FACTORS AFFECTING NUCLEAR RESEARCH REACTOR UTILIZATION ACROSS COUNTRIES

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Abstract

In view of the worldwide declining trend of research reactor utilization and the fact that many reactors in developing countries are under-utilised, a question naturally arises as to whether the investment in a research reactor is justifiable. Statistical analyses were applied to reveal relationships between the status of reactor utilization and socio-economic conditions among countries, that may provide a guidance for reactor planning and cost benefit assessment. The reactor power has significant regression relationships with size indicators such as GNP, electricity consumption and R&D expenditure. Concerning the effectiveness of investment in research reactors, the number of reactor operation days per year only weakly correlates with electricity consumption and R&D expenditure, implying that there are controlling factors specific of each group of countries. In the case of less developed countries, the low customer demands on reactor operation may be associated with the failure in achieving quality assurance for the reactor products and services, inadequate investment in the infrastructure for reactor exploitation, the shortage of R&D funding and well trained manpower and the lack of measures to get the scientific community involved in the application of nuclear techniques.

1. INTRODUCTION

The utilization of nuclear research reactors (NRR) worldwide has been going down since the late 1970’s. During the seventies and eighties, 128 NRRs were commissioned instead of 195 shut down, mostly in industrialised countries [1]. This trend persisted during the nineties with 23 reactors commissioned instead of 71 shut down. In the developing world, 40 NRRs were operated in 1980, increasing to 53 by 1990, and during 1990’s 16 reactors were shut down instead of 9 commissioned. NRRs are built and operated only in 25 out of 55 developing countries having populations greater than 10 million. Public attitude toward nuclear technology seems to have been contributing to this declining trend. This situation may have an impact in reactor planning, and a question naturally arises as to whether and in what conditions investment in a NRR is justifiable.

The question becomes most challenging for less developed countries (LDC), where the lack of adequate budget for R&D and the shortage of well trained manpower are typical factors greatly limiting the effectiveness of the investment in NRRs. However, it is in these countries new NRRs are expected to be set up in the future. By achieving some level of development, the investment in NRR becomes feasible and the impact on the socio-economic development can be expected. This paper intends to reveal worldwide trends of reactor utilization in relation to socio-economic conditions that may shed some light for the reactor planning and cost benefit assessment especially in the case of LDCs.

2. RELATIONSHIPS BETWEEN NRR UTILIZATION AND SOCIO-ECONOMIC INDICATORS

A survey of worldwide NRR information [1] reveals a strong variability in reactor utilization across countries in terms of installed reactor power, number of operating facilities and operation records. This obviously reflects the diversity in the size and the level of development of reactor-owned countries [2, 3]. Simple statistical analyses will be used to search possible relationships between indicators relevant to reactor utilization and socio-economic conditions. As to reactor utilization, the capability and the performance of a country are considered. The reactor capability is measured as the total installed power in megawatts (POWER). The reactor performance can be
measured using the number of operation days per year (DAY). For countries having more than one NRR, the highest number of operation days will be chosen. The two selected indicators are relevant in cost-benefit assessment. In fact, the cost increases with POWER, while DAY reflects the volume of demands on reactor operation and hence, the benefit of investment.

Concerning socio-economic indicators the most relevant are the gross national product (GNP). Other indicators which are thought to have relationships with the reactor indicators are the country’s expenditure for research and development (RD) and the country electricity consumption (ELEC). The later was considered to be relevant from the viewpoint that electricity generation may be among national long term goals of the nuclear science development programme. These three indicators characterise the size of the economy (size indicators). To characterise the level of development of a country, per capita (pc) indicators should be considered, namely pcGNP, pcRD and pcELEC. Besides, the educated manpower resource is also an important aspect to be considered. This can be measured as the number of students at the 3rd level per 100,000 inhabitants (EDU). Socio-economic indicators correlate with each other more strongly within each group than between different groups.

The statistics from 57 reactor owned countries worldwide were used for data analysis. The reactor statistics are compiled in the 1998’s IAEA Directory of NRRs [1]. The socio-economic data were taken from the 1993’s Annual Reports by UNDP [2] and UNESCO [3]. Preliminary statistical analyses had revealed seven “outlier countries”, whose research reactors are either too small (Colombia, Finland, Italy, Brazil and Mexico), or too large (Latvia and Uzbekistan) compared to their economy. The exclusion of these outliers from the input data will enhance the significance of statistical relationships which may exist between reactor and socio-economic indicators.

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| TABLE I. CORRELATION BETWEEN SOCIO-ECONOMIC AND NRR INDICATORS |
|---------------------|---------------------|---------------------|---------------------|
|                     | Size indicators     | Development indicators | Reactor indic.     |
|                     | GNP     | RD      | ELEC | pcGNP | pcRD | pcELEC | EDU | MW     | DAY     |
| MW                  | 0.81    | 0.84    | **0.85** | 0.43   | 0.56 | 0.45    | 0.45 | 1      |          |
| DAY                 | 0.49    | 0.52    | **0.58** | 0.34   | 0.34 | 0.42    | 0.30 | 0.57   | 1        |

2.1. Reactor utilization capability

Among the three size indicators, ELEC explains a largest amount of variances of POWER (72%). However, as GNP is the most characteristic indicator of an economy, a statistical relationship between POWER and GNP will be more useful for practical purposes.

Figure 1 displays a scatter plot of POWER vs. GNP. The regression model is

\[
\text{Ln}(\text{POWER, MW}) = -3.16 + 1.19 \text{Ln (GNP, billion USD)}, \quad R^2 = 0.65 \quad (1)
\]

which can explain 65% of the variations in reactor power among 50 reactor owned countries. In view of such a high statistical significance, the simple model (1) can be regarded as a worldwide trend, which simply suggests that an 1% growth of GNP may justify an 1.2% increase in reactor power.
FIG. 1. Scatter plot and regression model of reactor POWER and GNP.

\[
y = 1.19x - 3.16
\]

\[R^2 = 0.65\]

FIG. 2. Reactor POWER and values predicted by model (2).

\[R^2 = 0.76\]
Based on this trend the minimum GNP level that becomes appropriate for establishing a NRR can be estimated. Assume that the reactor power to be installed should at least be 1 MW, then the GNP should not be below 14 billion US$ according to model (1). At present at least 7-8 “non-reactor” countries in the developing world had achieved this GNP level. Also from Fig. 1 it can be speculated, for example, that countries such as Syria, Portugal, Thailand and Australia would have increased their reactor power to meet demands of their economy and in compatibility with the worldwide trend. In fact, a new research reactor of 10 MW will be set up near Bangkok in coming years [4], bringing the Thailand’s data point in Fig. 1 closely to the world regression line.

As the data points in Fig. 1 are rather strongly scattered around the regression line, there should be other socio-economic indicators controlling the variations in reactor POWER. Because socio-economic indicators are inter-correlated, the stepwise multiple regression technique will be used to reveal among seven selected socio-economic indicators the most relevant ones as to reactor power variability. These indicators are ELEC and RD, and the regression model is as follows:

\[ \ln(\text{POWER, MW}) = a + b_1 \ln(\text{ELEC, } 10^9 \text{ kWh}) + b_2 \ln(\text{RD, } 10^6 \text{ USD}), \]

\( R^2 = 0.76 \) \hfill (2)

where

\[ a = (-9.4 \pm 1.9) \quad [t = -5.2, s = 0.000] \] \hfill (3)
\[ b_1 = (0.80 \pm 0.22) \quad [t = 3.6, s = 0.001] \] \hfill (4)
\[ b_2 = (0.44 \pm 0.14) \quad [t = 3.1, s = 0.003] \] \hfill (5)

The regression coefficient/intercept \( a, b_1, b_2 \) are given with standard errors, t-statistics \( t \) and the statistical significance \( s \). According to model (2) only size indicators control the variations in reactor POWER, per-capita indicators do not explicitly show up. The model (2) explains 76% of the variations in reactor POWER among 50 countries, so that the prediction of POWER based on ELEC and RD according to model (2) will be much reliable than using the simple model (1).

2.2. Reactor utilization performance

The reactor utilization performance weakly correlates with socio-economic indicators (Table I). The multiple regression of DAY on seven socio-economic indicators revealed only ELEC (or RD) as a single explanatory variable at 0.05 significance level, which accounts only for 33% (or 27%) of the variations in the number of reactor operation days per year. Therefore, the reactor utilization performance is controlled by factors specific of each group of countries. For example, in some countries reactor utilization is largely linked with the nuclear power and/or nuclear weapons development programmes.

3. FACTORS AFFECTING THE LOW EFFICIENCY OF RESEARCH REACTOR UTILIZATION IN LDCs

The simple models (1, 2) help to estimate the power of the reactor to be set up based on the size of the economy. These models, however, have nothing to do with the benefit that the investment in a research reactor can bring about to the nation. Roughly, the higher the benefit, the more often the reactor in operation is. It was shown that no significant relationship exists between the number of reactor operation days with socio-economic indicators across countries.

In 25 out of 57 countries, research reactors are in operation for less than 75 days (20%) in a year. The under-utilisation is apparent with small reactors in LDCs There are 32 small reactors in the
developing world with power from 30 kW to 3 MW, most of which are unique in the country, so that they are used as multi-purpose for supporting the application of radioisotopes, neutron activation analysis (NAA), and neutron beam experiments. Although these techniques are proven in advanced countries, this may not be the case in LDCs. The low customer demands on reactor operation reflects the failure in achieving quality assurance for reactor products and services that may be associated with a number of factors as discussed below.

3.1. Low neutron flux constraint

Small research reactors gain advantages of low cost and high flexibility at the expenses of satisfying customer demands due to their low neutron fluxes. While a neutron flux of $\sim 10^{13}$ n cm$^{-2}$ s$^{-1}$ is still suitable for NAA and for the preparation of radioisotope tracers for industrial applications [5], such a low neutron flux generally cannot meet demands on radioisotopes for nuclear medicine. The case of Vietnam may best illustrate this situation. The demand on radioisotopes for nuclear medicine has drastically increased (about 120 times) over 15 years since the reconstructed Dalat NRR becoming operational in 1984. The domestically produced radioisotopes stimulated such an increasing demand and monopolised the market for many years. However, at present domestic products account only for about 50% of the total activity (about 350 curies), and such a market share is hard to maintain in the future. As to specific activity, the local $^{99m}$Tc-labelled compounds are also inferior to the imported products. The increase in reactor operation is not expected to significantly improve the situation. Similar problems happen with neutron beam experiments. Prompt Gamma Neutron Activation Analysis with the neutron flux at the target of $\leq 10^7$ n cm$^{-2}$ s$^{-1}$ finds very few practical applications [5].

The low neutron flux constraint often stimulates innovative R&D efforts, such as the installation of neutron spectrum shift devices, the improvement in the detection efficiency of measuring systems etc. However, the most radical option is to upgrade the reactor power. In the case of Vietnam, the size of the economy by the years 2005-2010 would require a reactor of around 5 MW according the worldwide trends (1, 2), and a new reactor is therefore a best option to be considered.

3.2. Inadequate infrastructure for reactor exploitation

As a research reactor is a big R&D investment for LDCs, a situation may happen that too little budget is available for setting up an infrastructure for reactor exploitation. Let take NAA at the TRIGA reactor for illustration. Hundreds of samples can be irradiated in the “Lazy Susan” at the graphite reflector and by using pneumatic transfer systems installed in the reactor core. The treatment of such a large amount of irradiated samples requires a well equipped NAA laboratory for sample preparation, irradiation and gamma spectrometric measurements with an adequate level of automation. Complementary analytical techniques must also be needed. Without sufficient investments for such a laboratory, the advantage of NAA at a TRIGA reactor could not be exploited and NAA would be hard in the struggle for existence among modern multi-element analysis methods, which have become increasingly available nowadays in LDCs.

3.3. Failure in quality assurance for the reactor products and services

Although many reactor related techniques are proven to be effective or commercially advantageous in advanced countries, their successful application in LDCs requires innovative R&D efforts in performing the technology adaptation and quality assurance. In most cases the main reason for the failure in attracting reactor customers is the lack of quality assurance for the reactor products and services due to the shortage of R&D expenditure and the lack of experienced personnel. A “critical mass” of experienced personnel seems to be a precondition for running a research reactor in LDCs.
3.4. Lack of measures to get the scientific community involved in the application of nuclear techniques

A neutron flux of $\sim 10^{13}$ n cm$^{-2}$ s$^{-1}$ can still find many applications in medicine, biology, materials science, geology, hydrology, environmental studies, etc. The low use of a small research reactor usually reflects the situation that the reactor centre has a weak link with the scientific community and leading scientists in the above fields are not much interested in reactor utilization. This situation is rather typical of LDCs, where non-nuclear scientists are little aware of nuclear techniques and great efforts should be made to get them involved in using them. In advanced countries many small research reactors are exploited by universities so that nuclear techniques are at hand of the professional scientific community as well as students. Such a model may be worth to be considered in LDCs.

4. CONCLUDING REMARKS

Although the "golden age" of NRRs had been over and a worldwide declining trend of reactor utilization persists during the last 10-15 years, reactor facilities still play an important role in modern science and technology. For LDCs, a research reactor is a big investment in R&D, so that a careful cost benefit assessment is crucial. This task, however, is not easy as material benefits alone from reactor products and services usually cannot offset material investments, while the gain in human and technological development, which is much important for LDCs, is hard to be measured.

REFERENCES