The reactor accident of Fukushima Dai-ichi and its radiological consequences for the Japanese population

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Abstract

Five years after the accident, the resulting contaminations of the environment, the radiation exposures of the affected populations and the potential health risks can be assessed with some confidence based on international evaluations. This contribution presents the available evidence about the source term of the released radionuclides, about transport and fallout of the radionuclides and the contamination of the different environmental compartments and the assessments of the internal and external radiation exposures of the inhabitants of the different prefectures of Japan. The radiation doses of thyroid glands as well as the effective doses during the first year and their projections for lifetime are presented. The up-to-now available data regarding health effects are discussed[1].

Fukushima Dai-ichi: the plant and the reactor accidents

On the 11th of March 2011 at 14:46 an earthquake of magnitude 9.0 occurred 100 – 200 km off the coast of the Prefecture Miyagi in Northern Japan. The quake strongly damaged the northern prefectures of Japan. About 1 hour after the quake a Tsunami, height 7 m – 15 m, devastated the coastal regions. More than 15,854 deaths and 3,155 missing were counted in Northern Japan as a consequence of the quake and the tsunami (status as of 10.3.2012) and 380,000 people were homeless and had to live as evacuees Japan. More than 340,000 evacuees lived still in emergency accommodations in March 2012.

Japan was heavily relying on nuclear energy: In the year 2009, 28.9 % of electricity was obtained from nuclear energy; 51 nuclear reactors produced 263 TWh. After the quake the reactors in the affected regions, i.e. Onagawa, Fukushima Dai-ichi, Fukushima Daini, and Tokai, were automatically shut down and remained widely undamaged. The electricity supply in Northern Japan broke down after the quake.

The nuclear power station at Fukushima Dai-ichi (FDNPS) consisted of 6 units three of which were shut down for inspection at the time of the quake. The plant was designed to withstand quakes of magnitude 8 and 5.7 m high tsunamis. The off-site power supply was lost as a consequence of the quake; the three operating and now shut-down reactors at Fukushima Dai-ichi had to use the emergency power supplies and foreseen passive systems for cooling the reactor cores. The tsunami flooded resp. destroyed the emergency diesel generators, the service water buildings and the seawater inlet structures: the result was a total station blackout. From this time on, a melt-down of the three reactor cores was inevitable provided that no outside power supplies could be provided in time.

As a consequence of the melting cores, accompanied by production of hydrogen due to the zirconium-water reaction $Zr + 2 \cdot H_2O \rightarrow ZrO_2 + 2 \cdot H_2$, the pressure of the containments increased. Unit 1 was the first requiring venting during which a hydrogen explosion occurred on March 12, 2011 16:00 on the service platform of the reactor blowing away its roof. In

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[1] For further details see the viewgraphs of the manuscript under http://www.fze.uni-saarland.de/AKE_Archiv/DPG2016-AKE_Regensburg/Vortraege/DPG2016_AKE11.2_Michel_Fukushima-radiologFolgen.pdf

Unit 3, a hydrogen explosion occurred during venting on March 14, 2011 11:00 LT below the service platform and grossly destroying the building structure, leaving, however, the containment unharmed. In the early morning of March 15, 2011 a hydrogen explosion destroyed large parts of the building of Unit 4. This explosion was later explained as resulting from hydrogen which made its way from Unit 3 underground into the building of Unit 4. At 6:10 LT a bursting sound was heard from Unit 2 on March 15, 2011. This sound was later explained as indicating the failure of the containment of Unit 2 at low height near the dry well with a massive release of radioactivity to the environment.

Fig. 1: Fukushima Dai-ichi as of March 15, 2011 with Units 1 – 4 from the front to the rear; photo TEPCO.

Releases of radionuclides, transport, and fallout

The automatic stations for measuring ambient dose rates in Fukushima and adjacent prefectures were widely destroyed due to the natural disaster. This was also true for much of the measuring systems on the plant's premises. The few existing measurements of the ambient dose rates at FDNPS had indicated the releases starting with the first venting of Unit 1. Peaks in the ambient dose rates going up to 3 mSv/h were seen which allowed identifying the individual events (GRS 2015). In the morning of March 15, 2011 the ambient dose rates rose up to 12 mSv/h as a consequence of the failure of the containment of Unit 2. Later, local maxima can be attributed to repeated venting events of Unit 3. Only after March 22, 2013 the dose rates at FDNPS fell significantly below 1 mSv/h. It has, however, to be mentioned that locally the ambient dose rates at FDNPS remained high reaching even the order of 10 Sv/h.

Already in the evening of March 11, 2011 the Fukushima Prefecture ordered the evacuation of the close proximity of FDNPS: 2 km evacuation at 20:20 LT extending to 3 km at 21:23 LT. At a later time sheltering was ordered for people living in up to 10 km distance from the plant. On March 12, 2011 18:25 LT evacuation up to 20 km distance was ordered. Finally, sheltering was ordered in distances up to 30 km from the plant for the case of a further unfavorable accident development. This latter order lasted from April 15 to 22, 2011. In total, 80.000 people were evacuated from the 20 km zone and further 10.000 people from the so-called Deliberate Evacuation Zone; see Fig. 2.

The author followed the events in his role as chair of the crisis organization of the German Commission on Radiological Protection (see www.ssk.de). As the first two hydrogen explosions occurred information was rather limited and based on media reports and the excellent work of the German Gesellschaft für Reaktorsicherheit (GRS); see GRS (2015). Later, the data published by the Japanese government and by the French IRSN were extremely helpful. On March 12 and 14, 2011, we did not know what would happen in Fukushima, but it was clear that the weather would determine everything. Fortunately in spring time an East-Asia High causes winds to blow mainly from the west over the plant to the ocean. This changed, however, on March 15, 2011 when the wind started blowing into the Japanese mainland. It was an unfortunate coincidence that the failure of the containment of Unit 2 coincided with the wind blowing into the direction of Fukushima Town being thus responsible for the high fallout in north-westerly direction extending to Iitate Village. Also Tokyo got its share. On March 14 and 15, 2011 four radioactive clouds were seen in the automatic measuring stations passing Tokyo and also stations in Chiba and Ibaraki indicated transport and fallout of the radioactivity released at FDNPS (Fig. 3). These data allowed for first estimates of the potential radiation exposure of the people living in these regions.

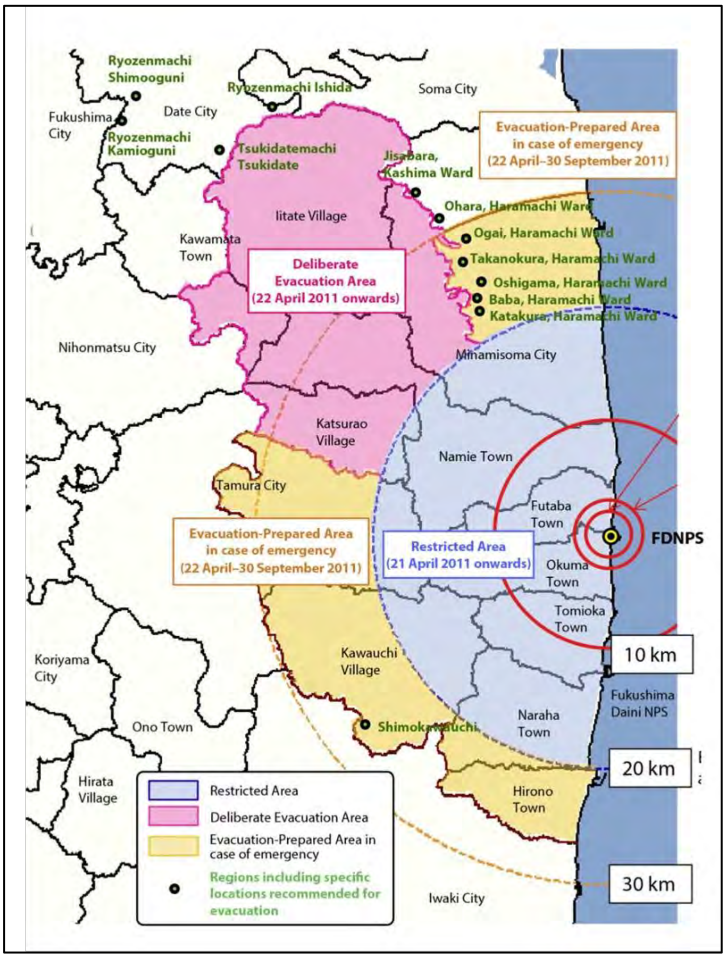

Fig. 2: Map with the regions where protective measures were applied (UNSCEAR 2014).

Based on simple heuristic principles an increase of the ambient dose rate by 2 µSv/h would indicate fallout of Cesium and Iodine radionuclides (Cs-137 or I-131) of about 1 MBq/m². The fact that the ambient dose rates increased just little after the passage of the clouds showed that the fallout remained well below 100 kBq/m^2; a value which was typical for some areas in Southern Germany in May 1986 after the Chernobyl accident. The respective data for the Prefecture Ibaraki in the southern neighborhood of Fukushima allowed predicting fallout of these radionuclides of about 100 kBq/m^2.

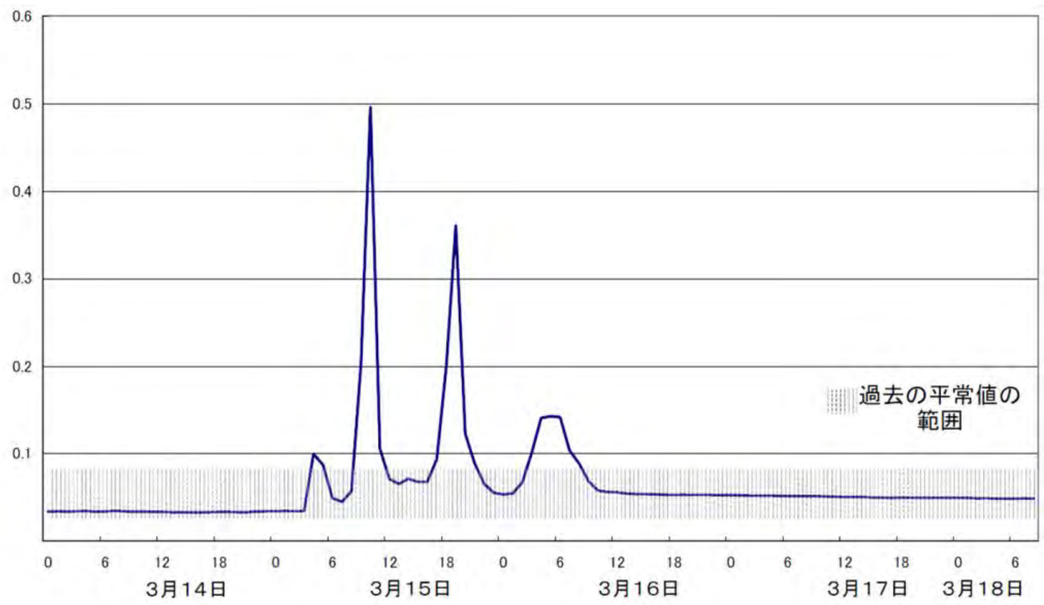

Fig. 3: Ambient dose rates in µSv/h measured in Tokyo on March 14 – 17 during the passage of radioactive clouds. The shaded area indicates the range of normal natural dose rates. Later and more complete data may be found at http://monitoring.tokyo-eiken.go.jp/en/index.html

Such data as in Fig. 3 also allowed estimating the doses of radiation exposure due to inhalation and external irradiation. Assuming permanent 24h/d stay outdoors in Tokyo – a highly unlikely behavior given the weather conditions and the time of the year – an external dose of 1.9 µSv, an effective dose for adults of 123 µSv and thyroid doses of 5.4 mSv and 2.5 mSv for 1 – 2 year old children and adults were calculated, respectively. For Ibaraki the respective estimates resulted in an external dose of 6.0 µSv, an effective dose for adults of 410 µSv and thyroid doses of 18 mSv and 8.3 mSv for 1 – 2 year old children and adults, respectively.

No estimates were possible for Fukushima Prefecture because of lack of information. On March 16, 2011 the first measurements of ambient dose rates measured from cars driving through the regions affected by fallout were reported by MEXT. They showed maximum dose rates of about 80 µSv/h in 20 km to 30 km distance from the plant. In an area to the north-west beyond the 30 km distance up to Iitate Village maximum dose rates of 20 µSv/h were measured. Starting on March 17, 2011 airborne measurements were performed by a cooperation of MEXT[2] and the US DOE and continued until comprehensive maps ambient dose rates and of the fallout of Cs-134 and Cs-137 in Northern Japan were obtained (Fig. 4).

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[2] MEXT is the Ministry of Education, Culture, Sports, Science and Technology in Japan, DOE is the US Department of Energy.

It became clear by the end of March that serious contamination was extending beyond the 30 km cycle around FDNPS and after April 22, 2014 a deliberate evacuation area extending beyond the 30 km zone to the north-west including the village of Iitate was established. The rationale was to limit the external radiation exposure to 20 mSv in the first year (temporal permissible limits as of April 20, 2011). It was assumed that people spent 33% of the day each outdoors, in schools or offices and in private homes and that occupancy (shielding) factors were 1, 0.7 and 0.1, respectively. This led to a dose rate criterion for evacuation of 3.8 µSv/h. The areas exceeding this limit are indicated in Fig. 4 by yellow, orange and red colors. The dose rate of criterion of 3.8 µSv/h conforms roughly with a criterion based on Cs-134 + Cs-137 fallout of 600 kBq/m^2 in April 2011.

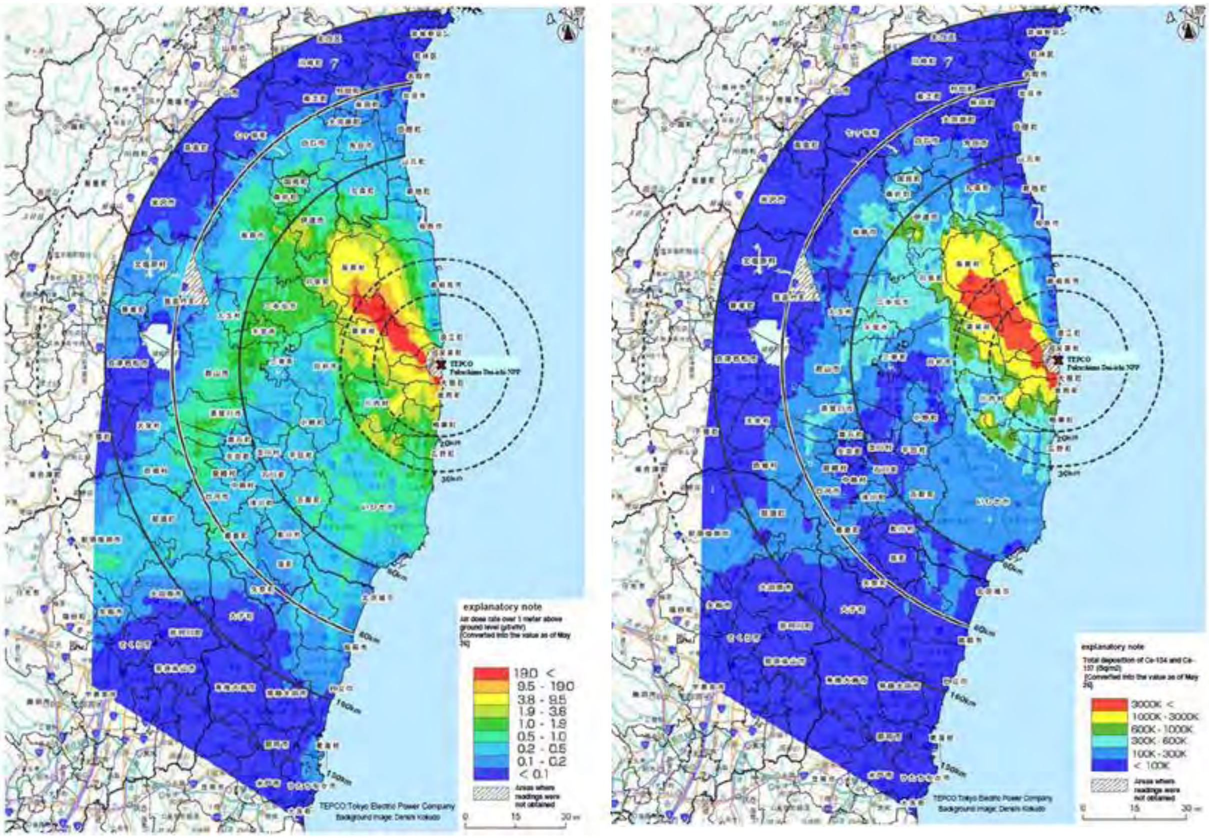

Fig. 4: Data from airborne survey measurements published on March 16, 2011 by MEXT and DOE.
Left: Ambient dose rates in areas from red to dark blue: >19 µSv/h, 9.5-19 µSv/h, 3.8-9.5 µSv/h, 1.9-2.8 µSv/h, 1.0-1.9 µSv/h, 0.5-1.0 µSv/h, 0.2-0.5 µSv/h, 0.1-0.2 µSv/h, <01. µSv/h, no data available for grey-hatched areas.
Right: Cs-134 + Cs-137 fallout in areas from red to dark blue: >3000 kBq/m^2, 1000-3000 kBq/m^2, 600-1000 kBq/m^2, 300-600 kBq/m^2, 100-300 kBq/m^2, <1000 kBq/m^2, no data available for grey-hatched areas.

The estimates of the total releases clearly showed that the accident at FDNPS was an INES 7 accident. There was a lot of public confusion about its severity compared to other accidents, in particular if compared to the Chernobyl accident. The French IRSN was the first to publish a source term on March 22, 2013 (Table 1). A lot of publications followed which will not be discussed here in detail. I rather quote in Table 1 data from the recent evaluations of UNSCEAR (2014) for FDNPS with those for the Chernobyl accident according to

UNSCEAR (2000) revealing the fact that the FDNPS accident was significantly smaller regarding the releases of Iodine and Cesium radionuclides than the Chernobyl accident. When comparing theses data one has to keep in mind that in Fukushima three cores melted while it was just one in Chernobyl. The difference simply results from the fact that in Chernobyl there was no containment, the reactor exploded, the reactor core lay open and after that a graphite fire and a melting of the residual core occurred. In Fukushima there were containments and the radioactivity from Units 1 and 3 were released during venting operations. Only 2.1 % of I-131 and 1.3 % of each, Cs-134 and Cs-137, of the total inventories of the three reactor cores were released. It remains to mention that about half the I-131 and Cs-134 plus Cs-137 activities were released when the containment of Unit 2 failed (Chino et al. 2011).

	Fukushima Dai-ichi			Chernobyl
	IRSN 22.03.11	UNSCEAR 2014		UNSCEAR 2000
Isotope	atmosphere		ocean	atmosphere
I-131	9.0E+16	1.2E+17	1.1E+16	1.8E+18
Cs-134	1.0E+16	9.0E+15	3.5E+15	4.7E+16
Cs-137	1.0E+16	8.8E+15	3.5E+15	8.5E+16

Table 1: Releases in Bq of some dose relevant radionuclides from the FDNPS in comparison with data for the Chernobyl accident.

Due to the frequent winds from the west which drove radioactive clouds and fallout over the Pacific Ocean and because of direct inflow of contaminated waters from the FDNPS also the marine environment was contaminated. High radioactivity concentrations were, however, widely confined to the close proximity of FDNPS. Strong marine currents off the East coast of Japan and finally incorporation into the North Pacific Circulation led to extreme dilution of the radioactivity concentrations. Though they are under intense investigation and of extreme interest for studies on oceanic circulation, they are of negligible importance for the radiological consequences for humans. In Northern Japan fishing stopped widely as a consequence of the quake and tsunami and in some prefectures of Northern Japan fishing was banned. Therefore, contaminated seafood did not enter the Japanese food basket. In the meantime (as of 2016) the radioactivity concentrations e. g. of Cs-137 are of the order of 1 Bq/L close to the FDNPS (Fig. 5). This is a consequence of large, however not yet completely successful efforts to retain the contaminated water on the station's premises.

For estimating the radiological consequences of the accident at FDNPS the fallout of other radionuclides than Cs-134 and Cs-137 has also to be considered. Next of importance is certainly I-131 together with short-lived Tellurium and Iodine radionuclides. Due to the circumstance of the Fukushima accident after the natural disaster there are no early measurements of the fallout of I-131. Evaluation of soil samples taken only in June 2011 gave a coarse indication of the fallout of I-131. Due to the short half-life of I-131 of 8.02 d the measured data needed huge decay corrections to obtain the relevant data for the time after March 15, 2011. Only on June 28, 2013 a Japanese TV station reported that researchers from the Japan Atomic Energy Agency and the US Department of Energy had now analyzed radiation data they jointly gathered using aircraft in April 2011." The I-131 data showed that I-131 fallout in the highly contaminated areas to the north-west of FDNPS was between 600 kBq/m^2 and more than 3,000 kBq/m^2 revealing a large potential for high thyroid doses of the inhabitants outside the 20 km zone.

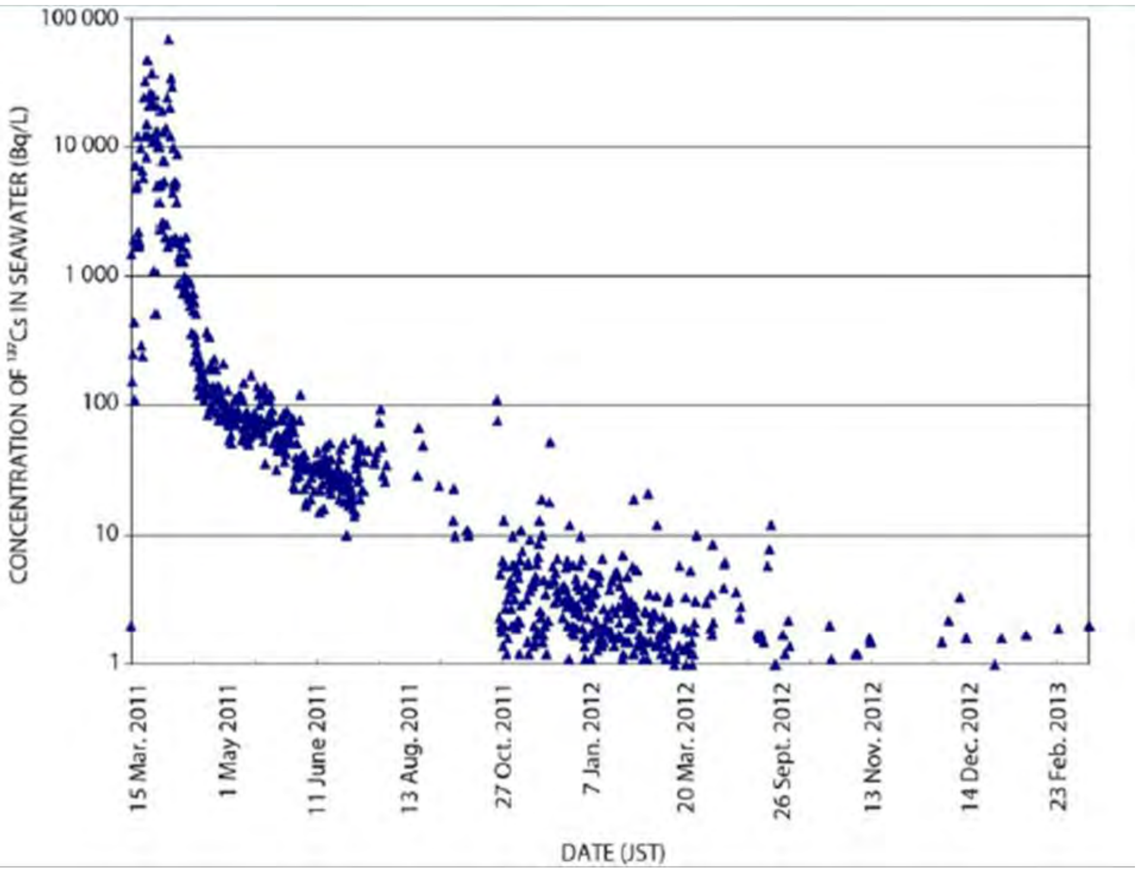

Fig. 5: Measured Cs-137 radioactivity concentrations in seawater near the FDNPS (UNSCEAR 2014).

Though the soil samples taken in June 2011 were rather insufficient for estimating I-131 fallout they were extremely helpful to obtain information on the potential relevance of Sr-89/Sr-90 and of actinides in the fallout from the accident. The results of Sr-89/Sr-90 analyses of Japanese soils demonstrate that there is no radiological relevance of Sr-90 in comparison to the radiation exposures from Cs-137 and Cs-134. Strontium radionuclides were much more retained in the containment than the Cesium isotopes. Just a few samples showed the presence of Sr-89 which due to its relatively short half-life is indicative for fresh fallout from a reactor accident. Most of the samples showed Sr-90 concentrations in the typical range of the residues from the atmospheric nuclear explosions in the 1960ties. The same is true for Plutonium isotopes. The Pu-239+240 concentrations were in a range which is typical for the environmental contamination due to the atmospheric nuclear explosions. In 6 samples, Pu-238/Pu239+240 activity ratios were observed which point to Plutonium from nuclear power reactors. Also these abundances lack radiological relevance.

Thus, one has a relatively simple situation when assessing the consequences of the Fukushima accident since in the first order only I-131, Cs-134 and Cs-137 have to be considered. I-131 determines the radiation exposure of the thyroid glands by the exposure pathways inhalation while the radioactive cloud is passing and by ingestion of I-131 in foodstuffs provided that contaminated foodstuffs are not banned. Regarding the long-term consequences Cs-134 ($T_{1/2}$ = 2.06 a) and Cs-137 ($T_{1/2}$ = 30.17 a) have to be considered since they cause a long-term whole body exposure via external irradiation from the fallout and via ingestion of Cs-134 and Cs-137 in contaminated foodstuffs. In the context of internal exposure it is to mention that the Cesium radionuclides have a biological half-life in the human body of about 100 d only.

Dose estimates

First dose estimates for the population of Northern Japan were published by the French IRSN (http://www.irsn.fr/EN/news/Documents/IRSN_fukushima-radioactivity-released-assessment-EN.pdf) on March 26, 2011. These estimates demonstrated that except for the closer proximity of FDNPS thyroid and effective doses would be low. These early estimates were in agreement with our own estimates of May 2011 (Michel 2011). In the year 2013 WHO published a detailed assessment including estimates of the associated health risks (WHO 2013). The dose assessments by WHO were rather conservative and the risks estimates therefore can be considered as upper limits. In 2014, UNSCEAR published a detailed report about levels and effects of the Fukushima accident. These results – though still relying on point estimates, neglecting the distributions of the exposures and in some aspects being conservative – are presently the most detailed and reliable ones. The assessments will be continued in the future; see UNSCEAR (2015). Also the report by IAEA (2015) has to be mentioned. We quote here some of the results obtained by UNSCEAR (2014).

Residential area	Thyroid absorbed dose in mGy	
	adults	1-year old
Prefecture Fukushima not evacuated	7.8 – 17	33 – 52
Precautionary evacuated settlements: Fotuba, Okuma, Tomioka, Naraha, Hirono, parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages	7.2 – 34	15 – 82
Deliberately evacuated settlements; Iitate village and parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages	16 – 35	47 – 83
Six neighboring prefectures: Miyagi, Yamagata, Niigata, Gunma, Tochigi, Ibaraki	0.6 – 5,1	2.7 – 15
40 other prefectures in Japan	0.5 – 0,9	2.6 – 3.3

Table 2: Range of estimated average absorbed doses to the thyroid to adults and to 1-year-old infants for typical residents of Japan following the Fukushima accident (UNSCEAR 2014).

The first question in a nuclear emergency, if no deterministic effects have to feared, is that for the thyroid doses. Table 2 gives the respective results obtained by UNSCEAR (2014). They are based on modelling the inhalation of Iodine radionuclides during the passage of the radioactive clouds and on ingestion of Iodine radionuclides with food. The thyroid doses thus obtained are rather moderate for an INES 7 accident. The ranges of estimates in table 2 are, however, still biased by conservative prefecture-wide estimates of ingestion doses thereby neglecting the inhomogeneous fallout in the individual prefecture.

To put these thyroid doses in perspective, in an examination of thyroid hypofunction 0.185 MBq – 0.555 MBq I-131 are applied resulting for adults in absorbed doses to the thyroid of 80 mSv – 240 mSv. After the Chernobyl accident thyroid doses of members of the public were higher by orders of magnitude in Belarus and Northern Ukraine. In the highly contaminated, not evacuated areas they reached maximum values for children of a few times ten Sv; see e.g. Michel et al. (2015). In Germany, the thyroid doses remained below 10 mSv after the Chernobyl accident (SSK 2006).

Age group as of 2011	Geographical area of Japan		
	Fukushima Prefecture not evacuated districts	6 Neighboring prefectures Miyagi, Yamagata, Niigata, Gunma, Tochigi, Ibaraki	Rest of Japan
Effective doses over the first year			
Adult, 20 year old	1.0 – 4.3	0.2 – 1.4	0.1 – 0.3
Infant, 1 year old	2.0 – 7.5	0.3 – 2.5	0.2 – 0.5
Exposure over the first 10 years			
Adult, 20 year old	1.1 – 8.3	0.2 – 2.8	0.1 – 0.5
Infant, 1 year old	2.1 – 14	0.3 – 6.4	0.2 – 0.9
Exposure over lifetime			
Adult, 20 year old	1.1 – 11	0.2 – 4,0	0.1 – 0.6
Infant, 1 year old	2.1 – 18	0.4 – 6,4	0.2 – 0.9

Table 3: Ranges of estimated average total effective doses (mSv) for adults and 1-year-old infants (as of 2011) for typical residents of Japan for the first year, the first 10 years and for lifetime exposures (UNSCEAR 2014).

In an accidental situation effective doses are assessed primarily for the first year after the accident. The temporal permissible limits set by the Japanese Government aimed for a reference value of 20 mSv in the first year and the goal was mostly attained (table 3). The radiation exposures in the first year after an accident in springtime are of particular interest since they allow forecasting the lifetime exposure by simple heuristic rule: For a rural self-sustained population the lifetime exposure without countermeasures will be two to three times the exposure in the first year. The predictions by UNSCEAR (2014) based on detailed modelling confirm this (table 3). People living in large towns will generally have a lower exposure. For comparison, the effective lifetime doses from the Chernobyl accident are between 2.2 mSv in Southern Germany and 0.6 mSv in Northern Germany (SSK 1987). The data in tables 2 and 3 comprise just some of the results of the assessments by UNSCEAR (2014) contains. The whole report can be downloaded for free under www.unscear.org.

The future of the evacuated zones and the exposures of people returning to their homes hardly can be assessed today. UNSCEAR (2014) reported dose estimates for the precautionary and deliberately evacuated regions as effective doses for the first year. The ranges of average effective doses were for the precautionary evacuated settlements (Fotuba, Okuma, Tomioka, Naraha, Hirono, parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages) 1.1 – 5.7 mSv for adults and 1.6 – 9.3 mSv for 1-year old children; for the deliberately evacuated settlements (Iitate village and parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages) the effective doses were 4.8 – 9.3 mSv for adults and 7.1 – 13 mSv for 1-year old children. Because of the large efforts made by the Japanese government to clean up the contaminated regions and because the effect of these decontamination measures can hardly be quantified today, an estimate of the expected lifetime doses of potential returnees cannot be made.

A closer look to the radiation exposures in Northern Japan

The dose estimates by UNSCEAR (2014) were mainly based on measurements of the fallout of radionuclides and on radioecological modelling. This was reasonable since direct measurements were extremely scarce in the aftermath of the natural disaster. The result was that some estimates remained conservative as e.g. the prefecture wide average values of ingestion doses. In the meantime, more detailed and improved modelling and also more measurements became available. UNSCEAR (2015) reviewed the up to now literature and scrutinized it with respect to information potentially challenging the 2014 statements. We therefore take a closer look on the few measurements available.

Radiation exposures of the thyroid glands

There are just two direct measurements of the I-131 activities of human thyroid glands. For 1.080 children from Kawamata direct thyroid measurements were performed with portable dose ratemeters between March 26,2011 and March 30, 2011 (i.e. after two half-lives of I-131). Kawamata is one of the most highly contaminated areas without evacuation. The distribution of dose rates was an extreme log-normal – nearly exponential – one. For 55.4% of the children no increased dose rates were observed. Based on the measured dose rates and the conversion factor that 1 µSv/h ≙ 480 mSv thyroid dose for infants, the thyroid doses were estimated. For 95% of the children the doses were below 60 mSv, for less than 1% they exceeded 100 mSv and one maximum value of 200 mSv was observed. The median of the doses was below 20 mSv.

Tokonami et al. (2012) calculated thyroid doses for 62 persons of the evacuees from the Fukushima nuclear accident based on nuclide specific measurements of the thyroids with a Na(I) detector. The measurements were calibrated with phantoms, and the age-dependent equivalent thyroid dose coefficients of ICRP were used. The distinguished two cases, namely that the total I-131 in the thyroids came from inhalation respectively ingestion on March 15, 2011. The results were widely independent from the way the I-131 was incorporated. The following conclusions about the thyroid doses can be drawn: all doses were below 50 mSv, the median was below 4 mSv. The results of both measurements are in fairly good agreement with the point estimates of thyroid doses by UNSCEAR (2014). However, die strongly tailed log-normal distributions are striking.

External radiation exposures in Japan

As the thyroid doses, the doses due to external exposure are extremely dependent on the individual behavior of the people and reconstruction is difficult. In Japan, large efforts were undertaken to reconstruct the external exposure. For example, data on the way of living during the first 4 months after the accident were obtained in interviews of the 1.700 inhabitants of Namie Town, Iitate Village and a district in Kawamata Town and the external exposure was accordingly modelled. The results published in February 2012 showed that 58% of the doses were below 2 mSv during the first 4 months after the accident and just 1% exceeded 10 mSv. The maximum value was 23 mSv. These efforts were continued by Fukushima Prefecture (Fig. 6).

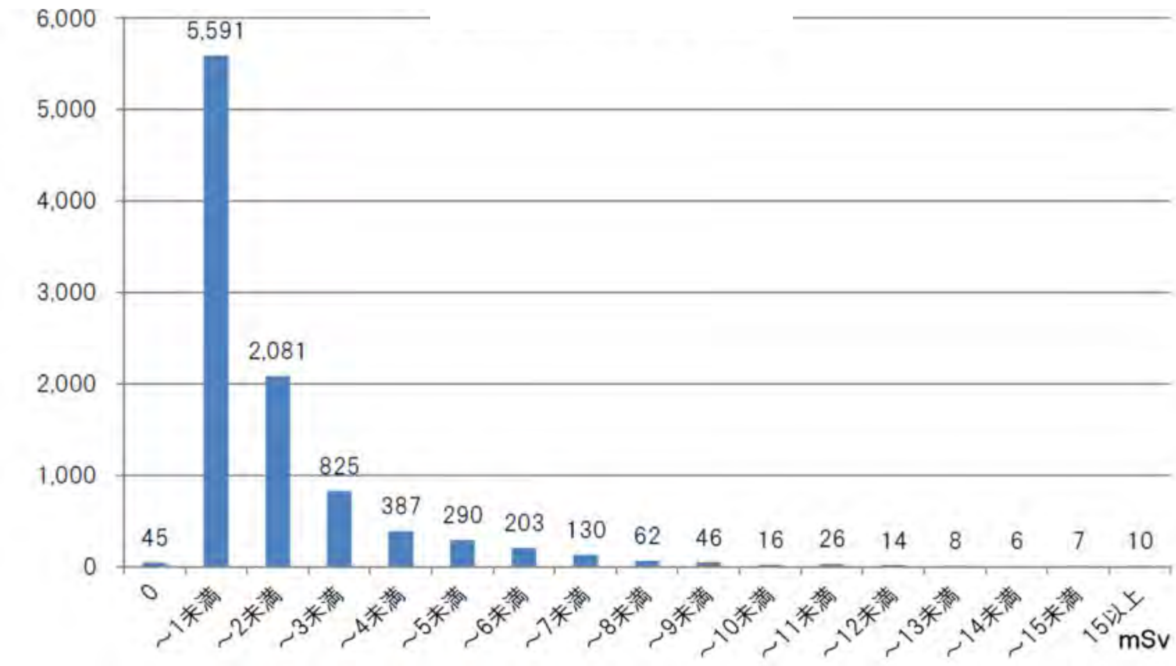

Fig. 6: Distribution of reconstructed external exposures during the first 4 month after the accident for 9.747 inhabitants of Namie Town (n = 7.250), Iitate Village (n = 1.944) and Kawamata Town (n = 553) during the first (24.2.2012)

Based on the fallout data of Cs-134 and Cs-137 for Northern Japan the 50-years effective doses from external radiation and inhalation of resuspended dust can be predicted using conversion factors for exposure to ground contamination according to IAEA (2000). Using the medians of the fallout in the Prefectures Fukushima, Iwate, Miyagi, Ibaraki, Tochigi, Gunma, Chiba, Saitama and Tokyo the calculated doses for the people in 208 settlements were between 0.1 mSv and 160 mSv. For only 14 settlements in the evacuated zones the predicted 50-years effective doses were higher than 10 mSv; all others were below 10 mSv. It has to be noted that these estimates did not anticipate countermeasures such as decontamination. Since large efforts of decontamination were and still are made in the highly contaminated areas, these doses cannot be used to argue whether or not the inhabitants of these settlements can return to their homes.

Internal radiation exposures in Northern Japan

Due to the release of radionuclides surface water, important for the drinking water supply, and plants were contaminated and the radionuclides made their way through the environment to man. For data on radioactivity in drinking water and foodstuffs see the viewgraphs of this presentation.

In 2011, it was unclear for quite some time how large the internal exposure to Cs-134 and Cs-137 would be. Intensive measurements of radionuclides in water and foodstuffs were performed by the prefectures in Northern Japan. Provisional limits for radionuclides in food were established in the year 2011 aiming to limit the internal exposure to 5 mSv per year. These limits were 200 Bq/L for drinking water (100 Bq/L for the preparation of baby food), 200 Bq/kg for milk and milk products and 500 Bq/kg for other foodstuff. On April 1, 2012 these limits were lowered aiming for a limitation of the internal dose of 1 mSv per year. The new limits were 10 Bq/L for drinking water, 50 Bq/kg for milk, milk products and infant food, and 100 Bq/kg for other foodstuffs. At the same time, the government stated that lowering the limits was not necessary from a radiological viewpoint; it was intended to improve the trust of the people in the foodstuffs. The actual internal exposure was estimated by the government to be below 0.1 mSv per year. Lowering the limits actually had not the desired effect because now people asked: Was the food not safe earlier? It was one more disaster for communication.

In the meantime, comprehensive whole body measurements of the inhabitants of the highly contaminated regions are available. First measurements of the specific Cs-137 body activity of 4.745 persons in Minami Soma, Fukushima Prefecture, measured with whole body counters from 26.9.2011 to 27.12.2011 revealed again an extreme log-normal distribution of internal doses. For more than 50% of the people no Cesium radionuclides were found in their bodies. The mode of the distribution of those for which Cesium radionuclides were detected was between 5 Bq/kg and 10 Bq/kg. This is equivalent to 35 μSv per year to 70 μSv per year for adults. For comparison, in Karlsruhe/Germany the Cs-137 specific body activities of Cs-137 reached 10 Bq/kg in the 1960ties due to the fallout from the atmospheric nuclear explosions and 8 Bq/kg after the Chernobyl accident in 1986.

Later more comprehensive measurements by JAEA at Tokaimura performed between July 11, 2011and January 2012 for 9,927 inhabitants of Iitate, Kawamata, Namie, and 8 other local communities became available (Momose et al. 2012). According to these measurements the maximum whole-body content of Cs-134 and Cs-137 together was 2.7 kBq for children < 8 years and 14 kBq for adults. The committed effective dose of 99.8% of the residents was below 1 mSv. There were 25 people with doses >1 mSv, and the maximum dose was 3 mSv. The extrapolated medians of the doses for 13-17 years old and those >17 years old were 0.02 mSv and 0.025 mSv, respectively. These findings are in line with investigations of the radioactivity in foodstuff using the total-diet method by Sato et al. (2013).

Health effects

Casualties among the workers at FDNPS and occupational radiation exposure

There were a number of causalities among the workers at FDNPS during and after the accident, but no deterministic radiation effects were observed. Two workers drowned from the tsunami inside the turbine building. They were found on 30.3.2011. There were injuries as consequence of the earthquake: two slightly injured TEPCO workers and two workers with broken legs from contractor companies. During the explosion of Unit 1 on March 12, 2011 two workers outside the controlled area were injured an during the explosion of Unit 3 four TEPCO workers, three workers from contractor companies, and four members of the Self Defense Forces were injured. Two workers from contractor companies were injured on March 22/23, 2011 when working at a temporary switch box of the power supply of the central spent fuel storage facility.

Detailed data on the occupational exposure of the workers at FDNPS are not presented here because of space limitation. They can be found in UNSCEAR (2014). Just so much: according to TEPCO 174 workers received more than 100 mSv; 100 mSv – 150 mSv:

137 workers; 150 mSv – 200 mSv: 28 workers; 200 mSv – 250 mSv: 3 workers, more than 250 mSv (309 mSv – 678 mSv): 6 workers. No deterministic effects were observed among the workers. Even those three workers who worked for some time in highly contaminated water did not get high enough doses to develop deterministic effects. Respective reports in the German TV were false and the pictures shown fakes.

In 2015, one case of leukemia among the workers at FDNPS was compensated as radiation induced after a radiation exposure of 20 mSv. Compensation is granted in Japan if a nuclear power plant worker has been exposed to an annual radiation dose of 5 mSv and has developed cancer more than a year afterward.

Collateral damage: chaotic evacuation orders

A total of 146,520 residents were evacuated as a result of the government's evacuation orders. However, many residents in the plant's vicinity evacuated without accurate information. Unaware of the severity of the accident, they planned to be away only for a few days and evacuated with only the barest necessities. Evacuation orders were repeatedly revised as the evacuation zones expanded from the original 3-kilometer radius to 10 kilometers and later, 20 kilometers, all in one day. Each time the evacuation zone expanded, the residents were required to relocate. Some evacuees were unaware that they had been relocated to sites with high levels of radiation. Hospitals and nursing homes in the 20-kilometer zone struggled to secure evacuation transportation and find accommodations. As a consequence, 60 patients died in March from complications related to the evacuation. Frustration among the residents increased (http://naiic.go.jp/en/blog/reports/main-report).

NHK reported that at least 5 people probably had died of starvation after being stranded in the evacuation zone around the Fukushima Dai-ichi nuclear plant following the disaster. Some people were left behind during evacuation. One man in his 70s, who lived about 5 kilometers from the plant, was found in late March on the 2nd floor of his home. The 1st floor had sustained damage from the tsunami. A woman in her 60s was found dead in April inside her home, where she lived alone. She had had trouble walking. All of the 5 dead were found grossly underweight. Police and medical authorities examined the 5 bodies and said they appeared to have been stranded, either because they were unable to evacuate on their own or could not ask for help (NHK March 5, 2012 18:40 +0900 JST).

Radiation induced effects in the population and reports of thyroid diseases

WHO (2013) has estimated the life-long health risks for the most exposed people in Fukushima Prefecture. The exposures were too low to provoke deterministic effects among the general population and the workers at the FDNPS. The exposures were also too low to cause fetal dysplasia. No increase of miscarriages, perinatal mortality, malformations or reduction of mental capabilities is to be expected. WHO calculated increased risks for leukemia, solid tumors, breast- and thyroid cancer for the most exposed people in Fukushima Prefecture. The results of the WHO calculations can be regarded as upper limits of the expected risks for cancer and leukemia. The risks are, however, so low that an increase of cancer and leukemia will hardly be discernible among exposed members of the public or their descendants.

In contrast to the above statement were surprising media reports that ultrasonic investigations of 40.000 children from Fukushima Prefecture exhibited for 35% of the children knots and/or cysts in their thyroid glands (Nagataki et al. 2012). The German ZDF reported on November 18, 2011in the daily news at 7 p.m. that thyroid diseases increased after the reactor accident in Fukushima. It was stated that the radioactive Cesium should be to blame. A Japanese scientist emphasized in an interview that no control data of comparative groups did exist.

Actually, in Japan a large scale screening of thyroid glands was undertaken for children from Fukushima prefecture using high-tech ultrasonic devices revealing a high prevalence of thyroid abnormalities (Table 4, left part). A comparative group was not investigated and it took until 2013 analogous investigations in the Prefectures Aomori, Yamanashi, and Nagasaki showed similar and partially even higher occurrences of such abnormalities (Table 4, right part). The respective investigations were continued and by the year 2016 more than 300,000 children have been screened in Fukushima Prefecture, resulting in the observation that approximately 50% showed solid nodules or cysts. Until the end of the year 2014, 110 thyroid cancers had been identified. Comparing the thyroid doses in Japan with those in Belarus and Northern Ukraine after the Chernobyl accident which have meanwhile caused more than 5,000 additional thyroid cancers, it appears highly unlikely that the observations in Japan are related to the radiation exposure. There are a lot of open scientific questions regarding this issue. The problem was recently commented in Science under the headline "Epidemic of fear" (Normile 2016).

Fukushima Prefecture			Prefectures Aomori, Yamanashi, Nagasaki		
Children aged 0 – 18 years			Children aged 3 – 18 years		
Status	No of children	fraction	Status	No of Children	fraction
A1	24.468	64,2 %	A1	1855	42,5 %
A2	13.460	35,3 %	A2	2466	56,5 %
B	186	0,5 %	B	44	1 %
C	0	0 %	C	0	0 %

Table 4: Results of ultrasonic examination of thyroids of children in studies in Fukushima Prefecture by Nagataki et al. (2012) and in the prefectures Aomori, Yamanashi, and Nagasaki by Taniguchi et al. (2013). Categories: A1 without nodules or cysts, A2 with nodules less than 5,0 mm and/or cysts less than 20,0 mm; B with nodules greater than 5,1 mm and/or cysts greater than 20,1 mm; C immediate further examination required.

Summarizing the health implications the UNSCEAR (2014) report stated

- No radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident.
- The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low.
- No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants.
- The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation.
- Effects such as depression and post-traumatic stress symptoms have already been reported. Estimation of the occurrence and severity of such health effects are outside the Committee's remit.

Psychological and social consequences

One of the important lessons learnt from Fukushima accident is that psychological and social consequence of such an accident may by far outweigh the direct radiation-induced health consequences. In June 13, 2012 the ASAHI SHIMBUN reported about a survey of evacuees on mental health issues related to the disaster. It was estimated that 20 percent were likely to be in need of counseling. Regarding children who were junior high school students or younger, 18 percent of the 13,000 who responded were considered likely to need some form of assistance or counseling in the future. The figure was reported to be nearly twice as high as the percentage for children under normal circumstances. On the adult side, 24 percent of the 35,000 people who responded to the survey were deemed to be in a high-risk category regarding mental health issues.

Similar effects have already been observed after the Chernobyl accident. Post-traumatic stresses, the loss of homes, of the economical basis and of the social structure find their manifestation in physical health problems which are not induced by radiation. One observes so-called learnt helplessness which is amplified by social stigmatization and marginalization. In the meantime, the term “Fukushima hibakusha” is used in Japan for the survivors assigning them to the same degrading status as the hibakusha of the atomic bombings at Hiroshima and Nagasaki.

Conclusion

There was a lot of good fortune in the course of the accident for the Japanese people. In spite of a lot of possible criticism, the accident was handled sufficiently well by the authorities if one considers the conditions after the natural disaster. However, the communication with the public was a disaster though information was widely spread. There was no understanding of the information and no trust in the government.

The radiation exposures remained relatively low, no deterministic effects occurred and the likelihood of future stochastic health effects is low. However, the social and psychological consequences will stay for long. The clean-up of the highly contaminated regions is still going on and its final success is not really foreseeable.

Several lessons had to be learnt by the international community. Major reactor accidents may happen. Emergency preparedness has to account for combined natural disasters and reactor accidents. Psychological and social aspects have to be taken into account in emergency preparedness. Emergency measures have to be discussed with the public before an accident occurs; after an accident it is too late. These will be some of the important task for radiation protection, regulators, practitioners and scientists – worldwide.

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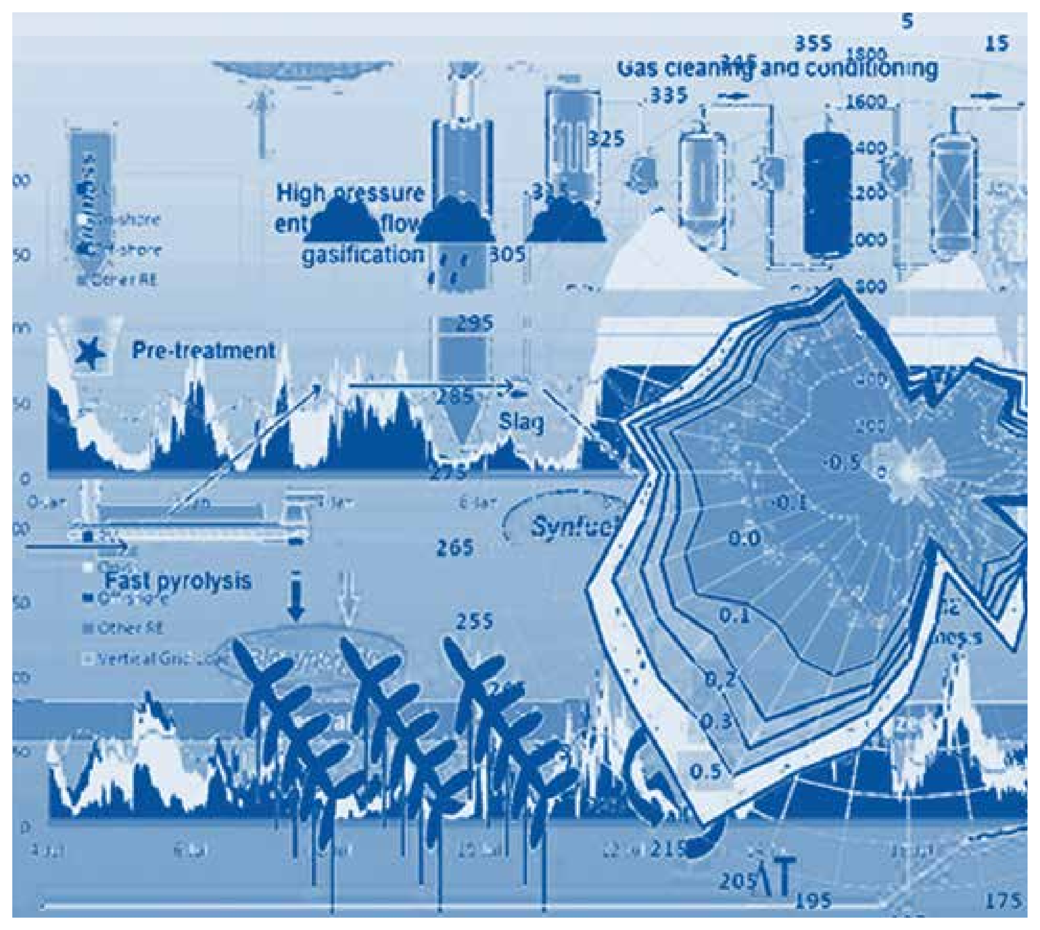
Arbeitskreis Energie



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Arbeitskreis Energie in der Deutschen Physikalischen Gesellschaft

Herausgegeben von Hardo Bruhns

Bad Honnef, August 2016

Frühjahrstagung des Arbeitskreises Energie in der Deutschen Physikalischen Gesellschaft

Regensburg, 6. bis 9. März 2016

Haupt- und Fachvorträge

Inhaltsverzeichnis / Table of Contents

Der vorliegende Band versammelt schriftliche Ausarbeitungen von Vorträgen auf der Tagung des Arbeitskreises Energie in der Deutschen Physikalischen Gesellschaft des Jahres 2016 in den Räumen der Universität Regensburg. Leider ist es nicht gelungen, von allen Vortragenden Manuskripte zu erhalten. Die Präsentationsfolien der meisten Hauptvorträge können auf der Webseite des Arbeitskreises über:

http://www.dpg-physik.de/dpg/organisation/fachlich/ake.html

(von dort gelangt man zum Archiv des AKE) eingesehen werden. Allen, die zu diesem Sammelband beigetragen haben, sei an dieser Stelle sehr herzlich gedankt.

Düsseldorf, im August 2016 Hardo Bruhns