31st International Conference Nuclear Energy for New Europe
NENE 2022
September 12-15
PORTOROŽ
SLOVENIA

Cross-Section Analysis for Neutron Producing Fusion Reactions in Pre-fusion Power Operation of the ITER Tokamak

Andrej Žohar[1], Anders Hjalmarsson[2], Žiga Štancar[3], Andrej Trkov[1], Gašper Žerovnik[1] and Luka Snoj[1]

[1]Reactor Physic Department, Jožef Stefan Institute
Jamova cesta 39, 1000, Ljubljana, Slovenia

[2]Department of Physics and Astronomy, Uppsala University
Box 516, SE-75120 Uppsala, Sweden

[3]United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre
Abingdon, Oxon OX14 3DB, UK

andrej.zohar@ijs.si, anders.hjalmarsson@physics.uu.se, ziga.stancar@ukaea.uk, andrej.trkov@ijs.si, gasper.zerovnik@ijs.si, luka.snoj@ijs.si

ABSTRACT

In hydrogen and helium fusion plasmas, which are commonly performed in the initial stages of tokamak operation, neutrons can be produced due to reactions of plasma ions with beryllium impurities in the plasma. Neutron emission in such a plasma therefore provides an opportunity to test and commission neutron detectors prior to the full power operational phase. Monte Carlo particle transport simulations with detailed and realistic particle sources are needed to computationally support detector commissioning. To generate the detailed realistic neutron sources, the reaction rates of the neutron emitting reactions must be calculated. One of the crucial parameters for the calculation of reaction rates are the reaction cross sections, which of poor quality or are not available in the evaluated nuclear data libraries for the reactions between ^{9}Be and fast plasma ions. For this reason, cross sections for the main neutron emitting reactions in the initial operating phase of ITER have been prepared and are presented in this paper. The two reactions studied are ^{9}Be(p,nγ)^{9}B and ^{9}Be(^{3}He,nγ)^{11}C. The reaction cross sections were generated based on experimental measurements and physical models describing the interaction of two charged particles. Evaluation of the generated cross sections was also performed to determine the uncertainty, which ranges from 2 % to 40 % for different energy ranges. The determined uncertainty represents an important parameter for the future calculation of reaction rates, namely the uncertainty of the calculated neutron production rates. Since the generated cross sections are not available in any evaluated nuclear data library, the evaluated cross sections will be submitted to the IAEA for inclusion in the next release of the fusion evaluated nuclear data library (FENDL).

1 INTRODUCTION

In the initial phase of fusion reactor operation, non-neutron emitting plasmas, such as the hydrogen plasma, are used to test and commission various systems before power operation with deuterium or deuterium-tritium plasma. For the ITER tokamak, this initial operation stage is called the pre-fusion power operation phase (PFPO) [1]. In ITER, the first wall will be covered with beryllium, some of which will be eroded by the interaction of the plasma ions with the wall. For this reason, beryllium will be present in the ITER plasma as an impurity [2]. Some of the reactions between plasma fuel ions, such as hydrogen or helium, with beryllium impurities emit neutrons. Therefore, neutrons will be emitted in ITER PFPO even though the main plasma is a non-neutron plasma, although the neutron yield will be small compared to the later power operation phase in a deuterium-tritium plasma (10^{14} n/s in ITER PFPO compared to 10^{21} n/s in ITER DT plasma) [2, 3]. Nevertheless, neutrons emitted from such a non-neutron fusion plasma offer the possibility of commissioning diagnostic systems before power operation begins.

To computationally support measurements and the commissioning of diagnostic equipment, reaction cross sections are crucial for the calculation of neutron emission rates [4, 5]. Unlike the major fusion reactions, such as the deuterium-deuterium and deuterium-tritium reactions, for which reaction cross sections are well known and available in evaluated nuclear data libraries, reaction cross sections for plasma ion reactions involving beryllium are less well known and commonly not available at all in evaluated nuclear data libraries or if they are, such as the reaction ^{9}Be(p,nγ)^{9}B which is available in the TENDL-2019 library, the cross sections are of poor quality. This is due to the fact that in current tokamaks the ions do not exceed threshold energies of the reactions or the emitted rates are small compared to main fusion reactions. ITER thus represents a unique tokamak reactor as it will begin operation with high energy ions and beryllium inner wall. The most important neutron-emitting reactions in ITER PFPO are the fusion reaction between hydrogen and beryllium ions (^{9}Be(p,nγ)^{9}B) and the reaction between helium-3 and beryllium ions (^{9}Be(^{3}He,nγ)^{11}C).

In this paper, the cross sections for the reaction between plasma hydrogen and helium ions and beryllium impurities are analyzed based on cross section measurements collected in the EXFOR database [6] and physical models describing the cross sections for interactions between ions. The paper is organized as follows. In Section 2, the physical model used to determine the total cross section from experimental measurements is presented. Section 3 presents the measurements and the generated total cross section for the reaction ^{9}Be(h,nγ)^{9}B while section 4 presents the results of the analysis for the cross section ^{9}Be(^{3}He,nγ)^{11}C. In Section 5, the uncertainty of the created total cross sections is presented based on the uncertainty of the experimental measurements and the uncertainty of the physical model used. In Section 6 reaction between beryllium and secondary ions emitting neutrons are presented.

2 REACTION CROSS SECTION

The total cross section of a reaction between two charged particles can be described using a physics model divided into two parts which are approximately independent of each other. First is the physics of two nuclei approaching each other and the second is the physics, in case the two nuclei approach close enough for interaction. The dominant physics of two nuclei approaching each other is the repulsive Coulomb force and the cross-section is proportional to the tunnelling probability if the energy in the center of mass system is smaller than the Coulomb barrier. The interaction between two nuclei is described by quantum mechanics and is always proportional to the geometrical factor. At low energy both parts are rapidly varying functions of the energy. For this reason the cross section definition at low energy is a product of three separate energy dependent factors:

$$\sigma(E) = \frac{S(E)}{E} \mathrm{e}^{-B_g/\sqrt{E}} \tag{1}$$

Here the $S(E)$ is the astrophysical S-function and B_g is Gamow constant [7]. The motivation for this definition is that the two strong energy dependent factors (describing the Coulomb and interaction parts of the incident nuclei) are separated, leaving the S-function to represent the nuclear part of the probability for the occurrence of nuclear reaction. The S-function is a simple function when the interaction energy of the two nuclei is not near to the resonant energy of the reaction and can be written as division of two arbitrary polynomials [8]:

$$S(E) = \frac{A_0 + A_1 E + A_2 E^2 + ...}{1 + B_1 E + B_2 E^2 + ...} \tag{2}$$

The A and B coefficients are free parameters which are used for fitting the cross section to experimental data and the polynomial degree is chosen to best represent the experimental cross section data with as low as possible degree [9].

For the work presented in this paper the cross fitting function was used to determine cross sections for the two main neutron emitting reactions in ITER PFPO from experimental measurements as the two cross sections are not present in evaluated nuclear data libraries.

3 REACTION ^{9}Be(p,nγ)^{9}B

The total cross section for the reaction ^{9}Be(p,nγ)^{9}B does not exist in evaluated nuclear data libraries. For this reason, the total cross section was made based on eq. (1) and experimental data from the EXFOR database. Two sets of experimental data from the EXFOR database were used for the analysis, namely measurements by E. Teranishi in 1964 and J.H. Gibbons in 1959. The measurements are shown in Fig. 1. It should be noted here that both cross section measurements were without given uncertainty.

Eq. (1) is valid only for cross section regions without resonances. However, as can be seen from Fig. 1, the cross section for the reaction ^{9}Be(p,nγ)^{9}B exhibits a resonance at about 2.5 MeV. For this reason, the fitting process was divided into two parts, namely for energies up to 3 MeV and for energies above 3 MeV. The method used for the fitting process was the

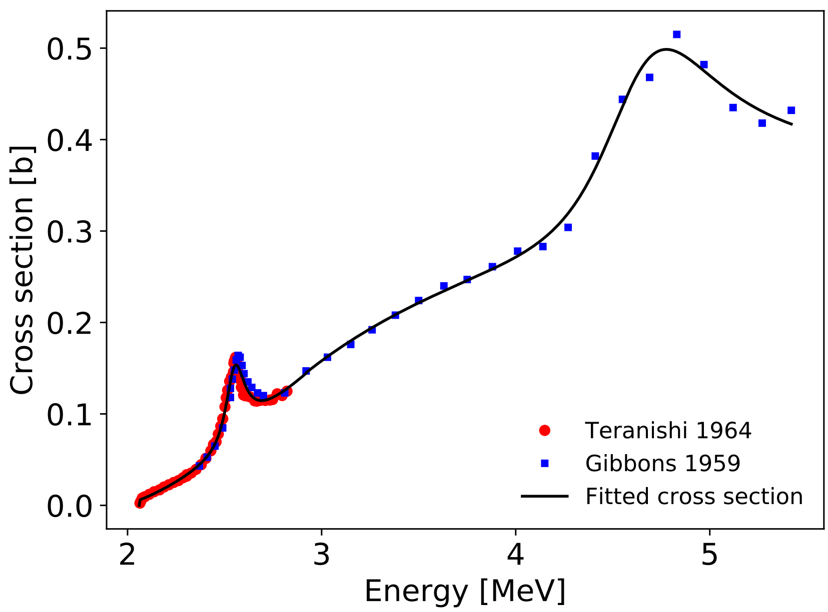

Figure 1: Experimental measurements and fitted cross section function for the ^{9}Be(p,nγ)^{9}B reaction.

non-linear least square method, and the best fit function was determined from the covariance matrix of the fit. For both parts, the best fit of the cross section function to the experimental data with the lowest order of $S(E)$ polynomial was:

$$S(E) = \frac{A_0 + A_1 E + A_2 E^2 + A_3 E^3 + A_4 E^4}{1 + B_1 E + B_2 E^2} \quad (3)$$

Both obtained fitted cross sections were merged into one and the resulting total cross section for the reaction ^{9}Be(p,nγ)^{9}B is presented in Fig. 1 and the obtained coefficient values are presented in Tab. 1.

The reaction has a threshold energy of about 2 MeV with a resonance peak at about 2.5 MeV and a second peak at about 5 MeV. At the time of writing, no measurements are available for energies above 5.5 MeV, so the shape of the obtained cross section for energies between 5 MeV and 5.5 MeV is subject to a larger uncertainty. Despite this uncertainty, the obtained cross section represents the best possible cross section for the reaction ^{9}Be(p,nγ)^{9}B based on the experimental measurements and will be used in the future to support neutron measurements during ITER PFPO.

4 REACTION ^{9}Be(^{3}He,nγ)^{11}C

As in the case of the cross section presented in the previous section, the cross section for the reaction ^{9}Be(^{3}He,nγ)^{11}C does not exist in evaluated nuclear data libraries. Three sets of experimental measurements of the cross section are present in the EXFOR database, performed by S.N. Abramovich in 1984, B. Anders in 1981, and R.L. Harn in 1966. The measurements are shown in Fig. 2. In contrast to the cross section presented in the previous sections, the cross section measurements for reaction of ^{3}He with ^{9}Be have experimental uncertainties.

Visual analysis of the measurements does not indicate a resonance peak in the cross section. For this reason, the function from eq. (1) was fitted over the entire energy range of the

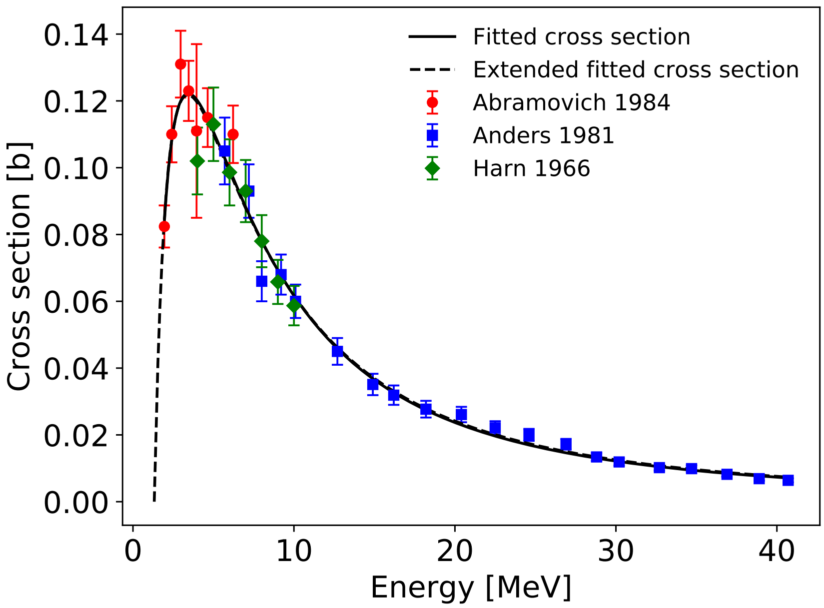

Figure 2: Experimental measurements and fitted cross section function for the ^{9}Be(^{3}He,nγ)^{11}C reaction.

measurements using the same methodology as for the previously analysed cross section. The best fitted $S(E)$ function was:

$$S(E) = \frac{A_0 + A_1 E}{1 + B_1 E + B_2 E^2} \tag{4}$$

The total cross section is presented Fig. 2 and the obtained coefficients are presented in Tab 1.

There are no measurements for energies below 1.95 MeV, therefore the energy dependence of the cross section below this energy is unknown. In addition, the lack of measurements means that the threshold energy for the reaction cannot be determined. To perform computational analysis to support ITER PFPO, the fitted cross section was extrapolated to lower energies to determine the reaction threshold. The reaction threshold was determined at 1.32 MeV and is shown in Fig. 2.

Table 1: Results on best fit parameters used to represent the energy dependence of the total cross section of the studied reactions.

Coefficient	^{9}Be(p,nγ)^{9}B up to 3 MeV	^{9}Be(p,nγ)^{9}B from 3 MeV	^{9}Be(^{3}He,nγ)^{11}C
A_0	0.992	-1.899	-0.496
A_1	-1.910	1.723	0.373
A_2	1.359	-0.545	–
A_3	-0.424	0.065	–
A_4	0.049	0.002	–
B_1	-0.785	-0.430	0.165
B_2	0.154	0.046	0.026

5 CROSS SECTION EVALUATION

The generated reaction cross sections can be used to determine neutron production rates for future ITER PFPO plasmas. An important parameter of the calculated neutron production rates is also the uncertainty of the calculated values due to the uncertainty of the generated cross sections. In order to estimate the uncertainty of the generated cross sections due to the uncertainty of the fitting and the measurements (covariance matrix of the fitting method), an evaluation of the two generated cross sections was performed.

The cross sections generated were evaluated using the covariance matrix generated by the fitting method and the diagonalization method. This method was used to determine the standard deviations of the generated cross section parameters [10]. Using the values of the cross section functions and the obtained standard deviation, 10 000 sets of cross sections were generated by random sampling the cross sectional function parameters with the obtained standard deviation. In some cases, the combination of the sampled cross section function parameters resulted in negative cross sections, however the fraction of such sections was below 0.01 %. These samples were discarded because the cross section values cannot be negative. The uncertainty of the generated cross sections was determined from the distribution of the generated cross sections, and the result is shown in Fig. 3.

For the reaction ^{9}Be(p,nγ)^{9}B, the cross section uncertainty varies from 2 % to 40 %. The largest uncertainty is at the ends of the produced cross sections, i.e. at the reaction threshold energy, around 3 MeV, where the two cross section functions were merged, and at the second peak at around 5 MeV. For the reaction ^{9}Be(^{3}He,nγ)^{11}C, the cross section uncertainty varies from 2 % at low energies to 15 % at the high particle energy.

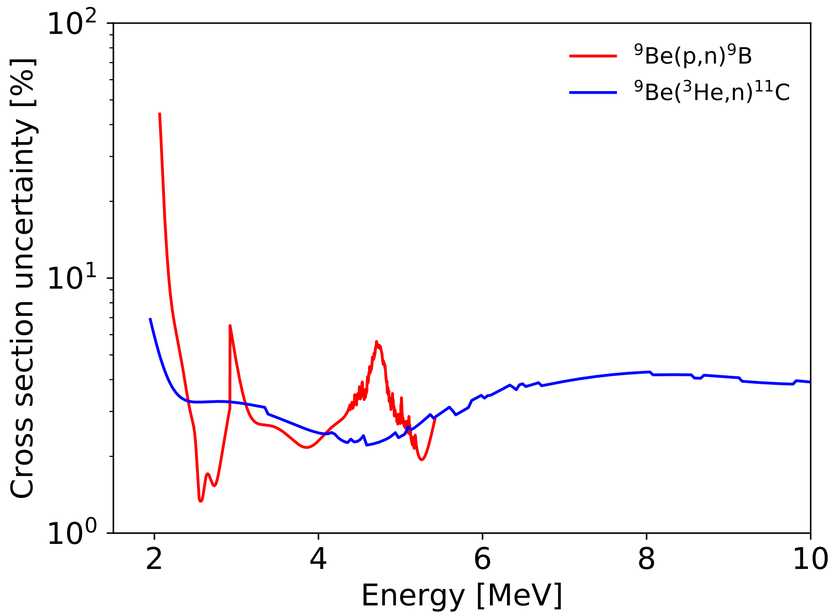

Figure 3: Uncertainty of generated total cross sections due to uncertainty of the fitted function and of the measurements.

6 SECONDARY REACTIONS

In ITER PFPO hydrogen plasmas neutrons will also be produced by reactions of secondary ions produced from reactions of hydrogen with beryllium. The most relevant reactions are [3]:

$$^{9}\text{Be} + p = d + 2\alpha \tag{5}$$

$$^{9}\text{Be} + p =^{6}\text{Li} + \alpha \tag{6}$$

$$^{9}\text{Be} + d =^{10}\text{B} + n + \gamma \tag{7}$$

$$^{9}\text{Be} + \alpha =^{12}\text{C} + n + \gamma \tag{8}$$

Reactions (5) and (6) produce deuterium and alpha particles, which interact with beryllium in the plasma via reactions (7) and (8) to produce neutrons and gamma rays. As with the reactions between beryllium, hydrogen, and helium, the cross sections for the above secondary reactions are not available in evaluated nuclear data libraries, but measurements are available in the EXFOR database. All available measurements for the above reactions are shown in Fig. 4.

The cross section for the reactions ^{9}Be(p,d)2α and ^{9}Be(p,α)^{6}Li are similar in energy dependence and magnitude with small differences at the energy above 100 keV. The cross section for the reaction ^{9}Be(α,nγ)^{12}C contains many resonance peaks at several different energies. The cross section for the reaction ^{9}Be(d,nγ)^{9}B is the simplest of those shown in Fig. 4, but to support ITER PFPO, the cross section for different excited states of ^{9}B needs to be created and evaluated, as this effects the spectra of the emitted neutrons [4].

Because of the complexity of some cross sections, the number of measurement points, and the excited states of the generated ions, the data shown in Fig. 4 have not yet been fitted with a physical model and evaluated.

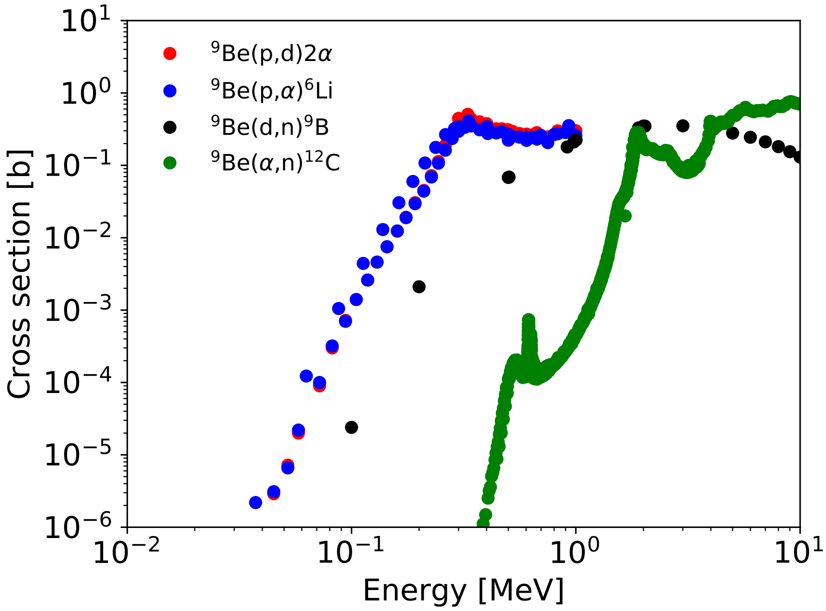

Figure 4: Cross sections for the most relevant secondary fast ions reactions with beryllium impurity.

7 CONCLUSION

Future work to support the ITER PFPO hydrogen and helium plasma discharges and to support the commissioning of the neutron detectors during this ITER operational phase will be creation of a realistic neutron and gamma ray particle source for Monte Carlo simulations. One of the most important parts of creating the particle source is calculating the reaction rates of the particle-emitting reactions to determine the emission profile in the plasma and the energy spectra of the emitted particles.

In this paper the analysis and creations of cross sections for two important ITER neutron-emitting reactions, namely, ^{9}Be(p,nγ)^{9}B and ^{9}Be(^{3}He,nγ)^{11}C which will be crucial for creation of realistic ITER PFPO neutron source. The cross sections were constructed based on experimental measurements and a physical model describing the interactions between two charged particles. The function of the cross sections was determined by fitting the function to experimental measurements. The uncertainty of the two generated cross sections was also evaluated based on the covariance matrix of the fit. The determined uncertainty ranges from 2 % to 40 % and is largest at the edges of the fitted function. The determined uncertainty of the cross sections will provide an important parameter, namely the uncertainty of the calculated reaction rates, for the computational support of ITER PFPO.

In ITER PFPO neutrons will also be produced by the reaction of secondary ions with beryllium impurities. The most important ions are deuterium and alpha particles produced by reactions of hydrogen with beryllium. The cross sections for these reactions are also not included in the evaluated nuclear data libraries and must be determined based on experimental measurements and physical models. For most reactions relevant to ITER PFPO, the cross sections will be generated in the near future to support the creation of a realistic neutron source for ITER PFPO Monte Carlo simulations.

The evaluated cross sections presented in the paper will be submitted to the IAEA for inclusion in the next release of the fusion evaluated nuclear library (FENDL) for use by other researchers in the field of fusion research.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

The work was supported by the Slovenian Ministry of Education, Science and Sport (projects codes: P2-0073 Reactor Physics; P2-0405 Fusion technologies).

REFERENCES

[1] ”ITER Research Plan within the stage approach”, 2018, ITER technical report ITR-18-03.

[2] M. Gatu Johnson, C. Hellesen, E. Andersson Sundén, et al, ”Neutron emission from beryllium reactions in JET deuterium plasmas with ^{3}He minority”, Nuclear Fusion, 50, 2010.

[3] A.R. Polevoi, A. Loarte, R. Bilato, et al, ”Impact of suprathermal ions on neutron yield in the pre-DT phase of ITER operation”, Nuclear Fusion, 61, 2021.

[4] Ž. Štancar, Z. Ghani, J. Eriksson, et al, ”Experimental validation of an integrated modelling approach to neutron emission studies at JET”, Nuclear Fusion, 61, 2021.

[5] A. Žohar, I. Lengar, M. Nocente, et al, ”Modelling of plasma gamma ray sources in large tokamaks”, Fusion Engineering and Design, 163, 2021.

[6] N. Otuka, E. Dupont, V. Semkova, et al, ”Towards a More Complete and Accurate Experimental Nuclear Reaction Data Library (EXFOR): International Collaboration Between Nuclear Reaction Data Centres (NRDC)”, Nuclear Data Sheets 120, 272, 2014.

[7] D. Clayton, ”Principles of Stellar Evolution and Nucleosynthesis”, The University of Chigago Press, 1983.

[8] M. Nocente, G. Gorini, J. Källne, M. Tardocchi, ”Cross section of the d + ^{3}He $\rightarrow \alpha$ + p reaction of relevance for fusion plasma applications”, Nuclear Fusion, 50, 2010.

[9] A. Žohar, ”Analysis and Modelling of Gamma Ray Emission in Large Tokamak Plasmas”, PhD thesis, Faculty of Mathematics and Physics, University of Ljubljana, 2022.

[10] G. Žerovnik, R. Capote, A. Trkov, ”On random sampling of correlated resonance parameters with large uncertainties”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 723, 2013.