this number in this assessment.

The number of affected people is open to some discussion. The Radiation Safety and Protection Association in Taiwan (RSPAT) estimated that the total number of residents might as high as 15,000, but such a figure would include persons present in the public areas of the buildings who would have received only very short-term exposures.

IV. ESTIMATE OF DOSES IN APARTMENTS

An estimation of the integrated doses to the residents was necessary to assess the health effects of the radiation exposures. Several dose reconstruction studies have been carried out and reported in national and international journals. Some used thermo luminescent detectors (TLDs) at different positions of the body;[4] some used suspended TLDs in air;[5] some relied on TLD necklaces,[6] and some used Rondo phantoms.[7] Our evaluation used a simplified method to approximate the doses received by the residents and to modify the AEC doses, estimated by the task team from the Institute of Nuclear Energy Research (INER), with reasonable factors.

In December 1996, the AEC estimated that 20% of the residents received an annual (1996) dose in the range from 5 to 160 mSv, therefore, 80% of the residents received a dose of less than 5 mSv.[1] A crude estimate of the average 1996 dose for each cohort is:

- High cohort (~11%): $(160 + 15)/2 =$ 87.5 mSv
- Medium cohort (~9%): $(15 + 5)/2$ 10
- Low cohort (~80%): $(5 + 1)/2$ 3

Therefore, in 1996, the mean annual dose received by all the residents was about 13 mSv (i.e., $87.5 \times 0.11 + 10 \times 0.09 + 3 \times 0.80$), and the maximum dose was 160 mSv.

For the year 1983, we calculate the mean dose to be about 74 mSv and the maximum to be about 910 mSv. Adjusting the mean dose for a residency factor of 0.7 and a correction of 0.95 to TLD doses gives 49 mSv.

The individual mean dose from 1983 until 2003 was 0.40 Sv for all cohorts. For the high cohort, the mean dose was 4 Sv, with a maximum of 6 Sv, assuming half of the residents moved out in 1996. The doses are summarized in Table 1.

A detailed reconstruction of individual doses for residents of medium and low contamination apartments was recently published.[8] These reconstructed doses are several times lower than the maximal doses assessed by the AEC.

V. OBSERVED HEALTH EFFECTS

Medical Examinations

Residents with annual doses greater than 5 mSv received medical examinations in AEC contracted hospitals,[1] and those with annual doses of 1 to 5 mSv were provided examinations by the city of Taipei.[9] Residents of apartments that had normal background radiation (< 1 mSv/y) received medical examinations on request. Additionally, thirteen of the highly exposed residents were sent to Mazda Hospital in Hiroshima, Japan, to undergo the medical examination protocol conducted for the survivors of the atomic bombing.[10]

Health Effects

Although many of the residents had received quite high total doses of radiation, the medical examinations did not reveal the presence of any harmful radiation sickness syndromes—as were seen in survivors of the atomic bombing or in acutely irradiated reactor workers following the Chernobyl accident.[11, 12]

When the residents in one of the highly radioactive buildings sued the government for compensation, the concerned hospitals testified that they had no evidence that the radiation had caused any harmful effects.[1] When a kindergarten child who had attended a school with a radioactive window frame later died of leukemia and another pupil who was in a radioactive classroom also died of leukemia, the media reported the opinion of a radiation specialist that a few children were shorter in stature

TABLE 1: Annual and accumulated doses

Cohort	Number of people	Mean annual dose in first year 1983 (mSv)	1983 to 2003 individual dose (mSv)	1983 to 2003 "collective dose" (person-Sv)
High	1,100	525	4000	2,660*
Medium	900	60	420	378
Low	8,000	18	120	960
Averaged	10,000	74	600	6,000
Adjusted	10,000	49	400	4,000

*From July 1996, 50% of residents relocated.

than average and that some children showed indications of abnormal thyroids. These reports were not substantiated in our study.

Cytogenetic Damage

Because many chromosomal aberration studies were conducted on the Japanese atomic bomb survivors and on reactor workers following the Chernobyl accident, a number of chromosome aberration analyses were conducted on irradiated residents. All those who received annual dose rates greater than 15 mSv/y or accumulated doses greater than 1 Sv were asked to give a blood sample for chromosomal aberration studies. Analyses of these samples were carried out by the INER Laboratory.

No significant aberrations were observed, compared with test results of new employees of INER.[13] Reports were also published in the AEC annual R & D achievements symposium and in several international journals. The reports indicated that no chromosome changes and no dose-effect relationships were observed.[14, 15] One group of specialists, studying the residents in the Min-Sheng Villa—a highly radioactive building, found that the frequency of micronuclei formation was higher than that seen in controls and that the lymphocytes of another group of residents were different from those of the control group.[16, 17]

The interpretation of these findings is that low-dose and low-dose-rate gamma radiation from any source of radiation induces cellular changes, but there is no indication that these changes produced any adverse health effect. The overall conclusion of the AEC is that the chromosome aberration studies indicated that groups that received higher doses seemed to have lower levels of chromosome aberrations.[1]

Comparison with ICRP Models

The "collective dose" of the exposed population is approximately 4000 person-Sv. Had the exposure been short term (acute), the linear no-threshold (LNT) hypothesis of radiation carcinogenesis would predict $4000 \times 7.8 \times 10^{-2} = 312$ "stochastic" *excess* cancer fatalities, with a latency of approximately 20 years. Since it was a chronic exposure, a hypothetical risk reduction factor between 2 and 10 could be applied.[18]

From the experience of the Life Span Study (LSS) of the Radiation Effects Research Foundation (RERF), such hypothetical excess solid cancers deaths would be difficult to discern from the natural (spontaneous) cancer deaths of the residents, especially after 20 years. But *excess* leukemia deaths, which have a much shorter latency period, should be readily observable, especially among those who received a total dose greater than 1 Sv.[19] Based upon the ICRP model, 70 *excess* leukemia and solid cancers deaths would be reasonably expected after 20 years, in addition to the number of spontaneous cancer deaths. In fact, a total of only two leukemia and only five solid cancer deaths were actually observed. The AEC did not attribute the two (child) leukemia deaths to radiation exposure.

Assuming that the exposed population has the same age distribution as the population of Taiwan in 2002, about 40% of them were in the reproductive age range, and their collective dose would be 40% × 4000 = 1600 person-Sv. For this dose, the standard ICRP model predicts that $1600 \times 1.3 \times 10^{-2}$ or 21 children with observable congenital malformations would be born, in *excess* of the usual number of children born with such hereditary defects.[18] In fact, only three children in total were born with congenital heart disease, and they are still in good condition. No other congenital malformations were observed.

In these comparisons, the health effects observed strongly contradict the predictions of the ICRP models. The actual number of cancer deaths and the actual number of congenital malformations are many times *smaller* than the numbers expected based on the natural incidence of cancer mortality and natural incidence congenital malformations (see below), whereas the ICRP models predict numbers in *excess* of the natural incidences.

Comparison of Health Effects: Exposed vs Non-Exposed

The mean cancer mortality in Taiwan during the period 1983-2002 (Figure 1) is 116 deaths per 100,000 person-years.[20] (The rising incidence is likely due to the increasing life expectancy of the population as in most modern countries.) Assuming that the cancer mortality in 2003 is the same as in 2002, the number of spontaneous cancer deaths that would be expected among the 10,000 people, over 20 years, would be 232 deaths (10,000 × 20 × 116/100,000).

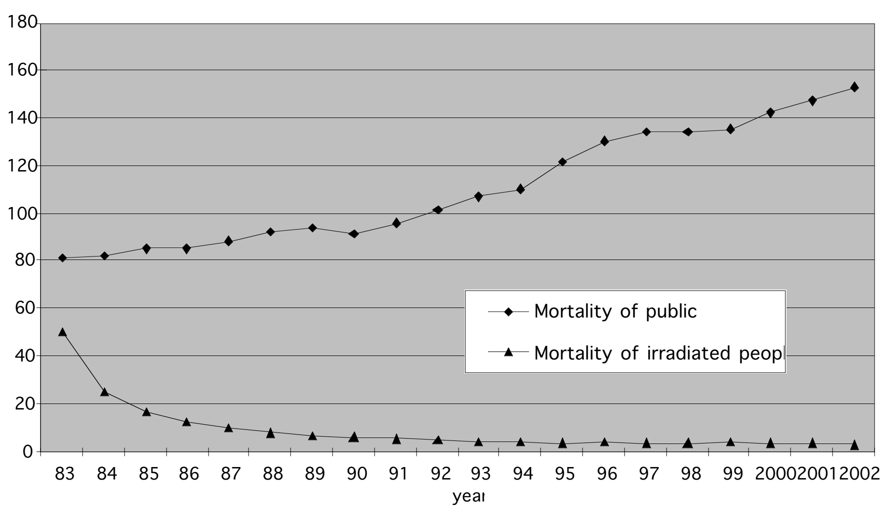

FIGURE 1. Cancer mortality of the general public and of the irradiated people

TABLE 2: The natural, predicted and observed results in 20 years

Result	No.	Notes
Natural (expected) cancer deaths	232	Includes 4-5 leukemia
Natural (expected) congenital malformations	46	All congenital diseases
ICRP model predicted cancer deaths	302	232 natural plus 70 caused by radiation
ICRP model predicted congenital malformations	67	46 natural plus 21 caused by radiation
Observed cancer deaths	7	3% of general public cancer death rate
Observed congenital malformations	3	6.5% of general public congenital disease rate

Based on the investigation conducted by the RSPAT,[10] the total number of cancer deaths among these residents is only 7 in 200,000 person-years or 3.5 deaths per 100,000 person-years—only 3% of the rate (i.e., 116) expected for the general population!

The cancer mortality rate of the exposed population is also shown in Figure 1. Both the cancer deaths and the cancer mortality rate differences have high statistical significance ($p < 0.001$). The mortality rate from all causes was not studied; only cancer mortality and congenital malformations were of interest in this population.

While there is no complete, official prevalence rate for congenital malfunctions in Taiwan, some estimates are available. Based upon partial official statistics[20] and hospital experiences described in the media, there are about 23 cases per 1000 children, including two infant deaths attributed to congenital malfunctions in 1000 births, about two cases of Down's syndrome and about 0.4 cases of cerebral palsy per 1000 children.

Assuming a population of 2,000 children under the age of 19 among the residents, an incidence of about 46 children with congenital abnormalities would be expected. Yet in fact, only three children, who are still in good condition, were observed to have congenital malformations (heart disease).[10] The congenital abnormality rate for this population appears to be only 6.5 percent of the rate for general population (3/46). This difference is also highly significant ($p < 0.001$).

Table 2 summarizes the comparisons between exposed and non-exposed populations.

VI. DISCUSSION

The results of this study strongly suggest that whole-body chronic irradiation, in the dose rate range that the apartment residents received, caused no symptomatic adverse health effects, such as radiation sickness, or the increased cancer or increased congenital disease that are predicted by ICRP theories. On the contrary, those who were exposed had lower incidences of cancer mortality and congenital malformations.

In such studies, it is very important to examine the confounding factors that could possibly affect the comparisons being made between the exposed population and the general population of Taiwan. Are there qualitative differences in the two populations? Although it is a critical factor, the age distribution of the exposed population has not yet been determined, and it was assumed that the age distribution of the exposed population is the same as that of the general Taiwan population.

However, the 2000 students who were included definitely have a different distribution. Those in kindergarten are ages 3-5, and those in elementary school are 6-12. Their average cancer mortality is only 2-4 persons/100,000. They should not be included in the affected cohort, and should be subjects of a separate study. If the students are not included, the expected and predicted cancer death rates in the 8000-person cohort would be 20 percent lower than those in the 10,000 person cohort, and the number of cancer deaths would be five, as shown in Table 3. But the number of congenital malformations will remain the same because the 2000 students were not born in the affected apartments.

Another important consideration is standard of living, as this affects diet and quality of medical care. This factor was reviewed and it determined that the residents have approximately the same distribution of income as the general populace.

How can such dramatic reductions in cancer and congenital defects be explained?

Radiation scientists, medical practitioners and toxicologists have long recognized beneficial health effects from acute, whole-body exposures to low doses and from chronic exposures to low dose rates of ionizing radiation. Many scientists over the past century have studied this phenomenon of radiation hormesis. It is an adaptive response of biological organisms to low levels of radiation stress or damage—a modest overcompensation to a disruption—resulting in improved fitness. Recent assessments

TABLE 3: The natural, predicted and observed results in 20 years (students not included)

Result	No.	Notes
Natural (expected) cancer deaths	186	Includes 4-5 leukemia
Natural (expected) congenital malformations	46	All congenital diseases
ICRP model predicted cancer deaths	242	186 natural plus 56 caused by radiation
ICRP model predicted congenital malformations	67	46 natural plus 21 caused by radiation
Observed cancer deaths	5	2.7% of general public cancer death rate
Observed congenital malformations	3	6.5% of the general public congenital disease rate

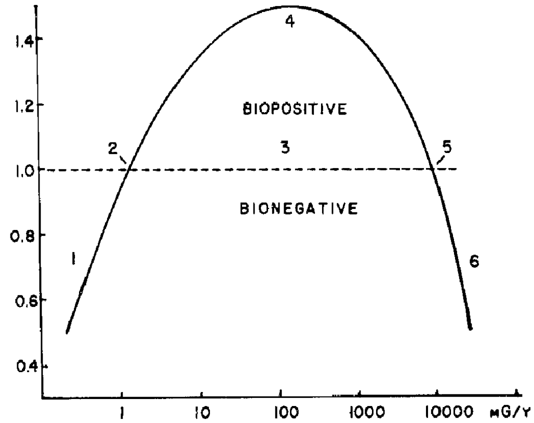

FIGURE 2. Idealized, complete dose-response curve. The ordinate indicates approximate responses compared with the controls. The abscissa suggests mammalian whole-body exposures as mGy/y. The numbered areas are: (1) deficient, (2) ambient, (3) hormetic, (4) optimum, (5) zero equivalent point, and (6) harmful.

of more than a century of data have lead to formulation of a well-founded scientific model.[21–24]

Living organisms have very capable defense mechanisms, which are significantly affected by radiation.[24] The typical, non-linear shape of the effect is shown Figure 2.[23] Unlike the adverse effects of increased rates of cancer and congenital disease associated with chronic dose rates greater than about 10 Gy/year or acute doses greater than about 0.3 Sv, which are "stochastic" and have long latency periods, the beneficial effects of low doses are typically observed very soon after the initial radiation exposure and affect all the individuals exposed. In the case of chronic exposure, significant biopositive effects are observed over a wide range of dose rate: four orders of magnitude, from 1 to 10,000 mGy/y. Hence similar beneficial effects would be expected for all three exposure cohorts. Recent studies on humans suggest that acute exposures can be employed to treat cancers and prevent metastases.[25]

The concept of beneficial health effects following any exposures to ionizing radiation is very controversial, because the LNT hypothesis of radiation carcinogenesis, which is based on the Hiroshima-Nagasaki LSS linear extrapolation to zero dose, is very well established. However, the evidence presented in this assessment is quite different than the LSS evidence and more relevant to chronic population exposures to long-lived radioactive contamination. Accordingly, an official, government-sponsored detailed epidemiological study ought to be carried out on these residents to address uncertainties arising from the assumption made in this study, and such studies have been promised.[26–28]

Methods used for dose estimation in this review are simplified. They are probably as accurate as the estimation methods used in the review of the effects of radiation on the health of the Japanese atomic bomb survivors and of the public affected by the Chernobyl accident. In 1997, Cardarelli *et al*, estimated the doses could be up to five hundred times the natural background rate.[4] In 1998, Tung *et al*, estimated that the maximal annual dose rate in 1983 was as high as 600 mSv/y and that, in 1996, the individual doses ranged from few mSv to several Sv.[5] Even so, we believe that refined dose assessments would not significantly affect the conclusions.

VII. CONCLUSIONS AND RECOMMENDATIONS

The observation that the cancer mortality rate of the exposed population is only about 3 percent of the cancer mortality rate of the general public (2.7 percent if the student are excluded) is particularly striking and is consistent with the radiation hormesis model. This assessment suggests that chronic radiation may be a very effective prophylaxis against cancer.

The findings of this study are such a departure from those expected by ICRP criteria that it is important that they are carefully reviewed by other, independent organizations and that population data not available to the authors be provided, so that a fully qualified epidemiologically valid analysis can be made. Many of the confounding factors that limit other studies used to date, such as the A-bomb survivors, the Mayak workers and the Chernobyl evacuees, are not present in this population exposure. It could be and should be one of the most important studies on which to base radiation protection standards.

The LNT hypothesis of radiation carcinogenesis results in the notion that all exposures to any amount of radiation are potentially harmful. Because this hypothesis is very well established and because many strong radiation protection organizations are in place, scientists and government officials are very reluctant to seriously consider the implications of the radiation hormesis phenomenon, which has very important public health consequences.

The medical evidence from this exposure clearly suggests that current radiation protection policies and standards are inappropriate. We therefore recommend that the radiation protection authorities change them to accurately reflect the actual benefits and hazards of exposures to radiation. This would have very important consequences for all the nuclear risk assessments carried out and the public attitudes toward all applications of nuclear and other technologies that involve ionizing radiation. Fear of small doses of radiation is the basis for political barriers blocking the construction of nuclear power plants and nuclear waste management facilities.

Medical treatments with long-term low dose rate ionizing radiation or with acute low dose exposures could be employed to prevent and control serious illnesses with no symptomatic side effects.[25] For example, the evidence suggests that an annual supplement of whole-body radiation—50 mSv in several fractionated exposures—to elderly volunteers would stimulate their defences and provide protection against the scourge of cancer. Unfortunately, physicians are generally not taught and are consequently not aware of the phenomenon and the scientific evidence. In view of the major efforts in most countries to understand cancer and find new treatments and cures, we recommend that all medical scientists pay careful attention to the results of this 20-year "serendipitous experiment" on this exposed population.

Over the past 25 years, medical and radiation biology scientists in Japan have been carrying out many studies designed to reveal both beneficial and adverse health effects of low doses of radiation on animals and humans.[29] Scientific investigations on low-dose effects have been underway in recent times in many other countries. However, in most cases, the experiments are either not designed to detect beneficial health effects or, when such effects are observed, they are ignored.[21] We recommend that radiation biologists and medical scientists pay close attention to studies that indicate evidence of hormetic effects.

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PROFILE OF THE AUTHORS

WL Chen	Director, Department of Medical Radiation Technology, National Yang-ming University; Head, Radiation Protection Department of AEC, and former Head, Health Physics Division of INER
YC Luan	Senior Scientist and Manager of Radiation Protection, NUSTA; consultant to NBC Society, and former Manager, Radioactive Waste Management Plant and Manager, Cobalt-60 Irradiation Plant of INER, AEC
MC Shieh	General Secretary, NUSTA; Professor of National Chung-Kung University, and former Manager, Uranium Conversion Project of INER, AEC
ST Chen	Senior Scientist and Head, Nuclear Reactor Engineering, NUSTA, and former Director, Nuclear Engineering Division of INER, AEC
HT Kung	Senior Scientist and Nuclear Material Manager, NUSTA, and former Manager, Nuclear Fuel Fabrication Plant of INER, AEC
KL Soong	Senior Scientist, NUSTA, and former Senior Scientist and Leading Scientist, Geology and Mineralogy Research Project of INER, AEC
YC Yeh	Secretary General, Chinese Nuclear Society; Senior Scientist, NUSTA, and former Director, Analysis Center of INER, AEC
TS Chou	Head, Radiation Research Group, NBC Society; Professor of Feng Chia University, and former Head, Chemical Engineering Division of INER, AEC
SH Mong	Head, Protection Research Group, NBC Society; former NBC consultant to Saudi Arabia, and Commandant, Army NBC School, Taiwan
JT Wu	Biology Consultant, NBC Protection Society, Taiwan; Professor of Pathology, School of Medicine, University of Utah, USA, and Medical Director, Special Chemistry and Reagent Development Laboratory at ARUP
CP Sun	Board Member, NBC Protection Society, and Assistant Professor of Risk Analysis, National Chiao Tung University

WP Deng Associate Professor, Biological Material Institute, Taipei Medical University, and former Associate Professor, Graduate Institute of Biomedical Materials, Harvard University, USA
MF Wu Professor of Pathology and Director, Animal Testing Center, College of Medicine, National Taiwan University, Taipei
ML Shen Professor, Biometry Division, Department of Agronomy, National Taiwan University, Taipei

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