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State of the art atmospheric dispersion modelling: should the Gaussian plume model still be used?

For regulatory purposes with respect to licensing and supervision of airborne releases of nuclear installations, the Gaussian plume model is still in use in Germany. However, for complex situations the Gaussian plume model is to be replaced by a Lagrangian particle model. Now the new EU basic safety standards for protection against the dangers arising from exposure to ionising radiation (EU BSS) [1] asks for a realistic assessment of doses to the members of the public from authorised practices. This call for a realistic assessment raises the question whether dispersion modelling with the Gaussian plume model is an adequate approach anymore or whether the use of more complex models is mandatory.

Atmosphärische Ausbreitungsrechnung nach dem Stand der Technik: Sollte das Gauß-Fahnenmodell noch verwendet werden? *Im Rahmen von Genehmigungsverfahren und der Aufsicht über Ableitungen von luftgetragenen radioaktiven Stoffen durch kerntechnische Anlagen wird in Deutschland nach wie vor das Gauß-Fahnenmodell verwendet. Bei der Simulation von komplexen Situationen soll das Gauß-Fahnenmodell jedoch durch ein Lagrangesches Partikelmodell ersetzt werden. Jetzt fordert die neue EU-Richtlinie 2013/59/EURATOM zur Festlegung grundlegender Sicherheitsnormen für den Schutz vor den Gefahren einer Exposition gegenüber ionisierender Strahlung [2] eine realistische Ermittlung der Dosis für Einzelpersonen der Bevölkerung durch genehmigungspflichtige Tätigkeiten. Diese Forderung nach einer realistischen Dosisermittlung wirft die Frage auf, ob die Verwendung des Gauß-Fahnenmodells noch ausreichend ist oder ob komplexere Ausbreitungsmodelle zur Anwendung kommen sollten.*

1 Introduction to regulatory background

Chapter VIII of the EU BSS [1] deals with public radiation exposures, section 1 of this chapter concentrates on the protection of members of the public and long-term health protection in normal circumstances. Article 66 within this section treats the estimation of doses to members of the public. Paragraph 2 of this article, among other things, asks the Member States to "specify those practices for which this assessment" (of doses to members of the public) "needs to be carried out in a *realistic way* and those for which a screening assessment is sufficient". Concerning a screening assessment, Article 65 on operational protection of members of the public, paragraph 2 clarifies, that "discharge authorisations shall take into account, where appropriate, the results of a generic screening assessment *based on internationally recognised scientific guidance*, where such an assessment has been required by the Member State, to demonstrate that environmental criteria for long-term human health protection are met."

1.1 German administrative regulation for operational airborne radionuclide releases

In Germany a general administrative provision [3] (AVV) regulates the dose assessment for long-term operational releases of airborne radionuclides. For the atmospheric dispersion a Gaussian plume model is prescribed within this provision.

1.2 German administrative regulation for releases of conventional air pollutants

Concerning conventional air pollutants, the German first general administrative regulation pertaining the federal immission control act Technical Instructions on Air Quality Control – TA Luft [4] comes into play. In contrast to the Gaussian plume model used for atmospheric dispersion modelling of radionuclides in the AVV, the TA Luft demands a Lagrangian particle model to be used for the atmospheric dispersion modelling. The particle model has to comply with the VDI guideline 3945, part 3 [5]. The reference implementation, AUSTAL2000 software, of the model is available as a free, open source program [6].

2 The Gaussian plume model used in AVV

The Gaussian plume model is an approach to model atmospheric dispersion which is well established. A two dimensional normal distribution is used to estimate the pollutant concentration (radionuclides in case of the AVV) in air. The normal distributions are centered around the main plume axis, which itself is determined by the effective source height, wind speed and wind direction in the effective source height. The standard deviations of the normal distributions are called horizontal and vertical dispersion parameters. These parameters depend on the distance from the source and the atmospheric stability class (see Fig. 1).

The advantages of the Gaussian plume model are that it is quite simple and may be solved with a pocket calculator. There is nearly no risk of a faulty operation and the results are easily reproducible, even by non-experts of atmospheric dispersion modelling.

Shortcomings of the model are that only point sources and only a single particle size can be modelled in one model run.

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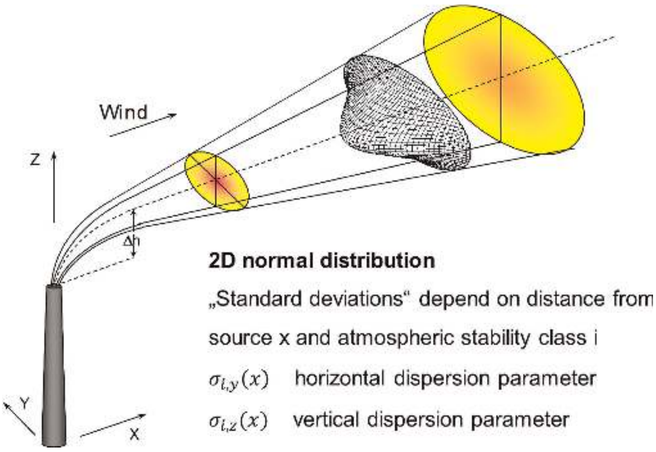

Fig. 1. Visualization of the Gaussian plume model used in the AVV. The airborne concentration of pollutants is modelled as a two dimensional normal distribution, which depends on the effective source height (stack height plus Δh), wind speed and wind direction in effective source height, distance from the source and atmospheric stability class

Conservatism is only granted for high sources and a medium to high roughness of the model area surface due to the fact that the dispersion parameters were derived experimentally for such conditions only. Wind speed and wind direction are assumed to be constant in the whole model region. Radioactive decay, dry deposition and washout are modelled indirectly by a reduction of the source strength. Buildings or orography influencing the wind and turbulence field are considered by reducing the effective source height, thus are modelled indirectly, too. The AVV does not claim to model the plume realistically, especially with the indirect approaches, but to give a conservative estimate for airborne concentrations, wet and dry deposition in its permitted range of application. This range of application is determined by the above mentioned experimental deduction of the dispersion parameters. Thus the model should not be used for low surface roughness and low sources.

3 A step towards realistic dispersion modelling: The atmospheric radionuclide transport model ARTM

With the shortcomings of the Gaussian plume model and the different approach used for conventional air pollutants in mind, a Lagrangian particle model to simulate airborne radionuclide dispersion was developed, sponsored by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety [7–9]. It is based on AUSTAL2000 using the same atmospheric dispersion code and underlying diagnostic wind field model TALdia [10]. As its parent code AUSTAL2000 the radionuclide transport model ARTM is an open source realization of the German regulatory guideline VDI 3945, part 3 [5] on particle models. Additional processes simulated by ARTM are e.g. radioactive decay of arbitrary nuclides, wet deposition, or the calculation of the gamma rays field out of a plume of radionuclides. The graphical user interface GO-ARTM is part of the free download package available at www.grs.de/en/artm-atmospheric-radionuclide-transport-model. The interface allows to easily set up and run a simulation as well as to create visualizations of the input parameters and simulation results.

The meteorological input for the dispersion simulation is specified via a meteorological time series or a dispersion class statistics. These time series or statistics represent point measurements at a single anemometer position within the simulation region. Wind speed, wind direction, precipitation rate and atmospheric stability class have to be specified within the meteorological input file. To get the wind and turbulence field within the whole simulation region either a boundary layer model in the case of a horizontally homogenous terrain or the diagnostic wind field model TALdia otherwise is utilized. In the former case an idealised wind and turbulence profile according to VDI guideline 3783, part 8 [11] and TA Luft is used. The VDI guideline 3783, part 8 is under revision currently [12]. This guideline uses a profile method based on the similarity theory by Monin and Obukhov [13]. Additional assumptions needed by ARTM to use the profile method taken from the TA Luft concern the boundary layer height (depending on the Coriolis parameter and thus the geographical latitude) and the wind shear with height (depending on boundary layer height). The wind and turbulence profiles calculated by the model are meant to represent the characteristic (mean) behaviour of the atmosphere but not to represent realistic weather conditions for each individual meteorological situation.

If the terrain is not homogeneous horizontally (structured terrain, buildings influencing the wind and turbulence field near the sources), the diagnostic mesoscale wind field model TALdia is utilized. A so called wind field library is precalculated by TALdia then: For each stability class and a given set of wind directions (southerly and westerly winds in case of orographic influence on the wind field, each 10 degrees in case of buildings, which have to be accounted for explicitly) a wind and turbulence field is simulated based on empirical assumptions. During the subsequent dispersion modelling of ARTM for each time step or statistics situation the two "nearest" precalculated fields are selected. They are interpolated in such a manner, that the wind speed and wind direction of the interpolated wind field fits to the prescribed one of the meteorological input file. Again, these modelled diagnostic wind fields are not meant to represent individual meteorological situations realistically but to give an estimation of the mean behaviour. Hence effects like back flows or eddies in the lee of buildings or wind tunnelling in orographically structured terrain are approximated by the wind field model.

As soon as the wind and turbulence field in the whole simulation region is available the dispersion modelling is performed by ARTM. The velocity of each particle in the model is determined by the mean wind speed and direction and an additional fluctuating velocity component. This fluctuating component depends on the turbulence in the atmosphere and thus the stability class of the atmosphere and where required additional turbulence generated by roughness elements like buildings. The wind speed and thus particle speed fluctuation is modelled as a Markow process [5]. As all model particles are treated independently of each other, the random speed fluctuation leads to a widening and thus dilution of the plume downwind of the source.

Just as the Gaussian plume model of the AVV the ARTM software package (including the boundary layer model and the diagnostic wind field model TALdia) does not claim to achieve realistic results for the airborne concentration, wet and dry deposition of airborne radionuclides and for the gamma cloud shine, but to give a conservative estimate of these variables for long term simulations within its range of application. ARTM's range of application is determined by the underlying wind field model. For the included diagnostic model TALdia this means, that the slope of the terrain should not exceed 0.2, no significant local wind phenomena like sea or mountain breeze should impact the wind and the source should be at least 1.2 times the height of buildings, which are less away from the source than 6 times the building height. If the influence of buildings on the wind field can be ruled out, source heights between ground level and atmospheric mixing layer height can be modelled.

4 ARTM versus AVV Gaussian plume model

Due to the shortcomings of the Gaussian plume model used in the AVV, the Lagrangian particle model ARTM shows to be more realistic for the situations concerning these shortcomings. For example, low sources or different roughness lengths in the model region can easily be considered with ARTM. This is shown in Fig. 2 exemplarily. Four simulation results for the surface level airborne concentration are compared. All model input parameters were equal in the test case simulations except for the roughness length of the ground. The source was located at the x-y origin in 10 m height (marked with a pink diamond in the plots). The source strength was 1 Bq/s of small ^{41}Ca aerosols (aerodynamic equivalent diameter AED < 2.5 µm). A 24 h meteorological time series with constant conditions of 1 m/s westerly winds at 10 m height, no rain and a neutral stability class (Pasquill Gifford stability class D) was modelled. For a better comparability the wind direction change with height was switched of in the ARTM simulations, as no such effect is dealt with in the Gauss plume model. As can be seen easily, the shape of the plume differs distinctly with the roughness length. The extra turbulence induced by the surface roughness leads to a widening of the plume. Pollutants may even be mixed upwind by the high turbulence (3rd plot). Such an upwind mixing will never be modelled with the AVV Gaussian plume model as the modelled concentrations in the luv of the source are always zero (white areas in the plots indicate regions with modelled concentrations below $1 \cdot 10^6$ Bq/m^3). The maximum values modelled in this test case range from round 1.2 mBq/m^3 to round 1.7 mBq/m^3, which is a comparatively small spread. However, the locations of the modelled maximum concentrations vary a lot (marked with white X in the plots). The actual numbers are compiled in Tab. 1. This table gives the numbers of surface grid cells, whose concentrations were modelled to be above given thresholds, too. Once again these numbers demonstrate the big influence of the roughness length on the dilution of the plume, an effect, which the AVV Gaussian plume model is unable to allow for. Additionally it can be mentioned, that due to the low source height in the test case of 10 m only, which is out of its range of application, the Gaussian plume model does not give conservative results near the source even for the high roughness lengths case.

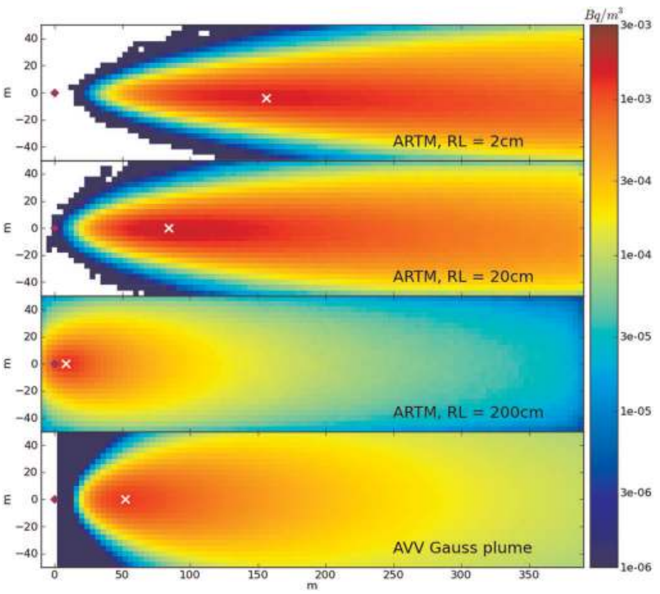

Fig. 2. Qualitative comparison of surface level airborne concentrations of radionuclides modelled by ARTM (upper three plots) and the AVV Gauss plume model (lowest plot) for a simple test case. The source location is marked by a pink diamond. The source height is 10 m. The white X marks the location of the modelled maximum concentration. The ARTM simulations differ in the used roughness length (RL). (See text for further explanation.)

The influence of orography on the wind field is not modelled in the AVV Gauss plume model. Instead the flow field is kept constant and the source height is reduced and thus the modelled airborne concentration of radionuclides is far from reality (Fig. 3, top). ARTM calculates a much more realistic wind flow and thereby concentration field within orographically structured terrain (Fig. 3, bottom). For both simulations shown in Fig. 3 the same 24 h meteorological time series is used: 2 m/s easterly winds 20 m above ground at the source location marked with a black X in the plots, no rain, stability class E (stable conditions). The source height is 50 m. The source strength is 1 Bq/s of small ^{137}Cs aerosols (AED < 2.5 µm). The simulation area is 400 km^2: The highest elevation reached in the shown region is about 1 km above sea level and the lowest is the sea level in the east.

5 Realistic dispersion modelling

Although ARTM in combination with the boundary layer model of VDI guideline 3783 part 8 and the diagnostic mesos-

Table 1. Modelled maximum airborne concentrations, distance from the source to the maximum and area affected (given as number of grid cells) by a concentration above a given threshold for the example test case of Fig. 2.

Model	Maximum airborne surface concentration	Distance from source to maximimum	Number of cells above		
			1 mBq/m^3	0.1 mBq/m^3	0.01 Bq/m^3
ARTM, RL = 2 cm	1.49 mBq/m^3	156 m	273	1477	1837
ARTM, RL = 20 cm	1.73 mBq/m^3	84 m	222	1754	2106
ARTM, RL = 2 m	1.31 mBq/m^3	8 m	16	839	2453
Gaussian plume model	1.20 mBq/m^3	52 m	36	2051	2244

cale wind field model TALdia is a step towards realistic dispersion modelling compared to the Gaussian plume model, it has to be admitted that ARTM is still far away from realism. Much more sophisticated computational fluid dynamics codes and further scientific concepts exist to handle dispersion issues, which may produce more realistic results compared to ARTM.

However, one difficulty in common for all kinds of dispersion simulations is the degree of knowledge concerning the input parameters. For example, the wind conditions may not be available as whole vertical profile measurements but only as point measurements at a sole height. Assumptions on the profile have to be applied then. Though, as mentioned above, assumed characteristic wind profiles may not represent the true situation of an individual meteorological situation. This is demonstrated in Fig. 4 with the measured wind speed profile data of the Roadside sound barrier tracer study 2008 [14, 15] Test 4 and the profiles assumed by the ARTM model according to [11]. Obviously, the special meteorological conditions during the first 2 h of the measurements cannot be met by the simple model assumptions.

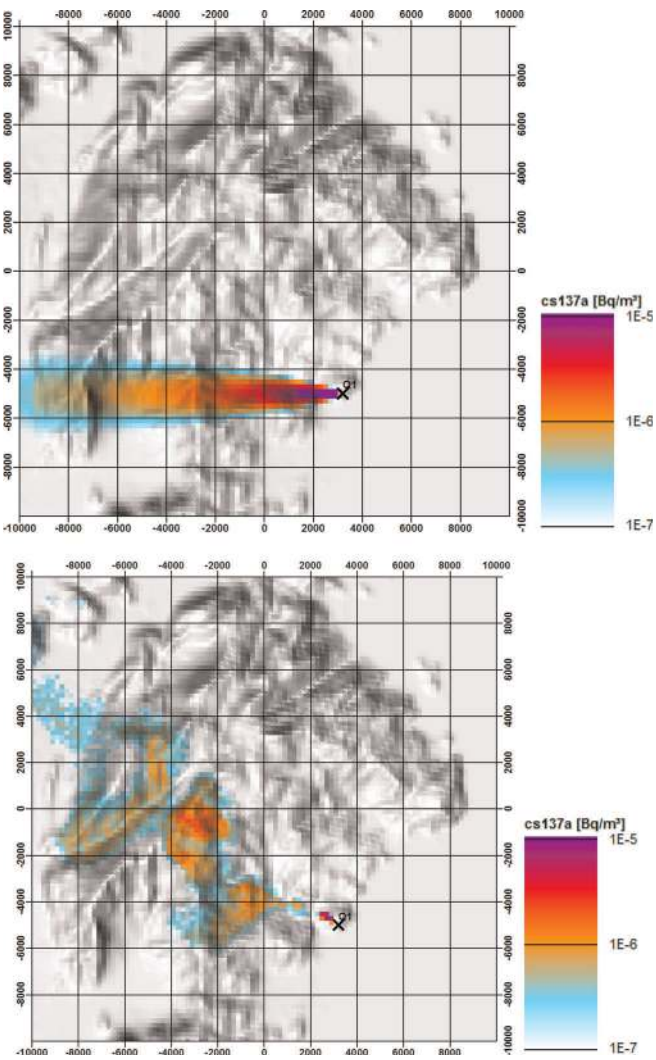

Fig. 3. Example visualisation of modelled airborne radionuclide concentrations in orographically structured terrain (gray shades). The Gaussian plume model does not consider wind field changes (top graphic) whereas the ARTM model (bottom graphic) does. For both model runs, the same meteorological conditions (wind from the east) were used. (See text for further explanation.)

Some input parameters, like the atmospheric stability class cannot be measured directly at all but have to be deduced from other measurements. Depending on the used method for the derivation the stability class will vary significantly (see for example [14], summary of test 2).

Given the uncertainty associated with input parameters and limited spatial and temporal resolution a realistic dispersion modelling can hardly be achieved. The improvements, which may be obtained by using more sophisticated models, are thus limited.

A cost-benefit estimate should therefore be performed, before a more complex model is recommended. The benefits being the more realistic modelling and supposed more realistic results (if all needed input parameters, model settings and boundary conditions are chosen reasonably). The costs being, beside likely expenses for the simulation code, the expert knowledge needed for the operation of the code, the increased requirements concerning the hardware and the input parameters, longer computing time as well as more stringent needs for a precise documentation of all input parameters and model settings to ensure the reproducibility of the simulation results. Especially for regulatory purposes reproducibility and confirmability by non experts of dispersion modelling are worthwhile features. Scientifically state of the art dispersions models hence will not automatically be the best option in this context. Especially if long term dispersion is of interest, as is the case in the stated EU BSS articles or the AVV, the benefits of more sophisticated models will even be reduced due to the smoother behaviour of averages compared to individual dispersion situations.

Provided that simple dispersion models as the Gaussian plume model or even to some extent the Lagrangian particle model ARTM are used within their validated range of application, these models will be preferable within regulatory purposes. This is due to the fact that simulation results may be reproduced and confirmed easily and despite the fact, that the dispersion calculation will not be truly realistic.

6 Conclusion

The ARTM model achieves much more realistic results compared to the AVV Gauss plume model in complex situations or beyond the range of application of the Gaussian plume model like low sources or very unruffled surfaces. Nevertheless, within the range of recommended application, the results of the AVV Gaussian plume model are alike the ones of ARTM.

The quality of a Lagrangian particle model like ARTM strongly depends on the quality of the underlying wind field model. Highly advanced computational fluid dynamics models may produce much more realistic wind and turbulence fields. However, these models require much more input parameters, which may not be known exactly but may influence the results distinctively. Knowledge gaps may be filled with sophisticated guesses or model assumptions. Expert knowledge is needed to perform the dispersion modelling in these cases. Reproducibility may be limited, if all the numerous input parameters and model assumptions are not documented carefully enough.

Using more sophisticated atmospheric dispersion models thus is a questionable approach in the field of regulatory purposes due to the limited confirmability of the results.

Existing modelling approaches (Gauss plume model or ARTM) aim to produce conservative results and do not aim to be realistic. Anyway it is not clear, how to do a realistic at-

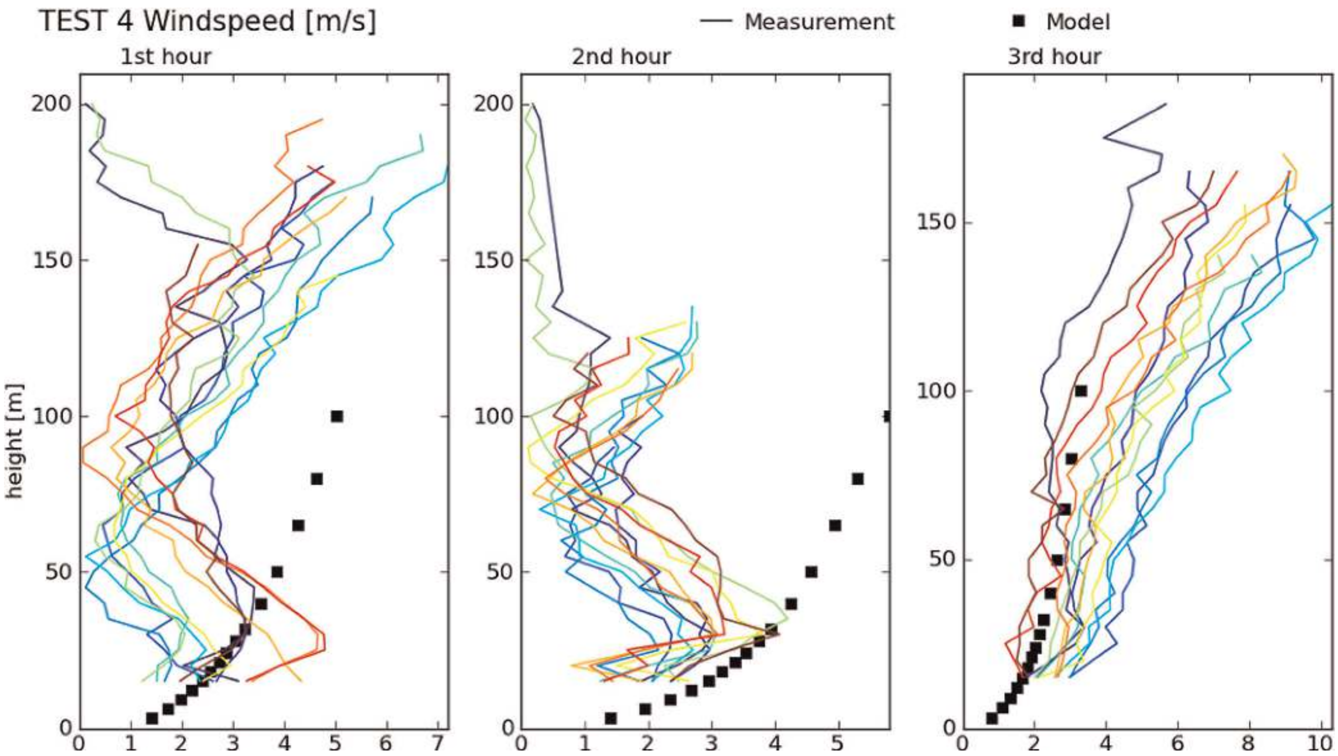

Fig. 4. Comparison of measured and modelled wind speed profiles. The measurements (solid lines) represent SODAR measurements of 5 minute time resolution during Test 4 of the Roadside sound barrier tracer study 2008 [14], the model (black squares) represent the profiles according to VDI guideline 3783, part 8 [11] used in ARTM

mospheric dispersion modelling indirectly postulated by the EU BSS or what the internationally recognised scientific guidance concerning atmospheric dispersion modelling is (see for example HARMO initiative [16]).

(Received on 29 February 2016)

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DOI 10.3139/124.110727
KERNTECHNIK
81 (2016) 5; page 559–564
© Carl Hanser Verlag GmbH & Co. KG
ISSN 0932-3902

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Introduction of Thorium in the Nuclear Fuel Cycle. Published by the OECD/NEA, NEA Report No. 7224, 133 pp., 2015, available online at: www.oecd-nea.org/rp/pubs/2015/

If the use of nuclear energy is to expand and become a sustainable source of energy, the major challenges of improving the utilisation of mineral resources while reducing ultimate waste streams will need to be addressed. In a post-Fukushima context, where deployment of fast neutron reactors is uncertain and the realisation of geological repositories has been delayed in some countries, continuing socio-political concerns are focused on the accumulation of spent fuel and its final disposal. In the absence of fast neutron reactors, the issue of plutonium management will have to be dealt with in the medium to long term, at least for current and future separated plutonium.

The use of thorium in the nuclear fuel cycle as a complement to the uranium/plutonium cycle shows potential for improving the medium-term flexibility of nuclear energy and its long-term sustainability. More specifically, options for thorium's introduction into the nuclear fuel cycle should be kept open and continue to be investigated, including:

- using thorium as a means of burning plutonium (and possibly other higher actinides) as an option for plutonium management;
- the possibility of reaching higher conversion factors in thermal or epithermal neutron spectra, using thorium-based fuels, in evolutionary generation III+ systems, with the aim of recycling the fissile material from used fuels;
- examining the promising physicochemical characteristics of thorium dioxide, which would offer improved performance of thoria-based fuels over current fuel designs.

The development of new fuels or new reactor concepts is a time- and resource consuming process likely to span several decades. Any industrial application of thorium as a nuclear fuel would continue to require the input of fissile material from the existing uranium/plutonium cycle until the required amounts of ^{233}U could be produced to ultimately make the thorium cycle self-sustaining.

If a thorium fuel cycle is pursued, an important factor governing the rate at which ^{233}U could be produced from the introduction of thorium/plutonium or thorium/uranium/plutonium cycles would be plutonium availability. The limitations imposed by fissile plutonium availability result in rather long transition periods between thorium/plutonium and thorium/^{233}U systems, which are likely to be of the order of many decades.

The development of a fully self-sustaining thorium/^{233}U cycle would also require the development of industrial scale reprocessing capabilities to recover ^{233}U from spent fuel, along with fuel fabrication facilities to prepare the material for reuse. In particular, impediments to closing the thorium fuel cycle arise from the following issues:

- To date, the THOREX process has been demonstrated in pilot-plant facilities, but is yet to reach the maturity of the commercial PUREX process. Other extractants and alternative processes (e.g. fluoride volatility) are also being investigated, but are still at a conceptual stage.
- A major challenge associated with the recycling of ^{233}U is the presence of radioactive ^{232}U. Remotely operated and fully shielded recycled fuel fabrication processes will be required, for which there are currently no proven equipment or processes at the industrial scale.
- A related challenge is the handling and storage of excess thorium, which will contain 228Th and its highly radioactive daughters for about 20 years.

Ultimately, thorium technologies require significant further development. Thorium fuel R&D initiatives are currently being funded by some countries concerned with longterm nuclear energy sustainability (as is the case of Canada). However, given their cost and the lack of clear economic incentives for nuclear power plant operators to pursue this route, industrial development activities for thorium remain somewhat limited at present.

If thorium fuel cycles are pursued, it is to be expected that short- to medium-term development of thorium fuels would be carried out in a step-wise fashion and in synergy with the existing uranium/plutonium fuel cycle.

In the longer term, the potential introduction of advanced reactor systems may present an opportunity to realise the full benefits of a closed thorium/^{233}U fuel cycle in dedicated breeder reactors (generation IV or beyond) that are presently in the design study phase.

Molten salt reactors in particular may offer the prospect of using thorium fuels with online recovery and re-use of the ^{233}U while recycling long-lived actinides and ensuring minimal losses to the final waste stream. It must, however, be recognised that the development, licensing and construction of such novel systems is a long-term undertaking.